An exploration of assessment options for eastern Bering Sea snow crab that consider additional time-variation in population processes

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A. Overview

Two assessment configurations were presented in September 2020: the status quo assessment model and an assessment based on the GMACS platform. The SSC chose the status quo model over the GMACS implementation for snow crab in October 2020 as a result of retrospective patterns and large estimates of the recruitment for 2015 from GMACS. The large estimates of recruitment from GMACS produced large OFLs and resulted primarily because GMACS fit the last two years of survey biomass better than the status quo model. When forced to fit the final two years of survey MMB similarly well as GMACS, the status quo model produced estimates of recruitment and the OFL comparable to GMACS.

Retrospective patterns are present in both the status quo model and the GMACS model. For example, in the 2019 SAFE document, the Mohn's rho ranged from 0.48 to 0.54 for four selected configurations of the status quo model (which was somewhat less than the 0.66 for the 2020 GMACS model). When confronted with retrospective patterns in a stock assessment, three options are commonly considered: 1) incorporate more model structure to allow the necessary flexibility to fit the data (e.g. allow a process to vary over time that was not previously varying over time), 2) perform post hoc adjustments of the management quantities based on the magnitude of retrospective patterns (similar to what the CPT suggested by increasing the buffer to 50% for the ABC in 2020), or 3) use a survey-based index of abundance or biomass to set the OFL (similar to the Tier 4 harvest control rules).

A CIE review occurred in March of 2021 for the snow crab assessment. Final reports have not yet been received, but retrospective patterns, their potential causes, and methods for addressing them were central themes of discussion. Reconsidering data weighting and further exploration of the CPUE data for use in assessment and management were also key suggestions.

This document primarily explores methods to address retrospective patterns in the snow crab assessment, given retrospective patterns were a common issue of concern for the CPT, the SSC, and the CIE reviewers. The most pressing problem for this assessment appears to be time-variation in multiple processes for which we lack informative data. Substantial time-variation in multiple processes not only makes estimation of the terminal year of exploitable biomass difficult, it also make the calculation and interpretation of reference points difficult. Ultimately, it is not clear how to overcome this problem. Each method presented has pros and cons, but none present a completely satisfying method to address retrospective patterns. Future work evaluating management strategies with data simulated from operating models that have multiple time-varying processes will hopefully illuminate a path forward. In the interim, either post hoc adjustments to the integrated assessment output or modifications of the Tier 4 methodology are likely the best way to address retrospective patterns in the snow crab assessment.

Before presenting the analyses, comments from the SSC are addressed below.

B. SSC comments + author responses

SSC comment: Generally, the SSC accepts a new model when it represents an improvement over the previous model. There are some improvements and advantages with the author-preferred GMACS model relative to the status quo model, but there are also some unresolved problems. Beyond improved fits to the data, one of the most important evaluation criteria is biological plausibility of the results, and a new modeling framework is only as good as the plausibility of the results. The SSC noted that it seems unlikely that the stock is 4x larger than last year's estimate, while lacking new survey data to support that conclusion.

The estimated MMB for the author preferred model in 2019 was 167 kt; in 2020 it was 276.7 kt (a ~65% increase). Model 20.3 did have a larger change than this, but it was not the author-preferred model. The changes in the author-preferred model were consistent with changes observed in the stock when similarly sized recruitments entered the population. The numbers at length in the survey from 2015-2018 consistently suggested a cohort larger than has ever been observed (Figure 1). However, the survey data from 2019 suggested a decline in numbers across all size classes. Even with that decline, the remaining numbers at length were comparable to the cohort that supported >100 kt catches in the late 1990s at a similar point in its development (see the 1996 numbers at length and compare that to the retained catches in 1997).

SSC comment: Despite this change in scale, there is still a very large positive retrospective pattern which is puzzling because one would expect this positive bias to be reduced if the previous model was overestimating stock size. The SSC recommends further efforts to reduce the large retrospective pattern in future models, perhaps through time-varying catchability, natural mortality changes, or different selectivity functions.

Author response: The retrospective patterns exist in both the status quo and GMACS model (see the SAFE from 2019 in which the retrospective pattern from the status quo model had a Mohn's rho of 0.54-0.48). Time-varying catchability and natural mortality are explored below in the status quo model and result in smaller retrospective patterns, but produce different management advice. Implementing any new time-varying process in an assessment with a retrospective pattern will improve the retrospective pattern, but management advice can be drastically in error if the incorrect process is allowed to vary (Szuwalski et al., 2019). Consequently, an understanding of what process is time-varying is recommended before implementation of time-variation in integrated assessments.

SSC comments: The author and CPT had concerns with how recruitment variability is controlled in Model 20.2, which does not appear to have been resolved with the extremely large estimated 2015 year class in the author's preferred model. The GMACS model (20.2) seemed to fit some of the data slightly better, most particularly the MMB survey data in the terminal years, but the SSC considered the recruitment deviation problem too big to ignore. Until a resolution is reached on how to appropriately control recruitment estimates, the author provided a sensitivity to each of the 2018 and 2019 survey data points. This sensitivity revealed that the model responded differently to each survey and showed that under either survey scenario, Model 20.2 was still providing higher estimates of MMB compared to the status quo model (20.1).

Large estimates of recruitment from the GMACS model compared to the status quo are primarily a result of poor fits of the status quo model to the survey data. An example is presented here in which the status quo model is forced to fit the survey data in the terminal years by inputting smaller CVs. This results in estimates of recruitment similar to GMACS (though not quite as large) and an estimated OFL of 175 kt. The 2015 cohort was on track to be the largest ever recorded based on the observations of numbers at length from 2015 to 2018 (Figure 2). However, the survey data in 2019 showed a substantially reduced cohort across most size classes. It is unclear whether this reduction was a result of a mortality event or changes in catchability.

SSC comments: Another feature of the author-preferred GMACS model is extremely high fully-selected fishing mortality in some years that would imply that 95 - 98% of fully-available large crab would have been harvested, which does not seem logistically possible.

Author response: This is actually a feature of the status quo model, not GMACS. Fishing mortality estimates from GMACS in the period over which those high exploitation rates occur in the status quo model are much lower. This is one of the reasons GMACS was the author-preferred model in 2020.

SSC comments: In addition, the authors noted that there were no jittering tests done on Model 20.2 and that the alternative GMACS configuration (20.3) had some convergence issues.

Jittering capabilities are still being developed for GMACS. The convergence issue was related to forcing catchability to match the BSFRF implied catchability, which has also resulted in convergence issues in the status quo model in the past.

SSC comments: The SSC requests the authors provide a biological rationale, if there is one, for differences in the sex ratio of recruitment.

Author response: Differences in growth, different spatial distributions, differences in time-variation in other processes like maturity are all possible reasons this might occur. All of that said, females do not enter either the federal or state harvest control rules. Given the numerous uncertainties in attempting to estimate mature male biomass, adding another source of uncertainty by forcing males to be linked to females does not seem sensible given the outcomes, which include even larger retrospective patterns than currently observed in the status quo and GMACS models.

SSC comments: As with all assessments, the estimation of natural mortality is a challenge for snow crab. The SSC recommends that the authors consider examining the web-based Barefoot Ecologist tool to develop a natural mortality prior distribution for snow crab.

Author response: The methods used to calculate a prior for natural mortality in the 2020 assessment were the same methods used by the Barefoot Ecologist when maximum age is available.

SSC: comments: VAST modeling for the bottom trawl survey was postponed this year and the SSC would like to see it move forward as model-based indices may help add robustness to future missing survey data or a potential change in spatial distribution into the northern Bering Sea.

Author response: A run with VAST indices is included this year. The estimates from VAST are markedly different in some years and, while CVs are smaller in many years, in other years they are much larger. It is not difficult to perform another run with a VAST-derived index each year, but understanding whether or not the outcomes are sensible when large differences appear is less easy. Given the number of other issues with the snow crab assessment, this should be a low priority.

C. Summary of assessment scenarios for May 2021

Seven Tier 3 assessment models are presented here:

- 20.1 – Last year's accepted model (status quo) fit to last year's data
- 20.1g – Last year's GMACS model fit to last year's data
- 20.2 – Last year's accepted model (status quo) fit to last year's data with down-weighted size composition data (all weights equal 100, rather than 200)
- 20.2q – 20.2 + time-varying survey catchability from 1989-present
- 20.2m – 20.2 + time-varying natural mortality for mature males and females
- 20.2qm – 20.2 + time-varying survey catchability from 1989-present and time-varying natural mortality for mature males and females
- 20.2v – 20.2 + VAST survey estimates

Growth was estimated outside of the model for 20.2 and the models with additional time-variation. Initial runs of models with additional time-variation did not converge while growth was estimated inside the model and, so, in order to retain comparability with 20.2, growth was estimated outside of the model for each of these models.

In addition to the Tier 3 status quo and Generalized Model for Assessing Crustacean Stocks (GMACS) runs, a series of modified Tier 4 models are also presented in which the random effects model used by the groundfish plan team is used to calculate the time series of mature male biomass (MMB) used in the harvest control rule and spawning biomass per recruit (SBPR) proxies for reference points are calculated using 'empirical' estimates of relevant population processes. Processes estimated within the assessment are compared to the empirically derived estimates and some differences are observed.

D. Status quo and GMACS

Model description

The integrated size-structured model currently used (referred to within as the 'status quo' model) was developed following Fournier and Archibald's (1982) methods, with many similarities to Methot (1990). The population dynamics in the status quo model tracks the number of crab of sex s, shell condition v, maturity state m, during year y at length l, $N_{s,v,m,y,l}$. A terminal molt occurs in which crab move from an immature to a mature state, after which no further molting occurs. The mid-points of the size bins tracked in the model span from 27.5 to 132.5mm carapace width, with 5 mm size classes. Parameters estimated within the assessment include those associated with recruitment, growth, natural mortality (subject to a fairly informative prior), fishing mortality, selectivity (fishery and survey), survey catchability, and probability of maturing. Weight at length, discard mortality, bycatch mortality, and parameters associated with the variance in growth and proportion of recruitment allocated to size bin were estimated outside of the model or specified. Growth parameters are estimated outside of the model for some runs presented here. See appendix A for a complete description of the population dynamics.

The General Model for Assessing Crustacean Stocks (GMACS) was recently developed to promote consistency and comparability among crab assessments (see appendix for equations). Several crab assessments have been developed in GMACS and subsequently approved for use in management by the Crab Plan Team. GMACS was developed with king crab-like life histories in mind, but has recently been modified to accommodate terminally molting life histories. The structure of the population dynamics model in GMACS is now very similar to the status quo assessment model and can reproduce the dynamics of the male component of the status quo model precisely with the correct configuration (see May 2020 CPT opilio document). A single model (20.1g) identical to the GMACS model presented in September 2020 is presented here.

Six models built on the status quo assessment (20.1) are presented here. The first change to the status quo model (model 20.2) alters the weights for all of the size composition data components from 200 to 100. A

calculation of the effective sample sizes was performed in the CIE review and, although each data source had different effective sample sizes, the average was closer to 100 than 200. A more thorough exploration of weighting schemes will be explored after methods for addressing retrospective patterns are identified.

Model 20.2 is the base for the remaining status quo assessments, three of which which introduce time-variation in natural mortality (M) or catchability (q) or both of these processes (20.2m, 20.2q, 20.2qm, respectively). Models 20.2m and 20.2qm add a dev_vector to the existing estimated parameters for mature natural mortality of both sexes, plus a smoothing penalty, which helps convergence. Models 20.2q and 20.2qm estimate survey catchability during 1989-present with a vector of bounded parameters (bounds = 0 and 1) with a smoothing penalty. Smoothing penalties were chosen by trial and error, with the aim of making them as small as possible while still avoiding convergence issues. The final status quo assessment (20.3) replaces the design-based survey indices and associated coefficients of variation (CVs) with model-based indices and CVs from VAST.

Retrospective analyses were performed in which the terminal year of data was removed sequentially from the model fitting for the models in which additional processes were allowed to vary over time. Then estimated management quantities (e.g. MMB) were compared between the most recent model and successive 'peels' of the data to identify retrospective patterns. A retrospective pattern is a consistent directional change in assessment estimates of management quantities (e.g. MMB or the OFL) in a given year when additional years of data are added to an assessment. Mohn's rho (which computes the average difference between the reference case and the peels) was calculated for each retrospective analysis (i.e. including and excluding the terminal year survey data) to quantify the retrospective patterns. Retrospective analyses were performed only for the status quo models given that the retrospective analyses for the GMACS model were presented in September.

Additional runs of the status quo model (20.1) from the January CPT meeting are included to show the impact of forcing the status quo model to fit the final years of survey data on estimates of recruitment.

Model fits

All models produced a positive-definite Hessian and had maximum gradient components less than 0.004, except 20.2mq, which had a maximum gradient component of 0.01 for one of the recruitment deviations for males (the rest were < 0.004). The smallest viable smoothing penalties tested were 1 and 10 for natural mortality and catchability (respectively) when they were the only additional time-varying process in the assessment. When both processes were allowed to vary, the penalty for natural mortality had to be increased to 15 or the model did not converge. The likelihoods of the models are not comparable across the model platforms, so those are not included in this document. The viable models from these analyses were the same as those presented in September and the data has not changed, so the quantitative measures of model fit presented then (e.g. median relative absolute error) are not presented here. Updated quantitative measures of model fit will be added in September 2021 when new data are available.

Survey biomass data

The GMACS and status quo models without time-variation in M or q fit the survey MMB similarly except for in the late 1980s through early 1990s and late 2010s, during which GMACS fit the data better (Figure 3). Allowing time-variation in q or M improved the fits to the MMB data in the status quo model, particularly in recent years (Figure 4). All models with time-invariant M and q (20.1, 20.2, 20.1g) missed the confidence intervals of the last 5 of 6 years of survey MMB.

The survey MMB produced using VAST indices of abundance are somewhat higher than the status quo model and the fits to the index are correspondingly higher (Figure 5). The status quo model (20.2) can be forced to fit the last two years of data in a similar manner to GMACS by decreasing the CV for the 2018 data to 0.06 (Figure 6); the impact of this on estimated recruitment and the OFL is discussed below.

Retrospective patterns in MMB were observed in the status quo model 20.2, with a Mohn's rho of 0.36 (Figure 7). Allowing additional time variation in natural mortality (20.2m), catchability (20.2q), or both (20.2mq) reduced the retrospective patterns in MMB.

Growth data

Model 20.1 estimated male growth curves that produced higher growth increments at small sizes and lower growth increments at large sizes than GMACS or the other versions of the status quo model in which growth was estimated outside of the model (Figure 8). GMACS estimates of growth increments were most similar to the estimates produced outside of the model.

Catch data

Retained catch data were fit by all models well, but the status quo models fit the data slightly better than GMACS (Figure 9). Female discard data were fit more closely by GMACS, which is a reflection of the transition to CVs that force greater precision than the weights used in the status quo assessment. Male discard data during the period for which data exist (early 1990s to the present) were well fit by every model (Figure 9).

Size composition data

Total and retained catch size composition were similarly fit by both GMACS and the status quo models. However, GMACS predicted larger numbers of animals in the largest size bins for the first few model years (Figure 10). This phenomenon disappeared in later years with fits to the data that were practically indiscernible among models. Total catch and bycatch size composition data were both similarly fit by the models, with total catch size composition being fit more closely than the bycatch data (Figure 11 & Figure 12).

Fits to size composition data for the BSFRF survey selectivity experiments produced some notable runs of positive and negative residuals for males (Figure 13). GMACS fit the data in 2010 (which are most important for informing catchability) better than the status quo assessment, but which model best fit the 2009 data was less clear.

Notable differences in fits to NMFS survey size composition data existed among models (Figure 14, Figure 15, Figure 16 & Figure 17). GMACS fit the immature female size composition data better in many years (e.g. 1984, 1986, 1996, 1997, 2007); GMACS fit the immature males more similarly to the status quo model than the immature females. Fits to mature male size composition data were also similar between models and the few differences seemed to favor GMACS (e.g. 1984, 1990, 2017-18). Differences between models for fits to mature female size composition data were the smallest for survey size composition data.

Estimated population processes and derived quantities

Estimated population processes and derived quantities varied among models. Model 20.2mq produced the largest historical estimates of MMB, resulting from allowing both M and q to vary over time (Figure 18). Model 20.1g (GMACS) produced the largest estimate of MMB in 2019.

All status quo and GMACS models estimated lower catchability in survey era 1 (1982-1988) relative to era 2 (1989-present) for males, except the model that used VAST biomass indices. The shapes of the NMFS selectivity curves were similar among all models; the largest changes were seen in the catchability coefficient (Figure 19). Status quo models that allowed at least one additional time-varying process (20.2q, 20.2m, 20.2mq) all had average catchabilities similar to the BSFRF implied catchability. However, the variability for 20.2q and 20.2mq was large, with estimated values ranging from ~0.2 to ~1 (Figure 20).

Predicted availability curves for the BSFRF experimental surveys were similar across assessments in years with similar configurations (Figure 21). The status quo assessment historically used a logistic curve for the availability for females in 2009, but this is likely overly restrictive. GMACS estimated a vector of availabilities for both years and sexes of BSFRF data, which more closely reflect the empirical availabilities.

The shape of the estimated curve representing the probability of maturing for both sexes were similar within sex, but the magnitude of the probabilities varied, most strongly for males in the 70-90 mm carapace width range (Figure 22). The estimated probability of maturing at smaller sizes was consistently higher for females in GMACS and this is related to the change from a kinked growth curve to a linear growth model. The 'hump' at 32.5 mm carapace width for females is likely related to the specified curve that determines what fraction of incoming recruitment is placed in which length bin, which has a peak at the same spot as the probability of maturing. Model 20.2mq had the highest fraction of sublegal and sub-industry-preferred crab maturing.

Estimated fishing mortality scaled with estimated population size across models (Figure 23). GMACS models generally estimated fishing mortality lower than the status quo models during survey era 1. Estimated fishery and discard selectivity were dissimilar between model type (i.e. GMACS vs. status quo), which is related to how selectivity and fishing mortality are treated in the code (see the May 2020 snow crab document for more discussion). GMACS estimates of female discard mortality were lower than the status quo, but, when balanced with changes in estimated selectivity, the estimated catches were similar to the status quo (Figure 9).

Patterns in estimated recruitment by sex were similar for both GMACS and status quo models, but GMACS estimates were more variable than the status quo estimates (Figure 24).There was a considerable amount of variability in recruitment estimates for 2015 among models, and GMACS had the highest estimates. Recruitment was larger in GMACS than the status quo model and the size of this recruitment is a strong driver of the current year MMB and OFL. When the status quo model is forced to fit the data in a similar manner to GMACS, the estimated recruitment from the status quo model is very similar to GMACS, as is the estimated OFL (175 kt; Figure 6).

Estimated natural mortality from the GMACS model for immature crab was higher than the status quo models, in spite of identical priors (Figure 25). Estimated immature natural mortality was generally higher than mature natural mortality in GMACS, which was not seen in the status quo model for females. Estimates of mean natural mortality were smaller for models in which natural mortality was allowed to vary over time than for those in which natural mortality was constant over time. Natural mortality sharply increased in the last several years for 20.2m, but only rose sharply in the last three for 20.2mq and reaching higher mortality levels (Figure 26).

E. Random effects model

Estimates of biomass

A random effects model was fit to the survey male biomass for estimation of the MMB and ABC. This model was developed for use in NPFMC groundfish assessments and is used for some Tier 4 crab assessments (e.g. PIRKC). The likelihood equation for the random effects model is:

$$\sum_{i=1} 0.5(log(2\pi\sigma_i^2) + \frac{(\hat{B}_i - B_i)^2}{\sigma_i^2}) + \sum_{t=2} 0.5(log(2\pi\sigma_p^2) + \frac{(\hat{B}_{t-1} - \hat{B}_t)^2}{\sigma_p^2}) \tag{1}$$

where B_i is the observed biomass in year i, $\hat{B}_t$ is the model estimated biomass in year t, σ_i^2 is the variance of observed biomass in year i, σ_p^2 is the variance of the deviations in log survey biomass between years (i.e. process error variance). σ_p^2 was estimated as $e^{2\lambda}$, where λ is a parameter estimated in the random effects model.

Deciding which time series of biomass to use as input to the random effects model (and then ultimately into the harvest control rule) requires some thought. The definition of 'legal' crab is greater than 78 mm carapace width, but the industry preferred size is >101 mm carapace width. In pursuing the industry preferred crab, smaller crab are caught incidentally and some mortality occurs. So, >95 mm carapace width may be an acceptable compromise that allows for considering total selectivity, rather than just retained. The reproductive contribution of each size is also important to consider (discussed more below). For the sake of comparison, all three indices were calculated with the random effects model.

Using a smaller size bin as the starting point for inclusion in the index predictably increased the scale of the time series (Figure 27). Estimated biomass in 2019 was 175 kt, 54.5 kt, and 28.9 kt for the time series based on >78 mm, >95 mm, and >101 mm crab, respectively. The random effects does not project estimates for years of biomass beyond which there are data, which is inconvenient for this document since survey data is not available in 2020 and this impairs comparison across models.

Survey selectivity and catchability

The random effects model assumes that catchability is 1 for the NMFS survey gear given the above inputs. 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 (Figure 28). These were aimed at understanding the efficiency of the NMFS trawl gear with respect to crab (see Somerton et al. 2013). Snow crab were targeted in 2009 and 2010, but also incidentally caught in 2016, 2017 and 2018 (Figure 29). The estimated numbers at length data gleaned from these experiments (and the NMFS survey observations occurring in the same areas; Figure 30 & Figure 31) can be used to estimate selectivity at size for the NMFS gear. The key assumption required to estimate the selectivity is that the selectivity of the BSFRF gear is equal to one for all size classes.

The empirical estimates of selectivity derived from these data vary from year to year (Figure 32). However, the general trend is the selectivity of the NMFS gear is considerably less than one for most sizes of crab (Figure 33). For those size classes that appear to have NMFS selectivity close to one (e.g. >110 mm), the sample sizes are quite small. There is no immediately obvious reason why the selectivity of a 101 mm carapace width crab would have a ~0.4 probability of capture and a 120 mm carapace width crab would have a ~0.9 probability of capture. Consequently, survey selectivity is assumed to be logistic in the assessment. For simplicity's sake, the catchability of the large size classes was assumed to be 0.5 to demonstration how these methods can be applied. This resulted in estimated biomass in 2019 of 350 kt, 109 kt, and 57.8 kt for the time series based on >78 mm, >95 mm, and >101 mm crab, respectively.

In the future, a distribution of the catchability of the different size classes of crab included in the time series entered into the random effects model could be generated by bootstrapping the inferred selectivity at size over years and potentially space. Then, the estimates of MMB from the random effects models could be adjusted based on these distributions of catchability. It may also be preferable to apply the catchability/selectivity to the survey data before entering it into the random effects model, as it would avoid collapsing the catchability information over size classes. However, it would also require many iterations of the random effects model to be run to characterize the distribution of MMB. If the CPT and SSC are interested in the modified Tier 4 methodology, this will be explored for September.

Tier 4 proxies for BMSY

Tier 4 assessments specify proxies for the biomass at which maximum sustainable yield occurs (BMSY) as the mean biomass over a period of time during which the stock is assumed to be fished at FMSY. This is a somewhat tricky assumption for recruitment driven stocks like snow crab. The periods of highest biomass correspond to the periods of the highest estimated fishing mortality in the integrated assessment. However, given a lack of better options, the Tier 4 proxy for BMSY is specified here as the mean over the entire time series for a given time series of estimates from the random effects model.

F. Spawning biomass per recruit proxies for FMSY

Historically, Tier 4 models have used natural mortality as a proxy for the fishing mortality that would produce maximum sustainable yield. The use of natural mortality is often a response to a lack of information on population processes like growth, selectivity, and maturity that are needed to calculate more accurate reference points like the fishing mortality that decreases spawning biomass per recruit (SBPR) to 35% of unfished levels (F35%; Clark, 1991). Both the status quo and GMACS assessments currently use SBPR proxies for fishing mortality and biomass reference points based on the estimates of population processes from within the assessment. Similar reference points can be calculated with a population dynamics model and the data that inform these processes in the assessment.

Here, I calculate SBPR proxies for FMSY, but, instead of estimating parameters associated with these processes within an assessment model, they are 'empirically' estimated and specified within a slightly simplified population dynamics model used for projections. The key simplifications being the lack of females and trawl mortality–the rest of the model structure matches the status quo population dynamics in appendix A. The empirically estimated parameters of the population processes are not perfectly known. To represent this uncertainty, 1000 Monte Carlo draws are performed for each of the population processes to develop distributions for F35%.

Life history characteristics

Estimated parameters for growth, fishery selectivity, natural mortality, weight at length, and probability of maturing are required to calculate F35%. Below is a description of the information available and the process for estimating the parameters and uncertainty associated with the population processes used to calculate F35%.

Natural mortality

Relatively few targeted studies exist to determine natural mortality for snow crab in the Bering Sea. In one of these studies, Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt (Figure 34). The total sample size was 21 male crabs (a combination of Tanner and snow crab) from a collection of 105 male crabs from various hauls in the 1992 National Marine Fishery Service (NMFS) Bering Sea survey. Representative samples for the 5 shell condition categories were collected from the available crab. Shell condition 5 crab (SC5 = very, very old shell) had a maximum age of 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years; carapace width of 110 mm). The average age of 6 crabs with SC4 (very old shell) and SC5, was 4.95 years (range: 2.70 to 6.85 years).

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.

Inspection of the survey data suggests that natural mortality for mature individuals is relatively high. A fraction of the mature population is not selected in the fishery (e.g. sizes 50-80 mm; Figure 35). 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.

Based on these pieces of information, the highest maximum age for snow crab in the Bering Sea is likely no more than 20 years. However, it could also be less than that. Here, a rough estimate for the distribution of potential maximum ages is generated by truncating a normal distribution with mean 20 and standard deviation 3 at 20. This results in a distribution of potential maximum ages that has 75% of its density between 16.47 and 20 years (Figure 36), which overlaps acceptably with the above information. This distribution of

maximum ages translates to a distribution of natural mortality that has 75% of its density between 0.27 and 0.33 using the maximum age based empirical estimator from Then et al. 2015 -(Figure 36).

Weight at length

Weight at length is calculated by a power function, the parameters for which were recalculated by the Shellfish Assessment Program in August 2016. No uncertainty was incorporated into the calculations of F35% based on the weight at length data, but this may be revisited in the future.

Maturity

Maturity is an important determinant of SBPR-based reference points because it demarcates the fraction of the population that constitutes the unfished biomass, which in turn determines the fishing mortality rates that will deplete the population to target levels.

In the current snow crab assessment, maturity is defined as 'morphometric' maturity, which is determined by chela height measurements. When male crab terminally molt, their claws (chela) are larger than an immature crab of the same carapace width. Chela height measurements are available starting from the 1989 survey (Otto 1998), and annual probabilities of undergoing a terminal molt to maturity were provided by the Kodiak Shellfish Laboratory using these data. The probability of maturing at a given size was calculated by subsetting the survey data to only new shell males, then calculating the proportion of males with large claws in a given year (Figure 37).

Morphometric maturity is one way to classify mature males, but the relative importance of morphometrically mature males of different sizes in mating is unclear (i.e. does a 70 mm carapace morphometrically mature male play the same role in reproduction as a 110 mm carapace width male?). Furthermore, old shell mature males may be disproportionately 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.

An appreciable fraction of males can terminally molt to maturity starting around 60mm, which consequently means that a large fraction of the morphometrically mature biomass is protected from the fishery by the industry-preferred size of >101 mm carapace width. If the sub-preferred size males are included in the biomass targets, this can result in high target fishing mortality rates on large individuals.

To test the sensitivity of F35% to the definition of maturity, four different probabilities of 'maturing' were used:

- The assessment estimated probability of terminal molt, representing the idea that all morphometrically mature animals are equally important in reproduction.
- The observed probabilities of terminal molt from 1990-2019 (with a few years missing due to a lack of chela height measurements). When observed probabilities were used, a year of probabilities was randomly sampled, then the entire projection to calculate F35% used that ogive. This also represents the idea that all morphometrically mature animals are equally important in reproduction, but changes the probability of becoming a morphometrically mature male at size.
- A knife-edged ogive that increases to a probability of 1 at 95 mm carapace width, representing the idea that males over 95 mm are most important in reproduction.
- A knife-edged ogive that increases to a probability of 1 at 101 mm carapace width, representing the idea that males over 101 mm are most important in reproduction.

Growth

Forty three pre- and post-molt data points are available to determine molt increment for male snow crab in the Bering Sea. Size transition matrices were developed by bootstrapping the data 15 points at a time and fitting a linear regression to predict post-molt carapace width from pre-molt carapace width. The resulting pairs of intercepts and slopes were sampled randomly to generate size transition matrices. The variability around a growth increment was defined using a discretized and re-normalized normal distribution with a standard deviation of 4. This results in size transition matrices similar to, but not precisely the same as those estimated in the assessment (Figure 38).

Fishery selectivity

Fishery selectivity has two components in the snow crab fishery: total and retained. Three data sources and (at least) 1 critical assumption were used to calculate total and retained selectivity for the snow crab fishery. The data include: total male numbers size composition data from the survey for the years for which observer data are available (1992-present), the total size composition data from the fishery (1992-present), and the retained size composition data from the fishery (1992-present). Fishery selectivity in a given year can be inferred from the relative shapes of the size composition data with the assumption that the maximum density in the catch size composition represents the first size class for which that selectivity is 1. This matches the assumption of logistic selectivity in the integrated assessment.

A worked example might clarify the idea. The survey size composition provides the relative numbers at length for the population and a reference for total selectivity (Figure 39). By assuming the maximum of the total catch represents the first size class where total fishery selectivity is 1, we can place the survey size composition data and the total size composition data on the same scale by rescaling each of the size compositions by a (different) constant that forces the value in the size class that is the maximum in total selectivity to equal one for both size compositions. The third panel of Figure 39 shows this transformation. Finally, the scaled total size composition is divided by the scaled survey composition to produce the inferred selectivity (bottom panel of Figure 39). Selectivities after the maximum of the unscaled catch size composition can be less than or greater than 1 (see bottom panel). In order to avoid cryptic biomass, all selectivity at size after the maximum of the total catch size composition is set to 1.

Comparison of empirical estimates to assessment estimates

Each of the processes estimated from the above methods has an estimated counterpart in the assessment and, although the estimates from the assessment and the empirical exercises are similar, they do not all perfectly match. For example, the assessment estimates of the probability of maturing are somewhat lower over the 70 mm to 95 mm carapace width range (Figure 37) and the size transition matrices are slightly different (Figure 38). The estimated total fishery selectivity from the assessment is shifted to the right of most of the 'empirical' estimates (Figure 40), but the assessment estimates of retained fishery selectivity are closer to the median of the observed (Figure 41). Although retained selectivity is closer to the observed, there is a clear difference over time with respect to rationalization. The respective assumptions made by both methods can result in different estimates for population processes. For example, the integrated assessment is fitting many data sources, so there can be tradeoffs between fits that are reflected in the estimates of parameters determining population processes. This does not happen in the 'empirical' analyses.

'Empirical' F35%

Distributions of F35% for different assumptions of reproductive contribution and fishery selectivity were developed by specifying distributions of each of the axes of variability (natural mortality, growth, maturity, fishery selectivity), then performing 1000 simulations in which the parameters determining each of theses processes were randomly drawn from the specified distributions. The random samples were held constant in

the projected population dynamics model and unfished biomass was projected given a constant recruitment. Then the fishing mortality that reduces the biomass to 35% of the unfished levels was found by the bisection method. This is the same methodology that occurs within the assessment method, only the parameters governing the population processes are specified based on analyses outside of the model.

Distributions of F35% varied widely based on the assumptions of what size of animals are important reproductively (Figure 42; fishing mortalities are translated to exploitation rates for ease of comparison in this figure). If only males greater than 101mm carapace width define the 'reproductive' stock, the median exploitation rate at which the number of 101mm carapace width males is reduced to 35% of unfished levels is 37%. If males greater than or equal to 95 mm carapace width are used, the exploitation rate increases to 52%. A target exploitation rate of 77% is produced when using the estimates of the probability of maturing from the assessment and this increases to >99% if the observed probabilities of maturing are used. These values are all calculated given the observed fishery selectivity for all years. Retained selectivity shifted to the right after rationalization, representing a more selective fishing process (Figure 41). If only the years of selectivity after rationalization are used, the calculated target exploitation rates all shift ~3% to the right.

The exploitation rate equal to the F35% calculated inside the integrated assessment in 2020 was 79%. This is very close the median of the distribution when the inputs to the SBPR calculations come from the assessment (77%). This suggests that the differences in the population dynamics models and the impact of sampling natural mortalities were relatively small.

G. OFL and ABC

Tier 3

The OFLs for the status quo and GMACS models were calculated using proxies for biomass and fishing mortality reference points and a sloped control rule. Proxies for biomass and fishing mortality reference points were calculated using spawner-per-recruit methods (e.g. Clark, 1991). After fitting the assessment model to the data and estimating population parameters, the model was projected forward 100 years using the estimated parameters under no exploitation 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. In models for which natural mortality or catchability varied over time, the average of the last 7 years of estimates of the varying process were used to calculate reference points. This is all similar to the procedure used for the empirical analysis, but bycatch mortality was not considered and time-variation was addressed through the Monte Carlo sampling.

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

$$F_{OFL} = \begin{cases} Bycatch & if\frac{MMB}{MMB_{35}} \leq 0.25 \\ \frac{F_{35}(\frac{MMB}{MMB_{35}}-\alpha)}{1-\alpha} & if0.25 < \frac{MMB}{MMB_{35}} < 1 \\ F_{35} & ifMMB > MMB_{35} \end{cases} \quad (2)$$

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

The calculated OFLs for the Tier 3 models ranged from 14 to 184 kt (Table 7). Although allowing for time-variation in natural mortality and catchability reduced the retrospective patterns in MMB, the resulting management advice could be drastically different. Model 20.2q and 20.2m produced OFLs that were 75-85% of the OFL produced from model 20.2. Model 20.2mq, however, was only 15% of the OFL from model 20.2. Much higher natural mortalities for the projection used to calculate F35% resulting from high estimates of M at the end of the survey time series produced very high target fishing mortalities (6.29 and 12.46 for model 20.2m and 20.2mq, respectively). Changing the smoothing penalty in 20.2m from 1 to 10 resulted in an OFL similar to 20.2mq (12.3 vs. 14, respectively).

Tier 4

The Tier 4 harvest control rule is similar to the Tier 3 rule, except the input target fishing mortality, target biomass, and current biomass are calculated differently (described above). Given no survey biomass estimates were available in 2020, the OFLs presented to demonstrate this methodology are for 2019. For reference, the OFL produced from the 2019 integrated assessment was 54.9 kt, ADFG set the TAC at 15.4 kt, and assessment estimated MMB, BMSY, F35% were 111.4, 126.1, 1.93, respectively.

Table 1: Management quantities from Tier 4 methods with varying assumptions. Row names represent the smallest size of crab included in the index. MMB in row names ending in '_q' was adjusted by a catchability similar to that implied from the BSFRF experiments. All weights are given in 1000 tonnes.

	MMB	BMSY	Status	F35	FOFL	OFL
78mm	175	162.9	1.07	1.64	1.64	119.2
95mm	54.5	98.04	0.56	0.81	0.41	15.52
101mm	28.9	71.32	0.41	0.47	0.16	3.56
78mm_q	350	325.9	1.07	1.64	1.64	238.4
95mm_q	109	196.1	0.56	0.81	0.41	31.05
101mm_q	57.8	142.6	0.41	0.47	0.16	7.13

The OFLs produced via this methodology ranged from 3.6 kt to 239 kt. The largest OFLs were produced when accounting for NMFS survey catchability, which doubled the MMB. When >78mm carapace width crab were considered to be the reproductively important portion of the population, the status of the population and OFLs were much higher. This is because the 2015 cohort was just starting to enter this size class in 2019, so there was an uptick in the biomass. This was not seen for >95mm or >101mm carapace width crab, which were still at historically low levels.

These methods are applied as other Tier 4 methodologies are (i.e. the proxy for FMSY is applied directly to the measure of MMB after decrementing the population by the appropriate number of months of natural mortality), but room for improvement exists. First, F35% was calculated for each scenario with a measure of fishery selectivity. So, when the FOFL is applied to the MMB , the fishery selectivity should be accounted for. This could be relatively easily done by pulling the terminal year survey size composition data into the calculation of the OFL after the FOFL is calculated. The uncertainty in the OFL could also be better represented by developing distributions for the OFL in a similar manner to the distributions for F35%. Instead of sampling population processes, MMB, F35 and BMSY would be sampled.

H. Risk table

The following template is used to complete the risk table:

	Assessment related considerations	Population dynamics considerations	Environmental ecosystem considerations	Fishery Performance
Level 1: Normal	Typical to moderately increased uncertainty or minor unresolved issues in assessment.	Stock trends are typical for the stock; recent recruitment is within normal range.	No apparent environmental or ecosystem concerns	No apparent fishery resource-use performance and/or behavior concerns
Level 2: Substantially increased concerns	Substantially increased assessment uncertainty/ unresolved issues.	Stock trends are unusual; abundance increasing or decreasing faster than has been seen recently, or recruitment pattern is atypical.	Some indicators showing adverse signals relevant to the stock but the pattern is not consistent across all indicators.	Some indicators showing adverse signals but the pattern is not consistent across all indicators
Level 3: Major Concern	Major problems with the stock assessment; very poor fits to data; high level of uncertainty; strong retrospective bias.	Stock trends are highly unusual; very rapid changes in stock abundance, or highly atypical recruitment patterns.	Multiple indicators showing consistent adverse signals a) across the same trophic level as the stock, and/or b) up or down trophic levels (i.e., predators and prey of the stock)	Multiple indicators showing consistent adverse signals a) across different sectors, and/or b) different gear types
Level 4: Extreme concern	Severe problems with the stock assessment; severe retrospective bias. Assessment considered unreliable.	Stock trends are unprecedented; More rapid changes in stock abundance than have ever been seen previously, or a very long stretch of poor recruitment compared to previous patterns.	Extreme anomalies in multiple ecosystem indicators that are highly likely to impact the stock; Potential for cascading effects on other ecosystem components	Extreme anomalies in multiple performance indicators that are highly likely to impact the stock

The table is applied by evaluating the severity of four types of considerations that could be used to support a scientific recommendation to reduce the ABC from the maximum permissible. These considerations are stock assessment considerations, population dynamics considerations, environmental/ecosystem considerations,

and fishery performance. Examples of the types of concerns that might be relevant include the following:

1. Assessment considerations—data-inputs: biased ages, skipped surveys, lack of fishery-independent trend data; model fits: poor fits to fits to fishery or survey data, inability to simultaneously fit multiple data inputs; model performance: poor model convergence, multiple minima in the likelihood surface, parameters hitting bounds; estimation uncertainty: poorly-estimated but influential year classes; retrospective bias in biomass estimates.
2. Population dynamics considerations—decreasing biomass trend, poor recent recruitment, inability of the stock to rebuild, abrupt increase or decrease in stock abundance.
3. Environmental/ecosystem considerations—adverse trends in environmental/ecosystem indicators, ecosystem model results, decreases in ecosystem productivity, decreases in prey abundance or availability, increases or increases in predator abundance or productivity.
4. Fishery performance—fishery CPUE is showing a contrasting pattern from the stock biomass trend, unusual spatial pattern of fishing, changes in the percent of TAC taken, changes in the duration of fishery openings."

Assessment considerations

Several assessment considerations exist for snow crab. As with all Bering Sea stocks, the 2020 survey data are missing for snow crab and analyses in September 2020 showed that the snow crab is particularly sensitive to missing survey data, particularly in the terminal years of the time series. This sensitivity is related to the second serious assessment consideration for snow crab: large retrospective patterns. Mohn's rho for MMB has ranged from 0.36 to upwards of 0.80 since retrospective analyses began being performed for this stock. Severing the link in recruitment for sexes improved the retrospective pattern in MMB, but did not entirely fix it. Finally, regardless of which model is chosen (GMACS vs. status quo), the estimated survey MMB misses the confidence intervals for 5 of the last 6 years. For these reasons, this element is given a score of 3.

Population dynamics considerations

The key population dynamics consideration for snow crab is uncertainty around the size of the cohort currently entering the exploitable biomass. In 2015, the largest cohort observed in the history of the survey recruited to the survey gear. The survey selectivity is low for small crab, so the cohort size in that first year was uncertain, but the cohort was tracked and developed until 2018, when the number of crab at ~50mm carapace width was the largest ever observed. The cohort appeared much smaller in 2019, presumably either due to a change in catchability or natural mortality. Given no data were collected in 2020, the fate of this cohort remains a mystery. The unprecedented size and uncertainty around this cohort earns this element a score of 4.

Environmental/ecosystem considerations

No immediate red flags are apparent, primarily because it is not clear what indicators would be appropriate for use as red (or green) flags. This element is given a score of 1.

Fishery performance

Fishery CPUEs have been on a general decline after a large peak post-rationalization in 2005. The fishery CPUE in the 2020/21 season was higher than the long-term average, but high CPUEs were sustained by fishing in statistical areas farther north than are usually productive. Because of the shift in spatial distribution of the fishery, this element is given a score of 2.

Assessment related considerations	Population dynamics considerations	Environmental ecosystem consideration	Fishery Performance considerations
Level 3: Major concerns	Level 4: Extreme concern	Level 1: no increased concerns	Level 2: Substantially increased concerns

I. Summary and recommendations

Although the exercises outlined in this document did not present a clear path for addressing the retrospective patterns in the integrated snow crab assessment, several useful things were learned.

Allowing additional time variation in population processes in the integrated assessment did improve retrospective patterns and fits to the survey biomass. However, without more data, it is difficult to justify choosing one process to vary over another (or both). Coupled with the fact that the management advice produced can be drastically different, just adding more structure to the model does not seem like a viable path for September 2021 model scenarios.

The 'empirical' exercise in developing distributions for F35% reaffirmed how important the metric for 'maturity' used is in defining reference points. Target exploitation rates ranged from 37% to 100% on fishery-selected biomass depending on what size of crab were considered important in reproduction. Understanding what part of the population is reproductively important is a key piece of information needed to understand what portion of the population needs to be protected.

The empirical exercise also showed that the estimates from the assessment for some key processes like fishery selectivity and the probability of maturing were different than implied by the input data. Differences in empirical selectivity may be a result of the assumptions made in calculating it and sensitivities to this assumption should be performed. It was less clear why the empirical probability of maturing was different from the estimates from the assessment. Regardless of the difference, it appears that, in addition to natural mortality and catchability, the probability maturing and fishery selectivity (particularly retained selectivity) appear to vary over time. Retained selectivity underwent a step change around rationalization and this change should be incorporated in whatever assessment is used going forward. More research is needed on the timing of transitions between maturity states and I am looking forward to the coming BSFRF symposium on the issue.

Generally, fitting multiple data sources in an integrated model is preferable when data are available to parameterize the model such that variation in the modeled processes are informed sufficiently enough to be estimated. Fitting multiple data sources at once allows the uncertainty in each process to be propagated appropriately, but also requires that the model is appropriately structured to make inference about population processes. This can be difficult if processes are confounded (like growth, natural mortality, and catchability). If confounded processes are also varying over time, estimating this variation can be exceptionally difficult (e.g. Johnson et al., 2014).

It is often thought that estimates of population processes can be improved by fitting multiple data sources because the information content in multiple data sources can corroborate and clarify the role of different processes in the population dynamics. This works well if the model is well-specified, but if it is not, estimating within an integrated assessment could result in incorrect inference about population processes. This could be one of the reasons that the empirical estimates differ from the assessment estimates of some population processes. The Tier 4 methods bypass the need to model the time-variation in population processes, and assumes that any time-variation in population processes will be faithfully represented in the observed size composition and survey biomass. This does not necessarily mean that the survey is an accurate absolute index of abundance, and it still may need to be scaled by a measure of catchability.

One of the key uncertainties is that we do not know if the variability observed in the survey biomass is caused primarily by issues related to the survey methods (e.g. time-varying catchability or measurement error) or by issues related to population dynamics (e.g. time-varying natural mortality or other sorts of process error).

This issue will not be solved by September, so, only two of the three commonly used options to address retrospective patterns are recommended. First, performing integrated assessments without time-varying M or q (but including time-varying fishery selectivity) could be coupled with post hoc revisions of management advice based on the magnitude of retrospective patterns. Secondly, a modified Tier 4 approach that uses the information available on variability in population processes to calculate distributions for F35% could also be useful.

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Appendix A: Status quo assessment model population dynamics

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

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

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

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

The dynamics after the initial year were described by:

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

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

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

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

$$Z_{s,v,m,y,l} = \gamma_{natM,m} M_{s,m} + \sum_f S_{s,f,y,l} F_{s,f,y,l} \tag{7}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Survey selectivity was informed by experimental surveys during the years 2009 and 2010. A portion of the NMFS summer survey tows were accompanied by an industry vessel using nephrops trawls with an assumed selectivity of 1 for all size classes. To represent the proportion of the population covered by the experiment, a vector was freely estimated for males, S_y^{free} (subject to a scaling parameter), and a logistic curve was estimated for females.

$$S_{ind,s,l,y} = \begin{cases} \frac{q_{ind,s,y}}{1 + e^{-log(19)\frac{L_l - s_{50,s,y}}{s_{95,s,y} - s_{50,s,y}}}}) & \text{if s = female} \\ q_{ind,s,y} S_y^{free} & \text{if s = male} \end{cases} \quad (18)$$

Based on this logic, after identifying the fraction of the crab at length covered by the experimental surveys, the length frequencies of the NMFS data collected simultaneously with the experimental trawls can be calculated by multiplying the numbers at length 'available' to the experimental trawls by the overall survey selectivity, $S_{surv,s,l,y}$. The predicted numbers at length for the NMFS and industry data from the selectivity experiment were calculated by multiplying the respective selectivities by the survey numbers at length.

$$S_{nmfs,s,l,y} = S_{ind,s,l,y} S_{surv,s,l,y} \quad (19)$$

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

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

$$FMB_y = \sum_{l,v} w_{fem,l} N_{fem,v,mat,y,l} \quad (21)$$

$$w_{s,l} = \alpha_{wt,s} L_l^{\beta_{wt,s}} \quad (22)$$

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

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

$$X_{s,l,l'} = \frac{Y_{s,l,l'}}{\sum_{l'} Y_{s,l,l'}} \quad (23)$$

$$Y_{s,l,l'} = (\Delta_{l,l'})^{\frac{\hat{L}_{s,l} - (\bar{L}_l - 2.5)}{\beta_s}} \quad (24)$$

$$\hat{L}_{s,l}^{post,1} = \alpha_s + \beta_{s,1} L_l \quad (25)$$

$$\hat{L}_{s,l}^{post,2} = \alpha_s + \delta_s(\beta_{s,1} - \beta_{s,2}) + \beta_{s,2}L_l \tag{26}$$

$$\hat{L}_{s,l}^{post} = \hat{L}_{s,l}^{post,1}(1 - \Phi(\frac{L_l - \delta_{a,x}}{stgr})) + \hat{L}_{s,l}^{post,2}(\Phi(\frac{L_l - \delta_{a,x}}{stgr})) \tag{27}$$

$$\Delta_{l,l'} = \bar{L}_{l'} + 2.5 - L_l \tag{28}$$

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

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

$$Rec_y = e^{(Rec_{avg} + Rec_{dev,y})} \tag{29}$$

$$Pr_l = \frac{(\Delta_{1,l})^{\alpha_{rec}/\beta_{rec}} e^{-\Delta_{1,l'}/\beta_{rec}}}{\sum_{l'}(\Delta_{1,l'})^{\alpha_{rec}/\beta_{rec}} e^{(-\Delta_{1,l'}/\beta_{rec})}} \tag{30}$$

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

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

$$L_x = \lambda_x \sum_y N_{x,y}^{eff} \sum_l p_{x,y,l}^{obs} ln(\hat{p}_{x,y,l}/p_{x,y,l}^{obs}) \tag{31}$$

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

Log normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y \frac{(ln(\hat{I}_{x,y}) - ln(I_{x,y}))^2}{2(ln(CV_{x,y}^2 + 1))} \tag{32}$$

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

Normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y (\hat{I}_{x,y} - I_{x,y})^2 \tag{33}$$

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

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

Appendix B: GMACS basic population dynamics

The basic dynamics of GMACS account for growth, mortality, maturity state, and shell condition (although most of the equations omit these indices for simplicity):

$$N_{hji} = ((\mathbf{I} - \mathbf{P}_{hji-1}) + \mathbf{X}_{hji-1}\mathbf{P}_{hji-1})\,\mathbf{S}_{hji-1}N_{hji-1} + \widetilde{R}_{hji} \tag{34}$$

where N_{hji} is the number of animals by size-class of sex h at the start of season j of year i, $\mathbf{P}_{hji}$ is a matrix with diagonals given by vector of molting probabilities for animals of sex h at the start of season j of year i, $\mathbf{S}_{hji}$ is a matrix with diagonals given by the vector of probabilities of surviving for animals of sex h during time-step j of year i (which may be of zero duration):

$$S_{hjil} = exp\,(-Z_{hjil}) \tag{35}$$

$$S_{hjil} = 1 - \frac{Z_{hjil}}{\widetilde{Z}_{hjil}}\,(1 - exp\,(-Z_{hjil})) \tag{36}$$

$\mathbf{X}_{hji}$ is the size-transition matrix (probability of growing from one size-class to each of the other size-classes or remaining in the same size class) for animals of sex h during season j of year i, $\widetilde{R}_{hji}$ is the recruitment (by size-class) to gear g during season j of year i (which will be zero except for one season – the recruitment season), Z_{hjil} is the total mortality for animals of sex h in size- class l during season j of year i, and $\tilde{Z}_{hjil}$ is the probability of encountering the gear for animals of sex h in size-class l during season j of year i. Equation 34 applies when mortality is continuous across a time-step and equation 35 applies when a time-step is instantaneous. Equation 33 can be modified to track old and new shell crab (under the assumption that both old and new shell crab molt), i.e.:

$$N_{hji}^{new} = \mathbf{X}_{hji-1}\mathbf{P}_{hji-1}\mathbf{S}_{hji-1}\left(N_{hji-1}^{new} + N_{hji-1}^{old}\right) + \widetilde{R}_{hji} \tag{37}$$

$$N_{hji}^{old} = (\mathbf{I} - \mathbf{P}_{hji-1})\,\mathbf{S}_{hji-1}\mathbf{P}_{hji-1}\left(N_{hji-1}^{new} + N_{hji-1}^{old}\right) \tag{38}$$

Equation 33 can be also be modified to track mature and immature shell crab (under the assumption that immature crab always molt and mature crab never molt and $\mathbf{P}_{hji}$ now represents the probability of molting to maturity), i.e.:

$$N_{hji}^{mat} = \mathbf{X}_{hji-1}\mathbf{S}_{hji-1}\mathbf{P}_{hji-1}N_{hji-1}^{imm} + \mathbf{S}_{hji-1}N_{hji-1}^{mat}N_{hji}^{imm} = \mathbf{X}_{hji-1}\mathbf{S}_{hji-1}(\mathbf{I} - \mathbf{P}_{hji-1})N_{hji-1}^{imm} + \mathbf{S}_{hji-1}N_{hji-1}^{mat} \tag{39}$$

There are several ways to specify the initial conditions for the model (i.e., the numbers-at- size at the start of the first year, i_1).

- An equilibrium size-structure based on constant recruitment and either no fishing for any of the fleets or (estimated or fixed) fishing mortality by fleet. The average recruitment is an estimated parameter of the model.

- An individual parameter for each size- class, i.e.: $N_{hi_11} = exp(\delta_{hi_1l})$

- An overall total recruitment multiplied by offsets for each size-class, i.e.:

$$N_{hi_11} = \frac{R_{init}exp(\delta_{hi_1l})}{\sum_{h'} \sum_{l'} exp(\delta_{hi_1l'})} \tag{40}$$

Recruitment occurs once during each year. Recruitment by sex and size-class is the product of total recruitment, the split of the total recruitment to sex and the assignment of sex-specific recruitment to size-classes, i.e.:

$$\widetilde{R}_{hjil} = \bar{R}e^{\epsilon_i} \begin{cases} (1 + e^{\theta_i})^{-1}p_{hl} & \text{if h = males} \\ \\ \theta_i(1 + e^{\theta_i})^{-1}p_{hl} & \text{if h = females} \end{cases} \tag{41}$$

where $\bar{R}$ is median recruitment, θ_i determines the sex ratio of recruitment during year i, and p_{hl} is the proportion of the recruitment (by sex) that recruits to size-class l:

$$p_{hil} = \int_{L_{low}}^{L_{high}} \frac{\frac{le^{-l/\beta_h}(\alpha^h/\beta^h)-1}{\beta_h}}{\Gamma(\alpha_h/\beta h)} dl \tag{42}$$

where α_h and β_h are the parameters that define a gamma function for the distribution of recruits to size-class l. Equation 41 can be restricted to a subset of size-classes, in which case the results from Equation 41 are normalized to sum to 1 over the selected size-classes.

Total mortality is the sum of fishing mortality and natural mortality, i.e.:

$$Z_{hijl} = \rho_{ij}M_{hi}\tilde{M}_l + \sum_f S_{fhijl}(\lambda_{fhijl} + \Omega_{fhijl}(1 - \lambda_{fhijl}))F_{fhijl} \tag{43}$$

where ρ_{ij} is the proportion of natural mortality that occurs during season j for year i, M_{hi} is the rate of natural mortality for year i for animals of sex h (applies to animals for which $\tilde{M}_l = 1$), $\tilde{M}_l$ is the relative natural mortality for size-class l, S_{fhijl} is the (capture) selectivity for animals of sex h in size- class l by fleet f during season j of year i, λ_{fhijl} is the probability of retention for animals of sex h in size-class l by fleet f during season j of year i, Ω_{fhijl} is the mortality rate for discards of sex h in size-class l by fleet f during season j of year i, and F_{fhijl} is the fully-selected fishing mortality for animals of sex h by fleet f during season j of year i.

The probability of capture (occurs instantaneously) is given by:

$$\widetilde{Z}_{hijl} = \sum_f S_{fhijl}F_{fhij} \tag{44}$$

Note that Equation 43 is computed under the premise that fishing is instantaneous and hence that there is no natural mortality during season j of year i. The logarithms of the fully-selected fishing mortalities by season are modelled as:

$$ln(F_{fhij}) = ln(F_{fh}) + \epsilon_{fhij} \text{ if h = males} \tag{45}$$

$$ln(F_{fhij}) = ln(F_{fh}) + \theta_f + \epsilon_{fhij} \text{ if h = females} \tag{46}$$

where F_{fh} is the reference fully-selected fishing mortality rate for fleet f, θ_f is the offset between female and male fully-selected fishing mortality for fleet f, and ϵ_{fhij} are the annual deviation of fully-selected fishing mortality for fleet f (by sex). Natural mortality can depend on time according to several functional forms:

- Natural mortality changes over time as a random walk, i.e.:

$$M_{hi} = \begin{cases} M_{hi_1} & \text{if i} = i_1 \\ M_{hi-1}e^{\psi_{hi}} & \text{otherwise} \end{cases} \tag{47}$$

where M_{hi_1} is the rate of natural mortality for sex h for the first year of the model, and ψ_{hi} is the annual change in natural mortality.

- Natural mortality changes over time as a spline function. This option follows Equation 46, except that the number of knots at which ψ_{hi} is estimated is specified.

- Blocked changes. This option follows Equation 46, except that ψ_{hi} changes between 'blocks' of years, during which ψ_{hi} is constant.

- Blocked natural mortality (individual parameters). This option estimates natural mortality as parameters by block, i.e.:

$$M_{hi} = e^{\psi_{hi}} \tag{48}$$

where ψ_{hi} changes in blocks of years.

- Blocked offsets (relative to reference). This option captures the intent of the previous option, except that the parameters are relative to natural mortality in the first year, i.e.:

$$M_{hi} = M_{hi_1}e^{\psi_{hi}} \tag{49}$$

It is possible to 'mirror' the values for the ψ_{hi} parameters (between sexes and between blocks), which allows male and female natural mortality to be the same, and for natural mortality to be the same for discontinuous blocks (based on Equations 47 and 48). The deviations in natural mortality can also be penalized to avoid unrealistic changes in natural mortality to fit 'quirks' in the data.

The model keeps track of (and can be fitted to) landings, discards, total catch by fleet, whose computation depends on whether the fisheries in season t are continuous or instantaneous.

$$C_{fhijl}^{Land} = \begin{cases} \frac{\lambda_{fhijl}S_{fhijl}F_{fhijl}}{Z_{hijl}}N_{fhijl}(1 - e^{-\hat{Z}_{hijl}}) & \text{if continuous} \\ \frac{\lambda_{fhijl}S_{fhijl}F_{fhijl}}{Z_{hijl}}N_{fhijl}(1 - e^{-Z_{hijl}}) & \text{if instantaneous} \end{cases} \tag{50}$$

$$C_{fhijl}^{Disc} = \begin{cases} \frac{(1-\lambda_{fhijl})S_{fhijl}F_{fhijl}}{Z_{hijl}}N_{fhijl}(1 - e^{-\hat{Z}_{hijl}}) & \text{if continuous} \\ \frac{(1-\lambda_{fhijl})S_{fhijl}F_{fhijl}}{Z_{hijl}}N_{fhijl}(1 - e^{-Z_{hijl}}) & \text{if instantaneous} \end{cases} \tag{51}$$

$$C_{fhijl}^{Tot} = \begin{cases} \frac{S_{fhijl}F_{fhijl}}{Z_{hijl}}N_{fhijl}(1 - e^{-\hat{Z}_{hijl}}) & \text{if continuous} \\ \frac{S_{fhijl}F_{fhijl}}{Z_{hijl}}N_{fhijl}(1 - e^{-Z_{hijl}}) & \text{if instantaneous} \end{cases} \tag{52}$$

Landings, discards, and total catches by fleet can be aggregated over sex (e.g., when fitting to removals reported as sex-combined). Equations 49-51 are extended naturally for the case in which the population is represented by shell condition and/or maturity status (given the assumption that fishing mortality, retention and discard mortality depend on sex and time, but not on shell condition nor maturity status). Landings, discards, and total catches by fleet can be reported in numbers (Equations 49-51) or in terms of weight. For example, the landings, discards, and total catches by fleet, season, year, and sex for the total (over size-class) removals are computed as:

$$C_{fhij}^{Land} = \sum_l C_{fhijl}^{Land} w_{hil} \tag{53}$$

$$C_{fhij}^{Disc} = \sum_l C_{fhijl}^{Disc} w_{hil} \tag{54}$$

$$C_{fhij}^{Total} = \sum_l C_{fhijl}^{Total} w_{hil} \tag{55}$$

$$\tag{56}$$

where C_{fhij}^{Land}, C_{fhij}^{Disc}, and C_{fhij}^{Total} are respectively the landings, discards, and total catches in weight by fleet, season, year, and sex for the total (over size-class) removals, and w_{hil} is the weight of an animal of sex h in size-class l during year i.

Many options exist related to selectivity (the probability of encountering the gear) and retention (the probability of being landed given being captured). The options for selectivity are:

- Individual parameters for each size-class (in log-space); normalized to a maximum of 1 over all size-classes (if indicated).
- Individual parameters for a subset of the size-classes (in log-space). Selectivity must be specified for a contiguous range of size-classes starting with the first size-class. Selectivity for any size-classes outside of the specified range is set to that for last size-class for which selectivity is treated as estimable.
- Logistic selectivity. Two variants are available depending of the parametrization:

$$S_l = \frac{1}{1 + exp(\frac{ln19(\bar{L}_l - S_{50})}{S_{95} - S_{50}})} \tag{57}$$

$$S_l = \frac{1}{1 + exp(\frac{(\bar{L}_l - S_{50})}{\sigma_S})} \tag{58}$$

where S_{50} is the size corresponding to 50% selectivity, S_{95} is the size corresponding to 95% selectivity, σ_S is the "standard deviation" of the selectivity curve, and $\bar{L}_l$ is the midpoint of size-class l.

- All size-classes are equally selected.
- Selectivity is zero for all size-classes.

It is possible to assume that selectivity for one fleet is the product of two of the selectivity patterns. This option is used to model cases in which one survey is located within the footprint of another survey. The options to model retention are the same as those for selectivity, except that it is possible to estimate an asymptotic parameter, which allows discard of animals that would be "fully retained" according to the standard options for (capture) selectivity. Selectivity and retention can be defined for blocks of contiguous years. The blocks need not be the same for selectivity and retention, and can also differ between fleets and sexes.

Growth is a key component of any size-structured model. It is modelled in terms of molt probability and the size-transition matrix (the probability of growing from each size-class to each of the other size-classes, constrained to be zero for sizes less than the current size). Note that the size-transition matrix has entries on its diagonal, which represent animals that molt but do not change size-classes

There are four options for modelling the probability of molting as a function of size:

- Pre-specified probability
- Individual parameters for each size-class (in log-space)
- Constant probability
- Logistic probability, i.e.:

$$P_{l,l} = \frac{1}{1 - (1 + exp(\frac{\bar{L}_l - P_{50}}{\sigma_P}))} \tag{59}$$

where P_{50} is the size at which the probability of molting is 0.5 and σ_P is the "standard deviation" of the molt probability function. Molt probability is specified by sex and can change in blocks.

The proportion of animals in size-class l that grow to be in size-class l' ($X_{l,l'}$) can either be pre-specified by the user or determined using a parametric form:

- The size-increment is gamma-distributed:

$$X_{l,l'} = \int_{L_{low}}^{L_{high}} \frac{((l - \bar{L}_l)/\tilde{\beta})^{I_l/\tilde{\beta}-1} e^{-(l-\bar{L}_l)/\tilde{\beta}}}{\Gamma(I_l/\tilde{\beta})} dl \tag{60}$$

- The size after increment is gamma-distributed, i.e.:

$$X_{l,l'} = \int_{L_{low}}^{L_{high}} \frac{(l/\tilde{\beta})^{(\bar{L}_l+I_l)/\tilde{\beta}-1} e^{-(l/\tilde{\beta})}}{\Gamma((\bar{L}_l + I_l)/\tilde{\beta})} dl \tag{61}$$

- The size-increment is normally-distributed, i.e.:

$$X_{l,l'} = \int_{L_{low}}^{L_{high}} \frac{e^{-(l-\bar{L}_l-I_l)^2/(2\tilde{\beta}^2)}}{\sqrt{2\pi}\tilde{\beta}} dl \tag{62}$$

- There is individual variation in the growth parameters L_∞ and k (equivalent to the parameters of a linear growth increment equation given the assumption of von Bertlanffy growth), i.e.:

$$X_{l,l'} = \int_{L_{low}}^{L_{high}} \int_{L_{low}}^{L_{high}} \int_0^\infty \int_0^\infty \frac{1}{L_{hi,l} - L_{low_l}} \frac{e^{-(ln(L_\infty) - \bar{L}_\infty)^2/(2\sigma_{L_\infty}^2)}}{\sqrt{2\pi}\sigma_{L_\infty}^2} \frac{e^{-(ln(k) - \bar{k})^2/(2\sigma_k^2)}}{\sqrt{2\pi}\sigma_{L_k}^2} dL_{L_\infty} dk dl_{l'} dl_l \quad (63)$$

- There is individual variation in the growth parameter L_∞:

$$X_{l,l'} = \int_{L_{low}}^{L_{high}} \int_{L_{low}}^{L_{high}} \int_0^\infty \frac{1}{L_{hi,l} - L_{low_l}} \frac{e^{-(ln(L_\infty) - \bar{L}_\infty)^2/(2\sigma_{L_\infty}^2)}}{\sqrt{2\pi}\sigma_{L_\infty}^2} dL_{L_\infty} dl_{l'} dl_l \quad (64)$$

- There is individual variation in the growth parameters k:

$$X_{l,l'} = \int_{L_{low}}^{L_{high}} \int_{L_{low}}^{L_{high}} \int_0^\infty \frac{1}{L_{hi,l} - L_{low_l}} \frac{e^{-(ln(k) - \bar{k})^2/(2\sigma_k^2)}}{\sqrt{2\pi}\sigma_k^2} dk dl_{l'} dl_l \quad (65)$$

The size-transition matrix is specified by sex and can change in blocks.

Table 4: Observed growth increment data by sex

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

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

Table 5: Observed retained catches, discarded catch, and bycatch.
Discards and bycatch have assumed mortalities applied.

Survey year	Retained catch (kt)	Discarded females (kt)	Discarded males (kt)	Trawl bycatch (kt)
1982	11.85	0.02	1.33	0.37
1983	12.16	0.01	1.3	0.47
1984	29.94	0.01	2.89	0.5
1985	44.45	0.01	4.21	0.43
1986	46.22	0.02	4.45	0
1987	61.4	0.03	5.79	0
1988	67.79	0.04	6.1	0
1989	73.4	0.05	7.01	0.1
1990	149.1	0.05	15.95	0.71
1991	143	0.06	12.58	1.5
1992	104.7	0.12	17.06	2.28
1993	67.94	0.08	5.32	1.57
1994	34.13	0.06	4.03	2.67
1995	29.81	0.02	5.75	1.01
1996	54.22	0.07	7.44	0.66
1997	114.4	0.01	5.73	0.82
1998	88.09	0.01	4.67	0.54
1999	15.1	0	0.52	0.47
2000	11.46	0	0.62	0.41
2001	14.8	0	1.89	0.31
2002	12.84	0	1.47	0.17
2003	10.86	0	0.57	0.46
2004	11.29	0	0.51	0.63
2005	16.77	0	1.36	0.2
2006	16.49	0	1.78	0.42
2007	28.59	0.01	2.53	0.18
2008	26.56	0.01	2.06	0.18
2009	21.78	0.01	1.23	0.47
2010	24.61	0.01	0.62	0.14
2011	40.29	0.18	1.69	0.15
2012	30.05	0.03	2.32	0.22
2013	24.49	0.07	3.27	0.11
2014	30.82	0.17	3.52	0.13
2015	18.42	0.07	2.96	0.13
2016	9.67	0.02	1.31	0.06
2017	8.6	0.02	1.93	0.04
2018	12.51	0.02	2.86	0.23
2019	15.43	0.02	5.07	0.24

Table 6: Observed mature male and female biomass (1000 t) at the time of the survey and coefficients of variation.

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

Table 7: Changes in management quantities for each scenario considered. Reported management quantities are derived from maximum likelihood estimates. Reported natural mortality is for mature males and average recruitment is for males.

Model	MMB	B35	F35	FOFL	OFL	M	avg_rec
20.1	144.11	120.46	1.59	1.59	95.25	0.30	109.70
20.2	133.51	121.47	1.23	1.23	88.90	0.29	103.91
20.2q	121.61	137.56	1.94	1.94	77.08	0.30	132.86
20.2m	43.29	17.85	6.29	6.29	70.88	0.17	152.61
20.2mq	92.20	28.06	12.46	1.86	14.72	0.75	241.96
20.3	140.88	118.13	1.26	1.26	95.37	0.30	104.45
20.1g	207.19	113.66	1.65	1.65	184.91	0.36	169.96

Table 8: Maximum likelihood estimates of predicted mature male (MMB), mature female (FMB), and males >101mm biomass (1000 t) and numbers (in millions) at the time of the survey from the chosen model. Columns 2-5 are subject to survey selectivity; columns 6-9 are the population values (i.e. the numbers at length are not modified by multiplying them by a selectivity curve–they are estimates of the underlying population).

Survey year	FMB	MMB	Male >101 biomass	Male >101 (millions)	FMB	MMB	Male >101 biomass	Male >101 (millions)
1982	87.91	118.2	38.25	62	434.7	292.2	92.14	149.4
1983	74.55	116.9	40.31	62.83	364.2	288.8	97.1	151.4
1984	54.85	117.1	48.08	77.5	268.2	289	115.8	186.7
1985	41.28	112.9	48.5	78.99	201.9	279.9	116.8	190.3
1986	34.9	107.3	42.46	69.86	171.2	267.6	102.3	168.3
1987	115	115.5	41.65	70.27	572.8	289.4	100.3	169.3
1988	193	141.6	55.06	92.64	956.3	354.4	132.7	223.2
1989	411.4	362	141.7	237.4	904.1	417.4	162.6	272.4
1990	315	427.6	193	323.9	690.5	492.5	221.5	371.6
1991	232.4	385.3	177.1	295	509.5	443.6	203.3	338.6
1992	193.9	293.6	123.8	205.8	426.1	338.2	142.1	236.1
1993	196.2	210.5	73.82	123.2	432.5	242.9	84.71	141.4
1994	203	183.1	48.47	80.4	447.4	211.8	55.62	92.26
1995	214.2	210.1	53.54	91.62	472.5	242.8	61.44	105.1
1996	201.2	284.7	109.7	186.7	442.7	328.1	125.8	214.2
1997	157.4	327.7	164.3	273.3	345.3	377.1	188.5	313.6
1998	114	257	132.2	216.8	249.9	295.6	151.8	248.8
1999	87.56	154.9	67.7	110.5	192.2	178.4	77.7	126.8
2000	93.07	118	48.33	78.31	205.5	136.1	55.46	89.86
2001	99.21	95.24	32.37	53.26	218.7	109.8	37.15	61.12
2002	84	90.71	31.2	53.33	184.5	104.5	35.81	61.2
2003	62.54	100.1	45.57	75.87	137.1	115.3	52.3	87.07
2004	45.3	99.28	46.93	76.48	99.32	114.5	53.86	87.77
2005	89.18	97.93	39.51	64.73	198.4	113.1	45.35	74.29
2006	126.8	111.8	39.98	67.52	280.2	129.2	45.88	77.48
2007	109.7	146.8	60.95	102.4	240.9	169.2	69.95	117.5
2008	80.5	169.7	78.06	130.2	176.5	195.4	89.58	149.4
2009	61.19	182.1	94.81	156.7	134.3	209.5	108.8	179.8
2010	158.6	174.2	98.11	159.9	353.5	200.4	112.6	183.6
2011	247	144.5	78.12	126.4	546.6	166.4	89.65	145.1
2012	229.2	102.5	42.39	70.3	503.9	118.1	48.65	80.68
2013	189.2	89.51	34.35	58.49	415.7	103.1	39.42	67.12
2014	151.5	82.62	35.74	59.73	332.8	95.15	41.02	68.54
2015	113	58.02	21.27	35.36	247.9	66.89	24.41	40.58
2016	91.55	44.35	12.44	20.85	201.2	51.27	14.27	23.93
2017	124.2	61.64	12.1	20.41	275	72.01	13.89	23.42
2018	184.8	127.4	15.49	26.46	409.3	148.7	17.78	30.36
2019	196.5	251.7	44.65	79.02	433	291.4	51.23	90.68
2020	160.8	486.1	204.3	352	352.9	559.7	234.5	403.9

Table 9: Maximum likelihood estimates of predicted total numbers (billions), not subject to survey selectivity at the time of the survey. These are maximum likelihood estimates.

Survey year	Total numbers
1982	5.061
1983	5.454
1984	6.099
1985	7.955
1986	16.21
1987	15.72
1988	15.5
1989	11.58
1990	9.641
1991	8.436
1992	13.55
1993	12.16
1994	10.78
1995	8.15
1996	6.108
1997	4.672
1998	4.455
1999	4.232
2000	3.513
2001	2.954
2002	2.985
2003	4.184
2004	5.966
2005	5.946
2006	5.45
2007	4.266
2008	3.566
2009	6.267
2010	5.618
2011	4.616
2012	3.886
2013	3.532
2014	3.006
2015	3.743
2016	11.75
2017	12.72
2018	9.729
2019	7.375
2020	6.487

Table 10: Maximum likelihood estimates of predicted mature male biomass at mating, male recruitment (millions) from the chosen model, and estimated fully-selected total fishing mortaltiy.

Survey year	Mature male biomass	Male recruits	Fishing mortality
1982	218.9	4.4	0.19
1983	212.2	1.75	0.19
1984	193.9	3.82	0.45
1985	171.2	6.49	0.72
1986	161.9	0.95	0.86
1987	170.5	3.08	1.13
1988	210.7	0.3	0.97
1989	253.4	0.64	0.83
1990	235.7	2.47	1.64
1991	203.8	5.12	1.79
1992	147.7	2.5	2.44
1993	127.9	0.39	1.82
1994	127.8	0.1	1.39
1995	155.3	0.14	1.02
1996	198.8	0.15	0.85
1997	193.5	1.76	1.14
1998	144.6	0.22	1.24
1999	124.5	0.36	0.29
2000	93.13	0.3	0.35
2001	67.75	1.63	0.87
2002	68.09	1.45	0.64
2003	79.21	1.8	0.32
2004	77.46	1.54	0.34
2005	70.01	0.4	0.72
2006	83.24	0.17	0.66
2007	102.8	0.63	0.77
2008	125.3	1.37	0.51
2009	141.5	0.23	0.32
2010	134.8	0.4	0.31
2011	89.63	0.15	0.87
2012	61.98	0.45	1.36
2013	54.34	0.35	1.52
2014	41.65	2.07	2.33
2015	31.32	15.73	2.64
2016	29.79	0.78	1.75
2017	48.04	0.18	1.79
2018	101.1	0.14	1.69
2019	207.2	0.18	0.54

Table 11: Maximum likelihood estimates of predicted total numbers (billions), not subject to survey selectivity at the time of the survey.

Survey year	Total females	Total males	Total numbers
1982	6.053	3.591	9.643
1983	4.885	6.881	11.77
1984	3.73	6.52	10.25
1985	4.485	8.305	12.79
1986	38.71	12.19	50.89
1987	34.08	9.346	43.42
1988	24.35	9.477	33.83
1989	17.74	6.774	24.52
1990	13.27	5.223	18.49
1991	13.87	5.839	19.71
1992	15.62	8.929	24.55
1993	15.08	8.492	23.57
1994	17.29	6.18	23.47
1995	12.55	4.332	16.89
1996	8.911	3.087	12
1997	6.368	2.192	8.561
1998	5.673	3.118	8.791
1999	8.511	2.256	10.77
2000	6.872	1.908	8.78
2001	4.933	1.604	6.537
2002	3.521	2.718	6.24
2003	2.577	3.321	5.898
2004	12.4	4.087	16.48
2005	8.906	4.366	13.27
2006	6.322	3.402	9.724
2007	4.522	2.509	7.031
2008	3.878	2.327	6.204
2009	23.54	2.949	26.49
2010	18.55	2.245	20.8
2011	14.16	1.933	16.09
2012	12.46	1.435	13.89
2013	8.896	1.397	10.29
2014	6.416	1.274	7.69
2015	6.442	2.895	9.337
2016	13.5	17.7	31.2
2017	17.12	13.06	30.18
2018	12.91	9.232	22.14
2019	9.39	6.527	15.92
2020	6.892	4.681	11.57

Table 12: Differences between GMACS and the status quo model.

Process	GMACS	Status quo
Recruitment	Yearly recruitment estimate + parameter to divide recruitment between sexes	Separate estimated recruitment deviations and average recruitment for both sexes
Fishing mortality	Total mortality and female discards treated consistently (see May CPT document)	Total mortality and female discards treated inconsistently (see May CPT document)
Growth	Linear growth for both males and females	Linear growth for males; kinked growth for females
BSFRF	Freely estimated availability curves for all sex/year combinations	Logistic availability curves for some sex/year combinations
Natural mortality	Estimated M for mature males, mature females, immature males, immature females (n=4)	Estimated M for mature males, mature females, immature males and females (n=3)
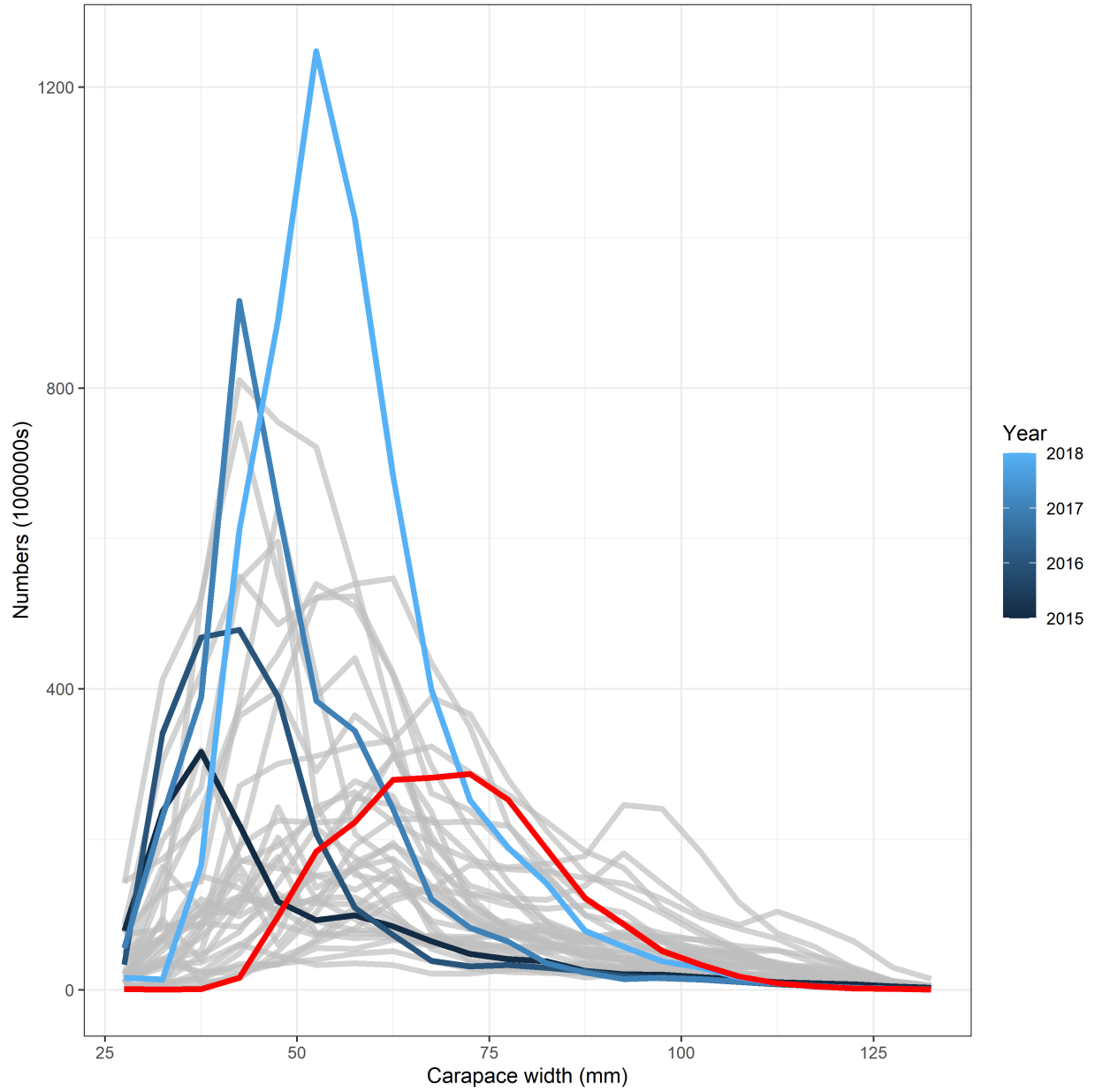
Figure 1: Raw total numbers at width of male crab observed in the survey. Highlighted years represent the development of the 2015 pseudocohort. Greyed years are all other years for comparison. Red line is 2019.
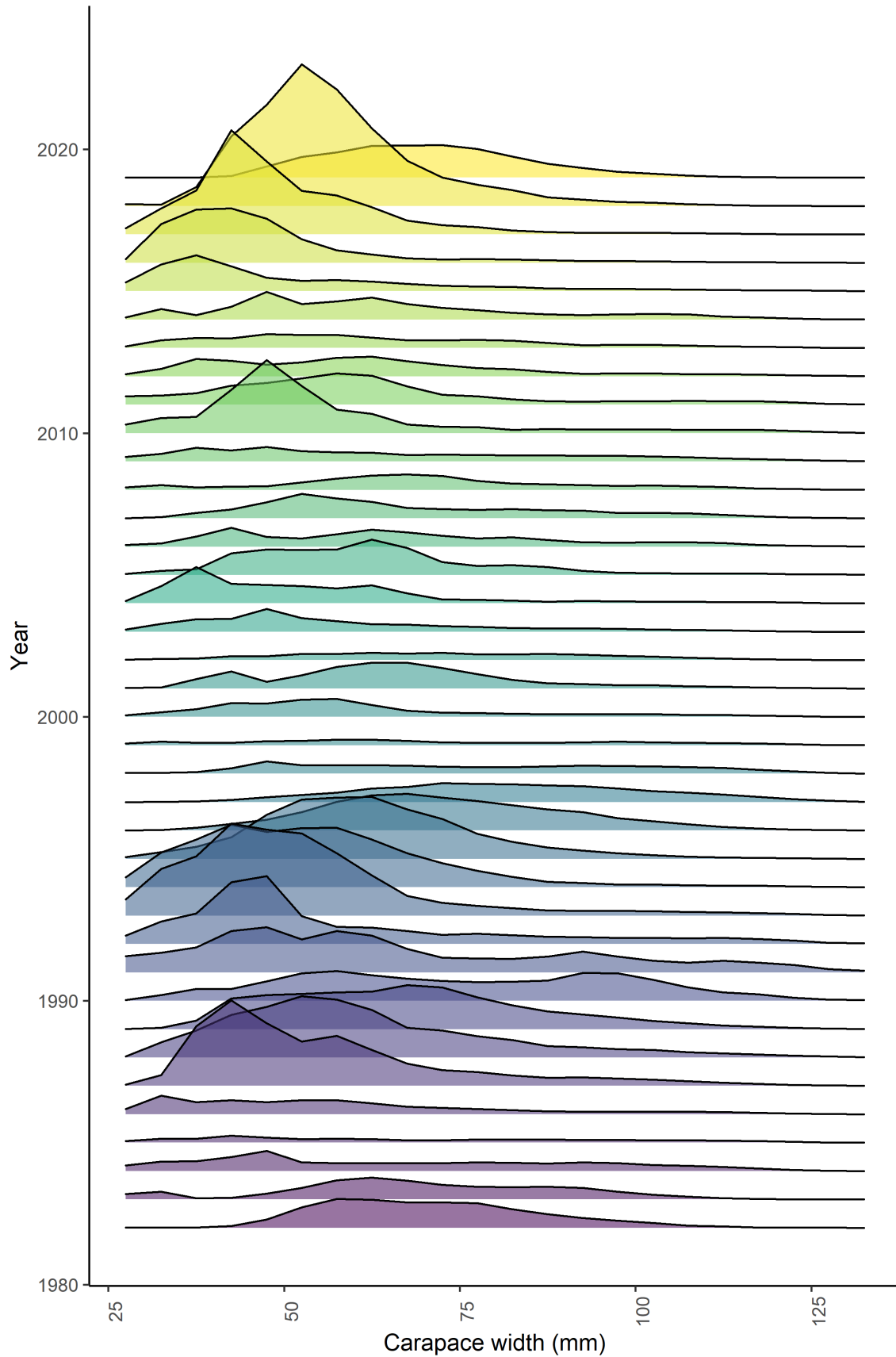
Figure 2: Raw total numbers at width of male crab observed in the survey.
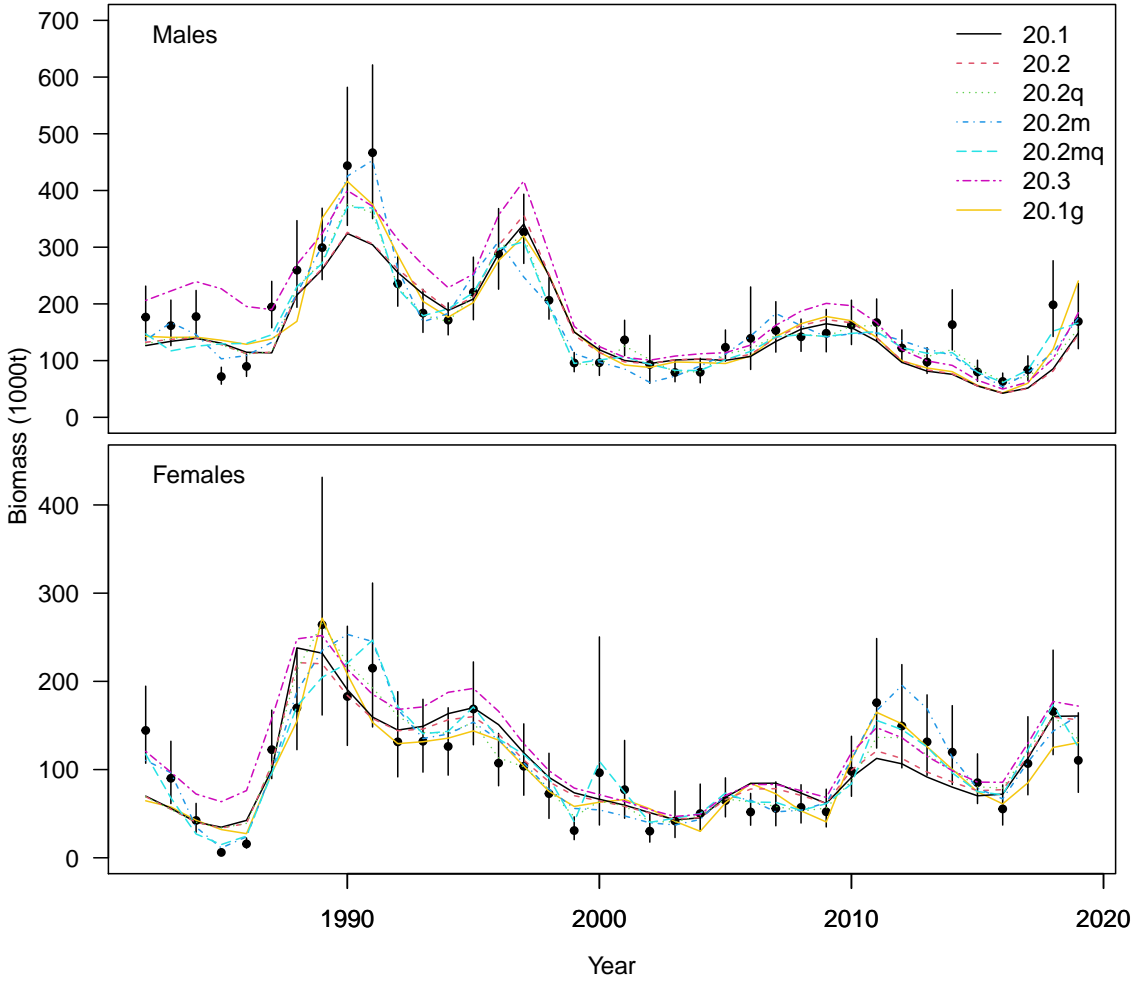
Figure 3: Model fits to the observed mature biomass at survey
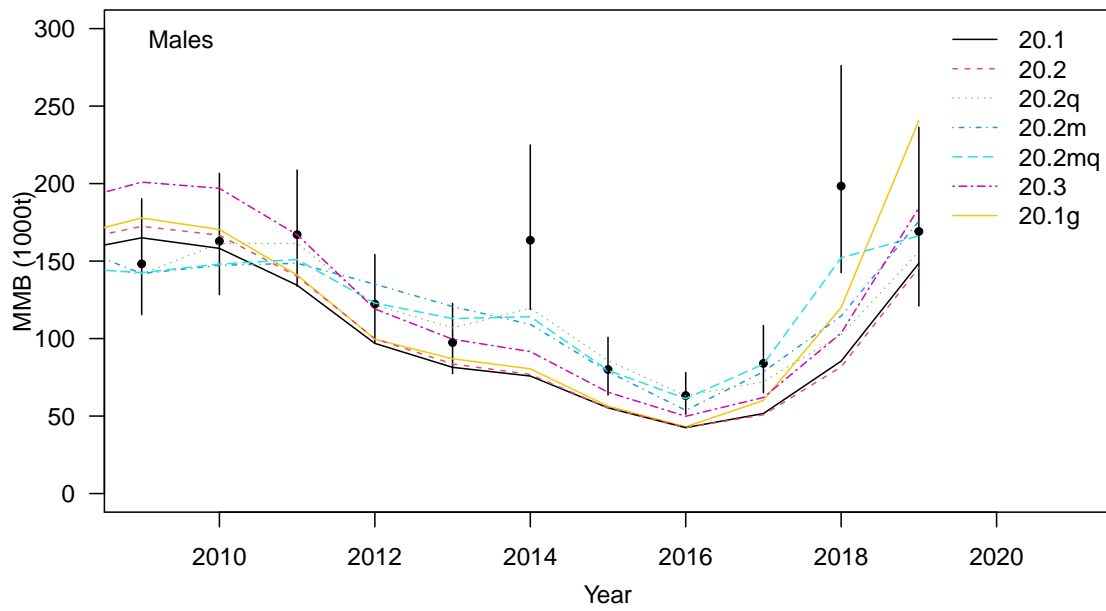
Figure 4: Model fits to the observed mature biomass at survey 2009-present
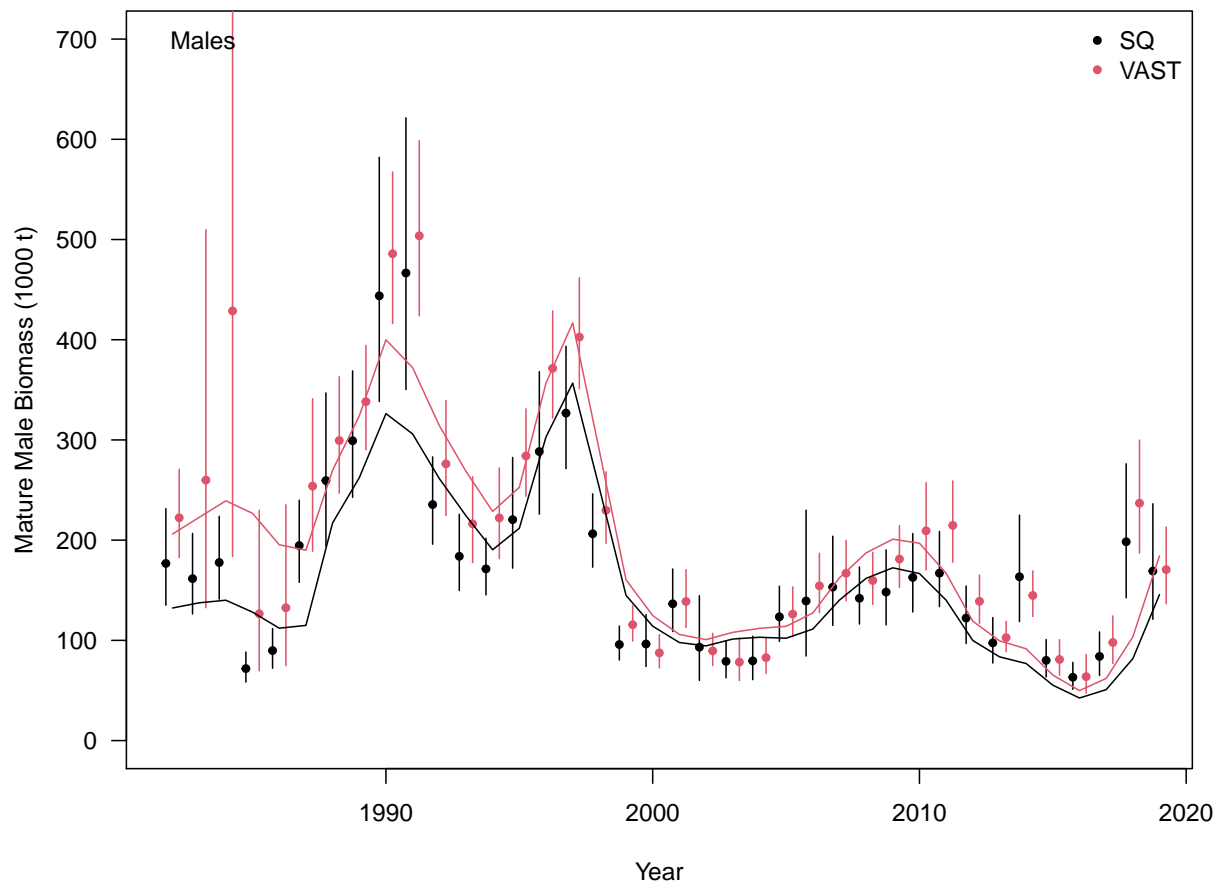
Figure 5: Model fits to the observed mature biomass at survey for the status quo model fit to a design-based index of biomass (SQ) and a model-based index of biomass (VAST).
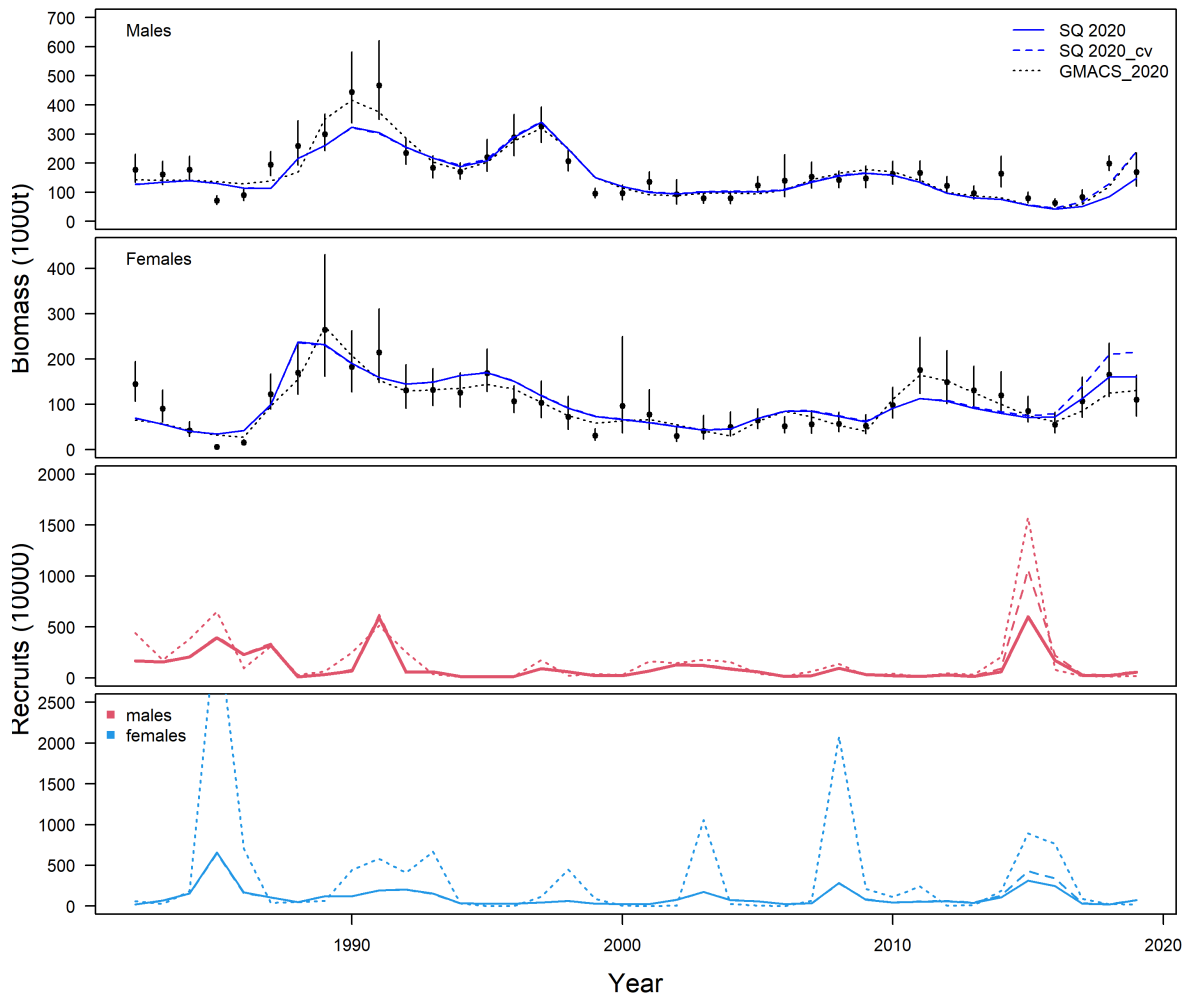
Figure 6: Comparison of estimated survey MMB from GMACS and the status quo model when the status quo model is forced to fit the last two years of survey data.
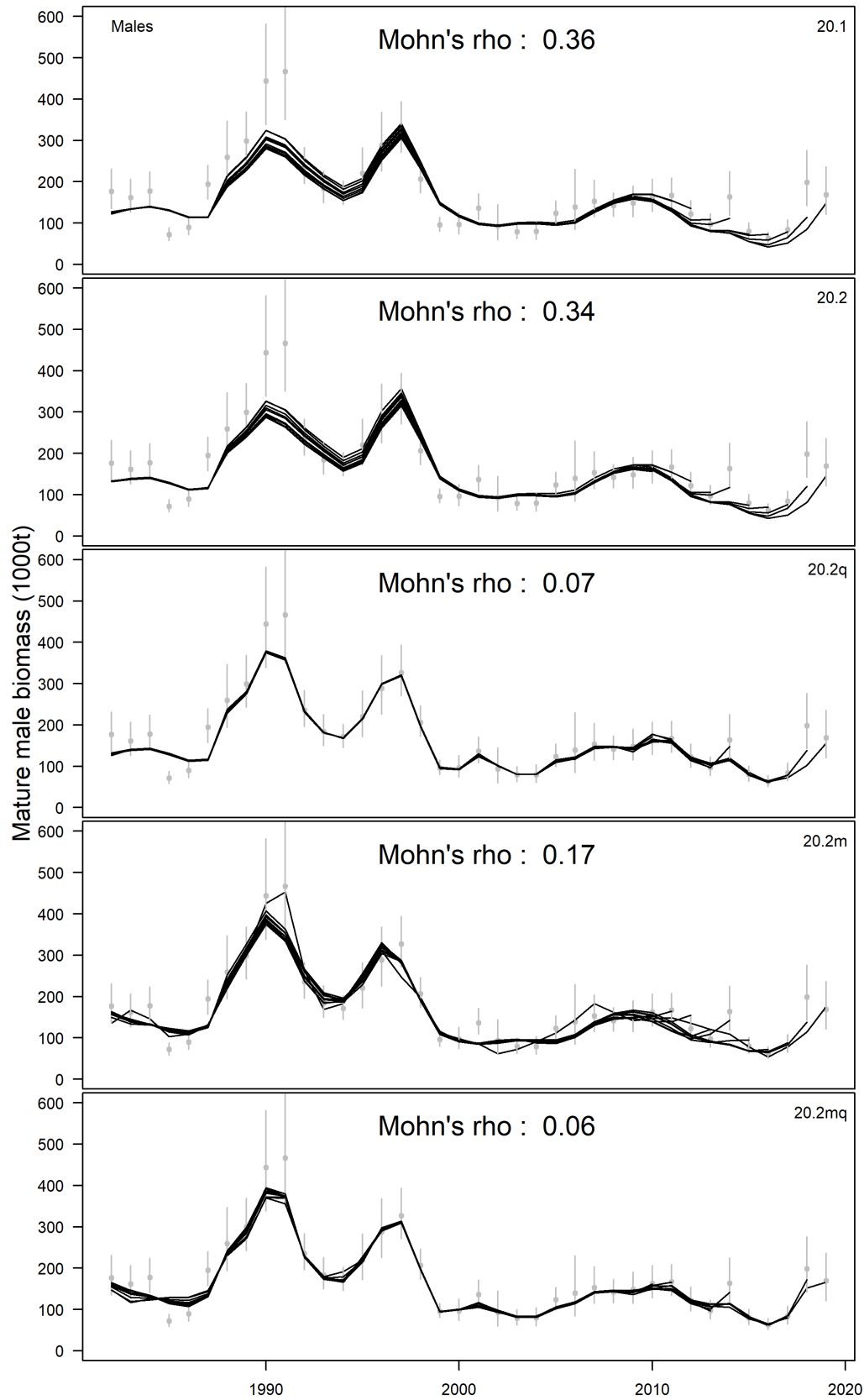
Figure 7: Retrospective patterns in mature male biomass for models 20.1, 20.2, 20.2q, 20.2m, and 20.2qm.
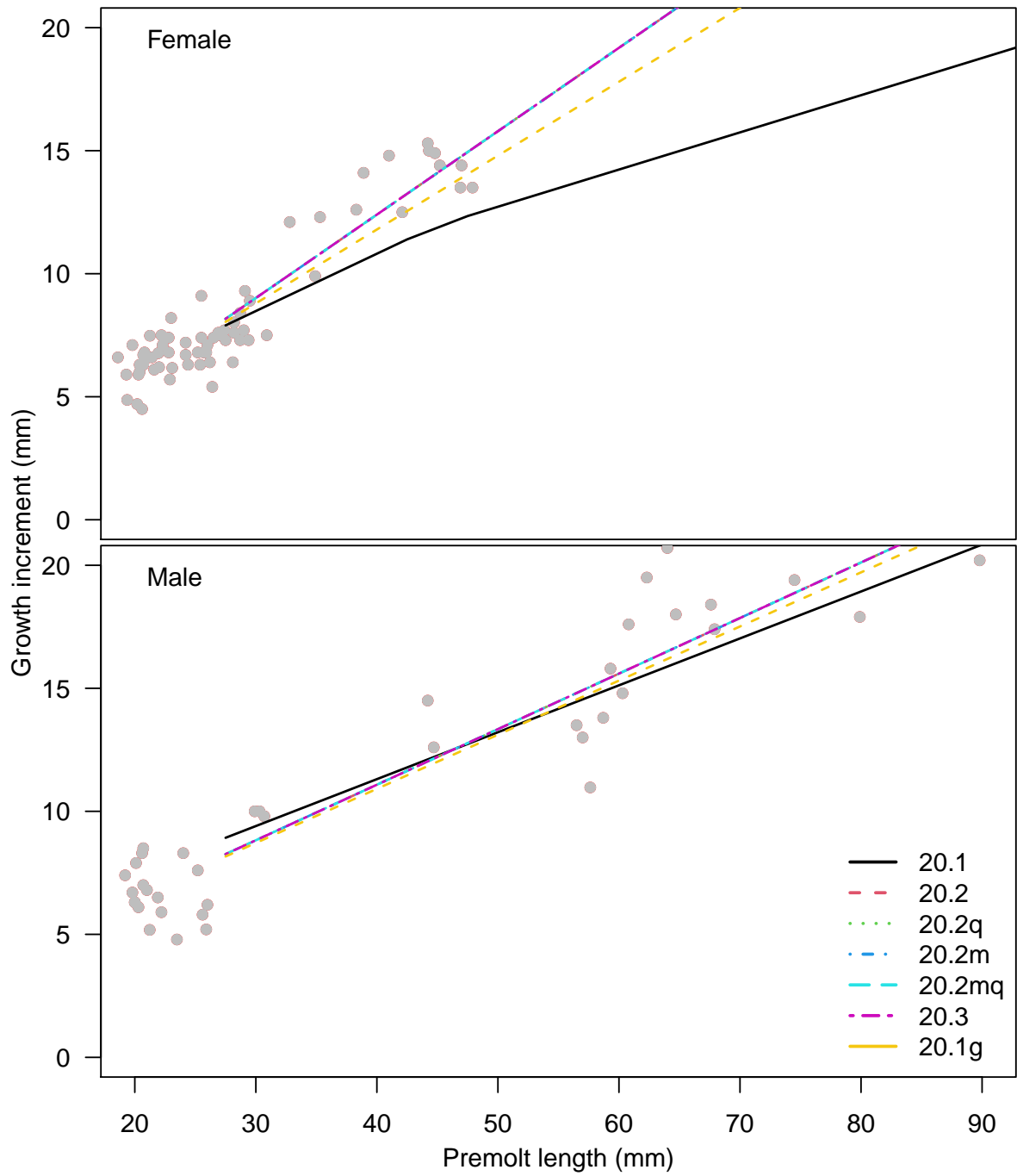
Figure 8: Model fits to the growth data
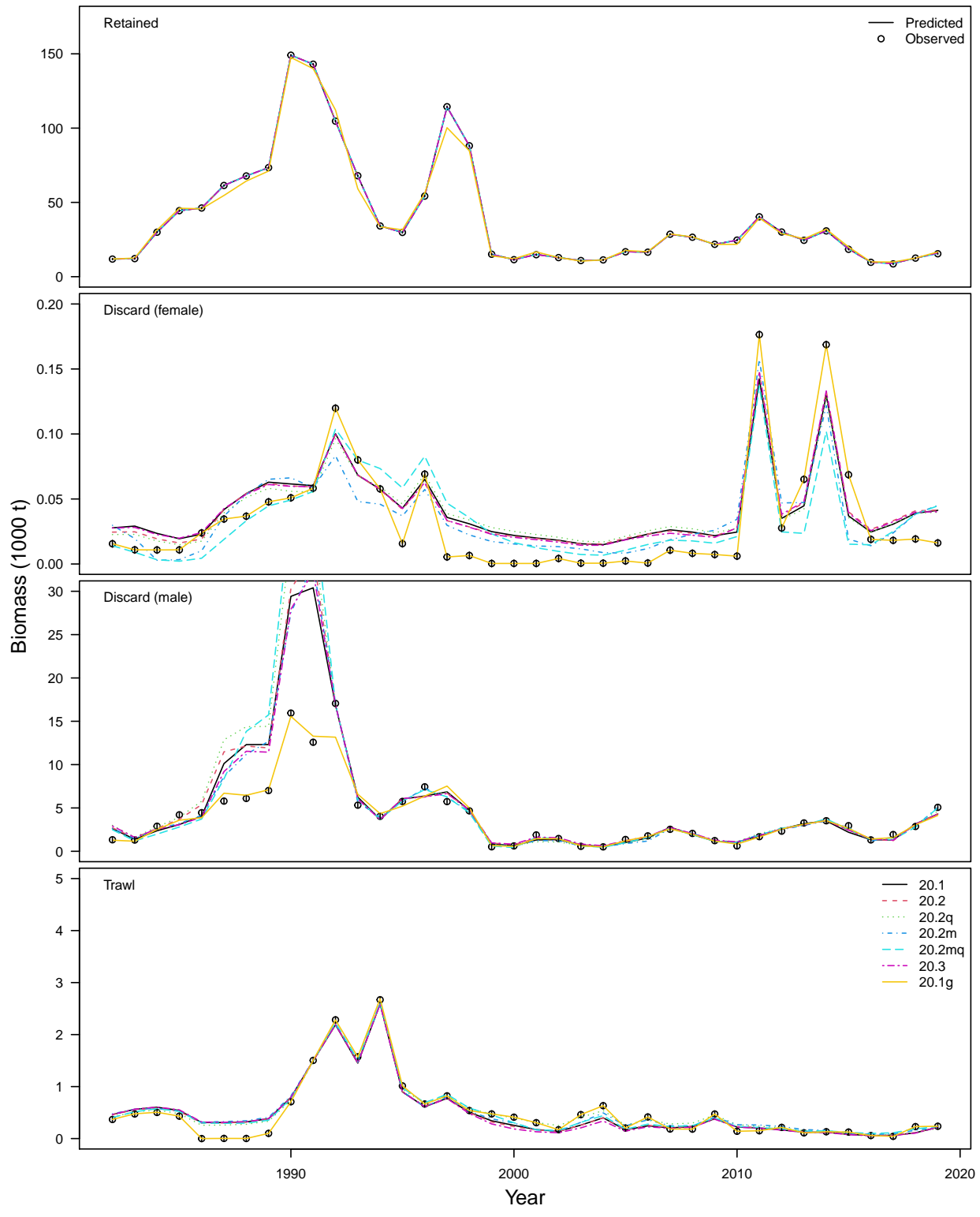
Figure 9: Model fits to catch data
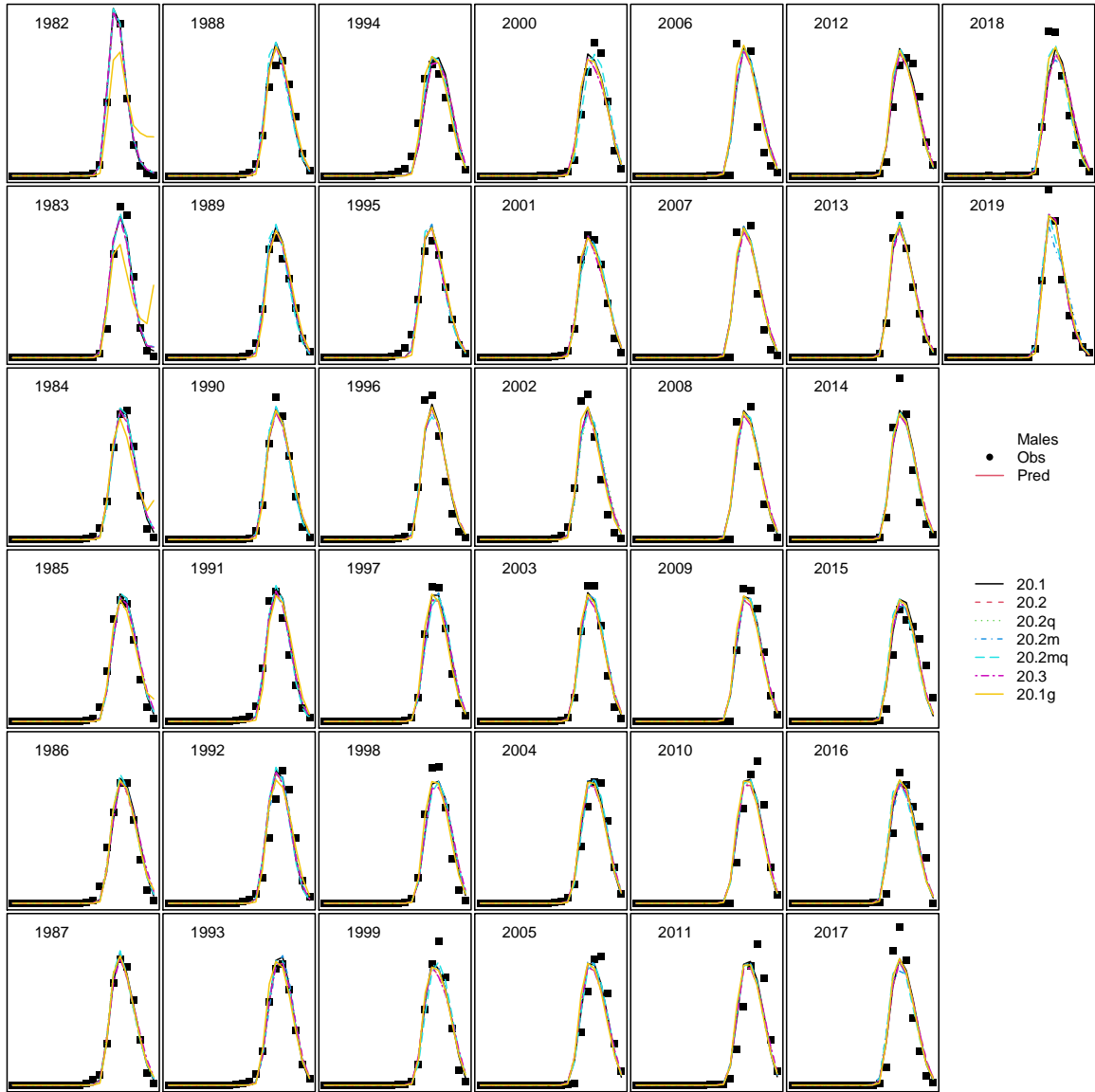
Figure 10: Model fits to retained catch size composition data
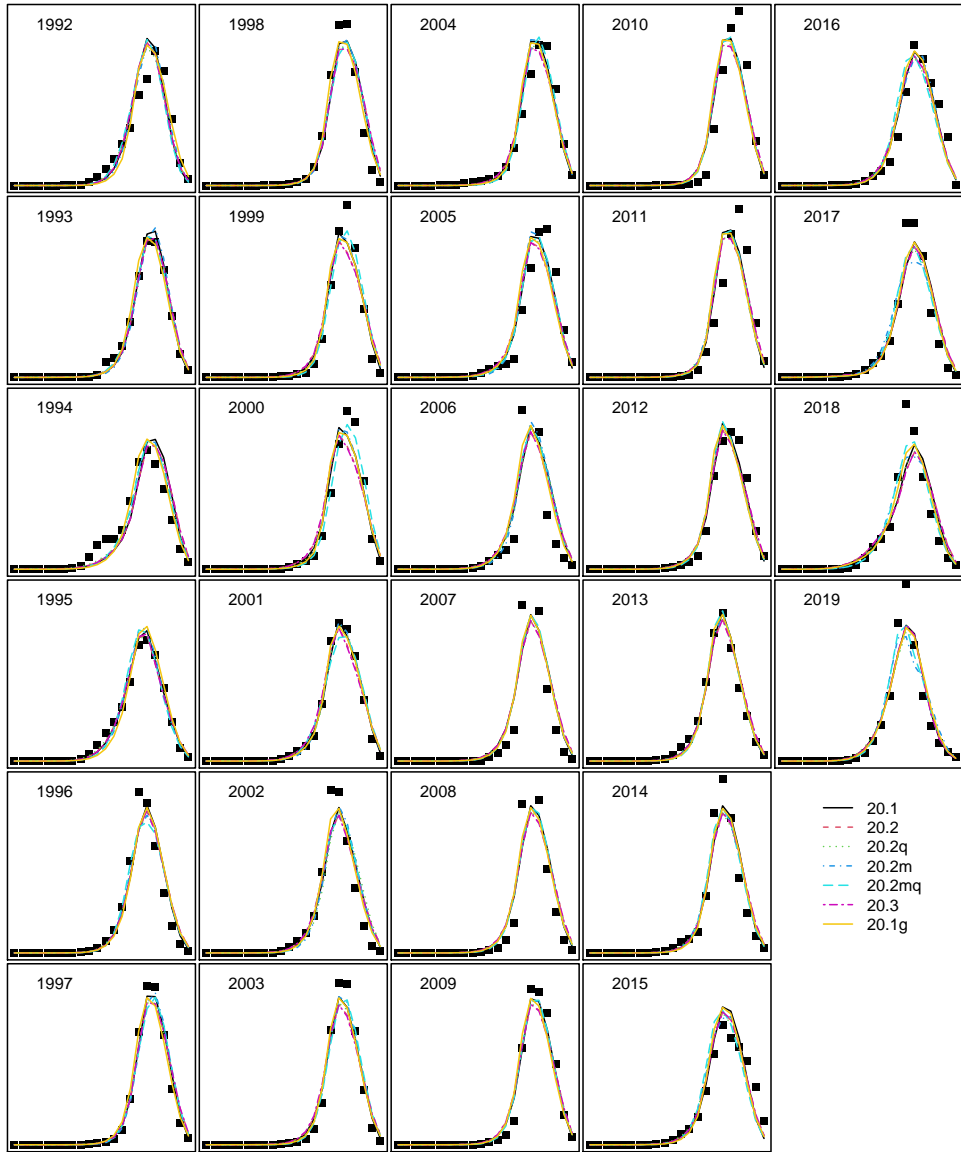
Figure 11: Model fits to total catch size composition data
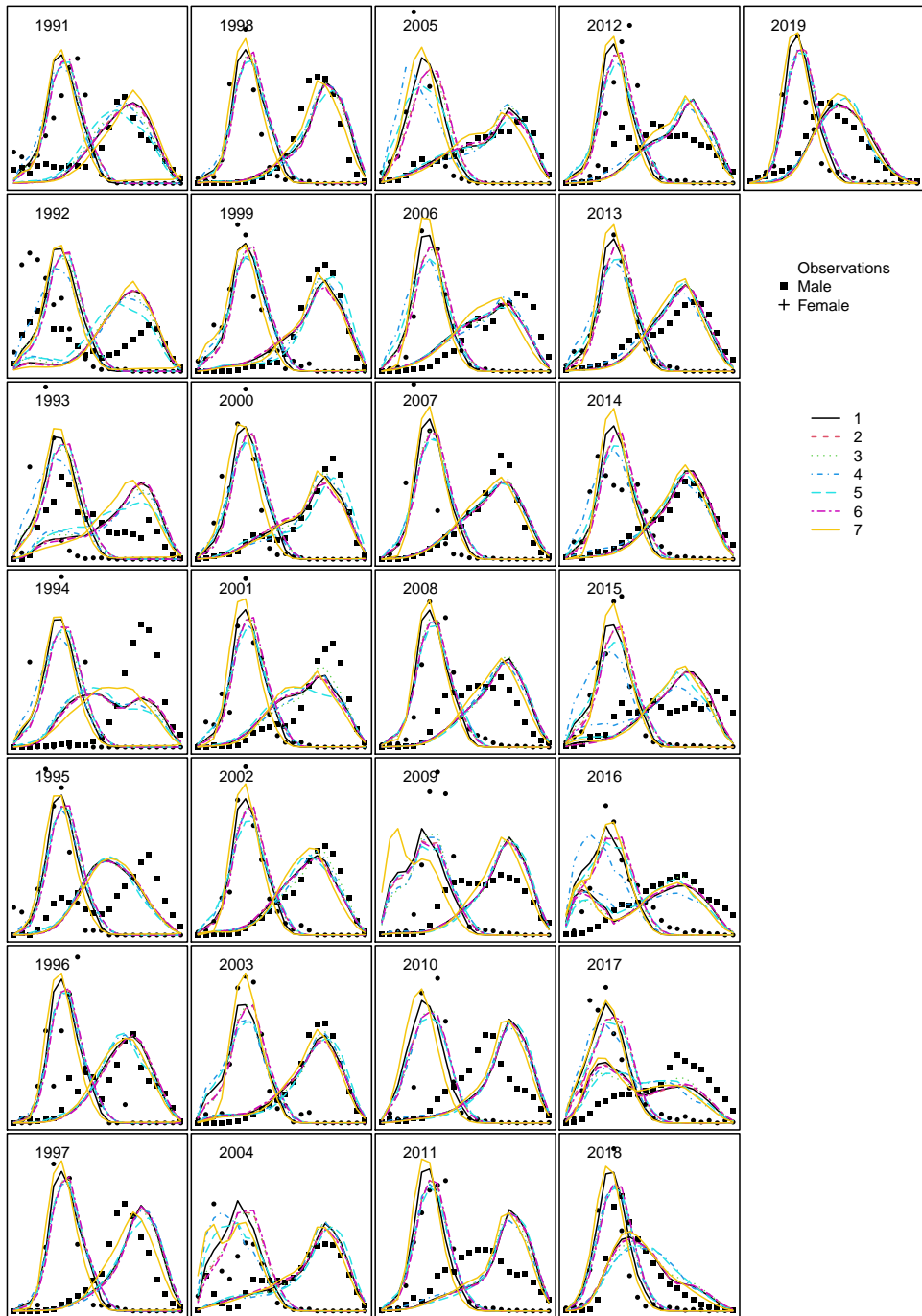
Figure 12: Model fits to trawl catch size composition data
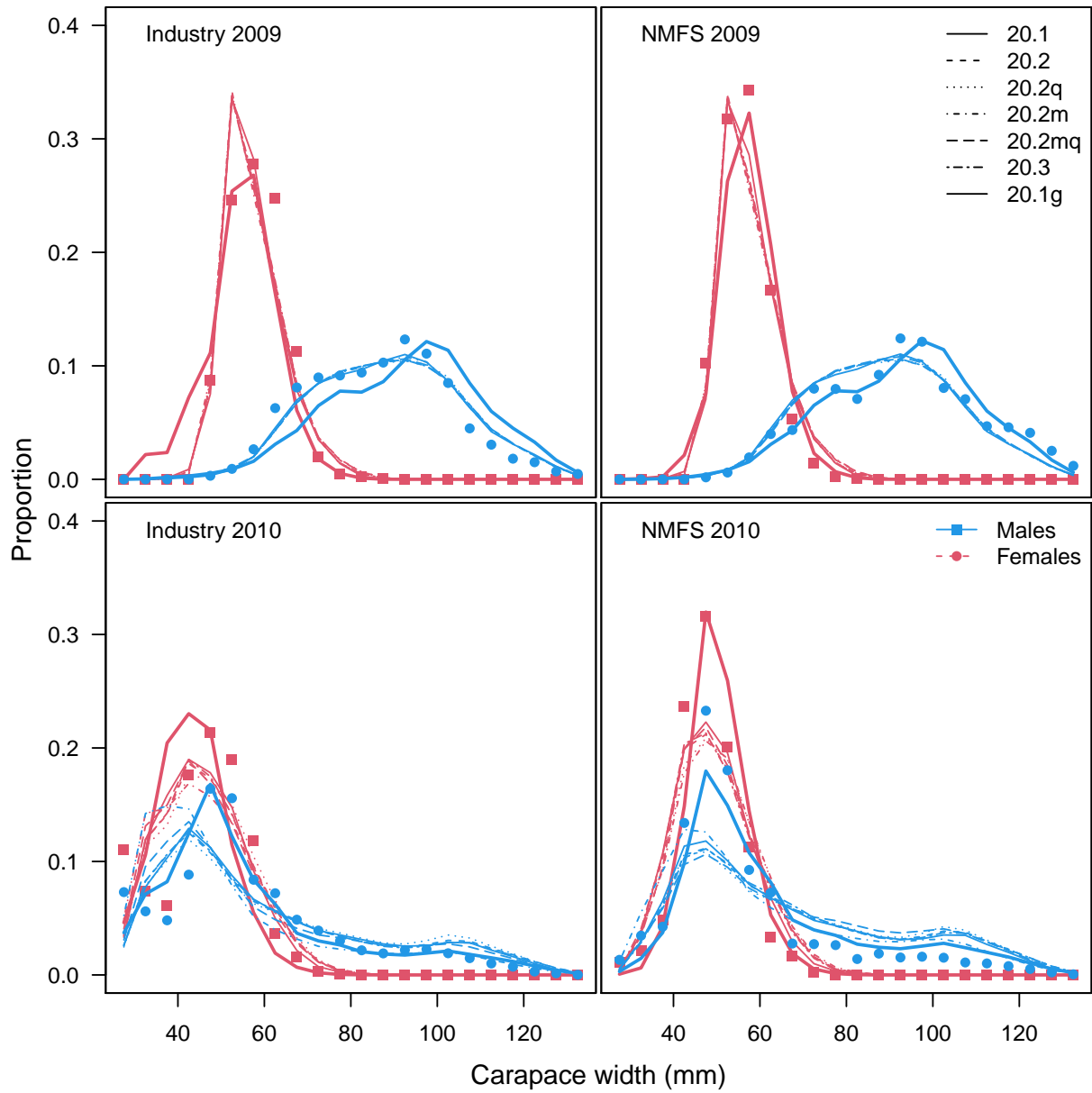
Figure 13: Model fits to size composition data from summer survey experiments (2009 & 2010)
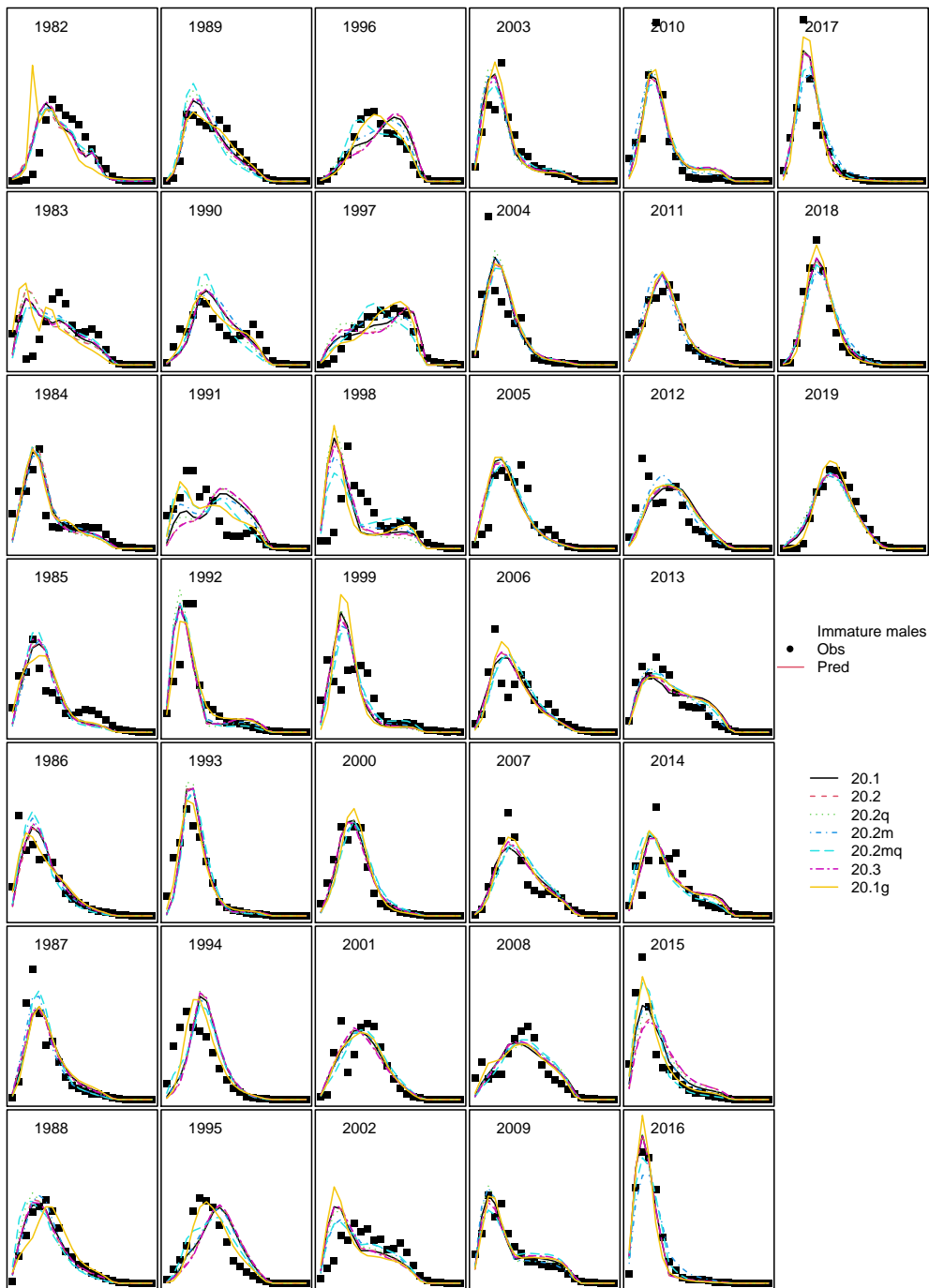
Figure 14: Model fits to immature male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.
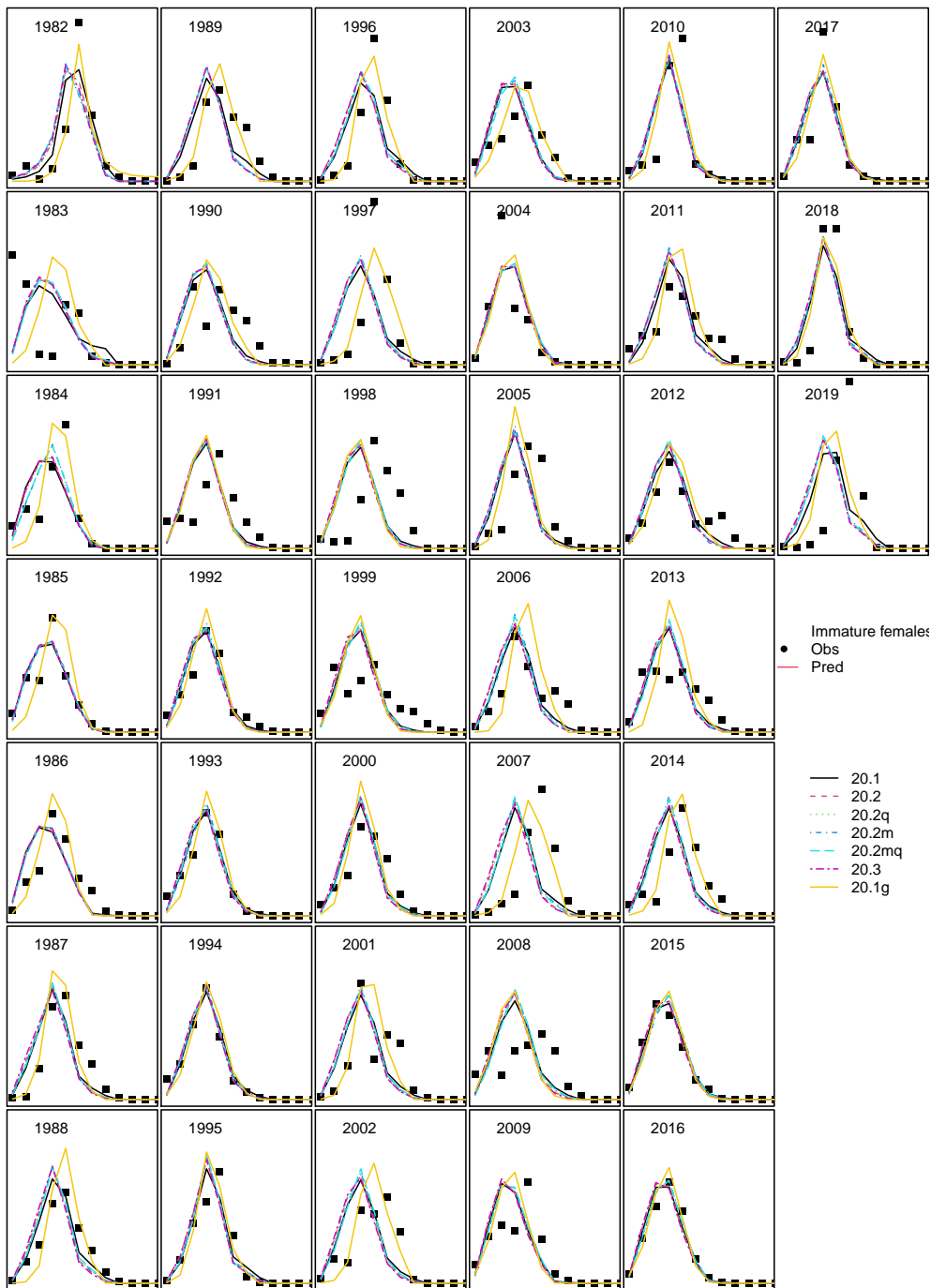
Figure 15: Model fits to immature female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.
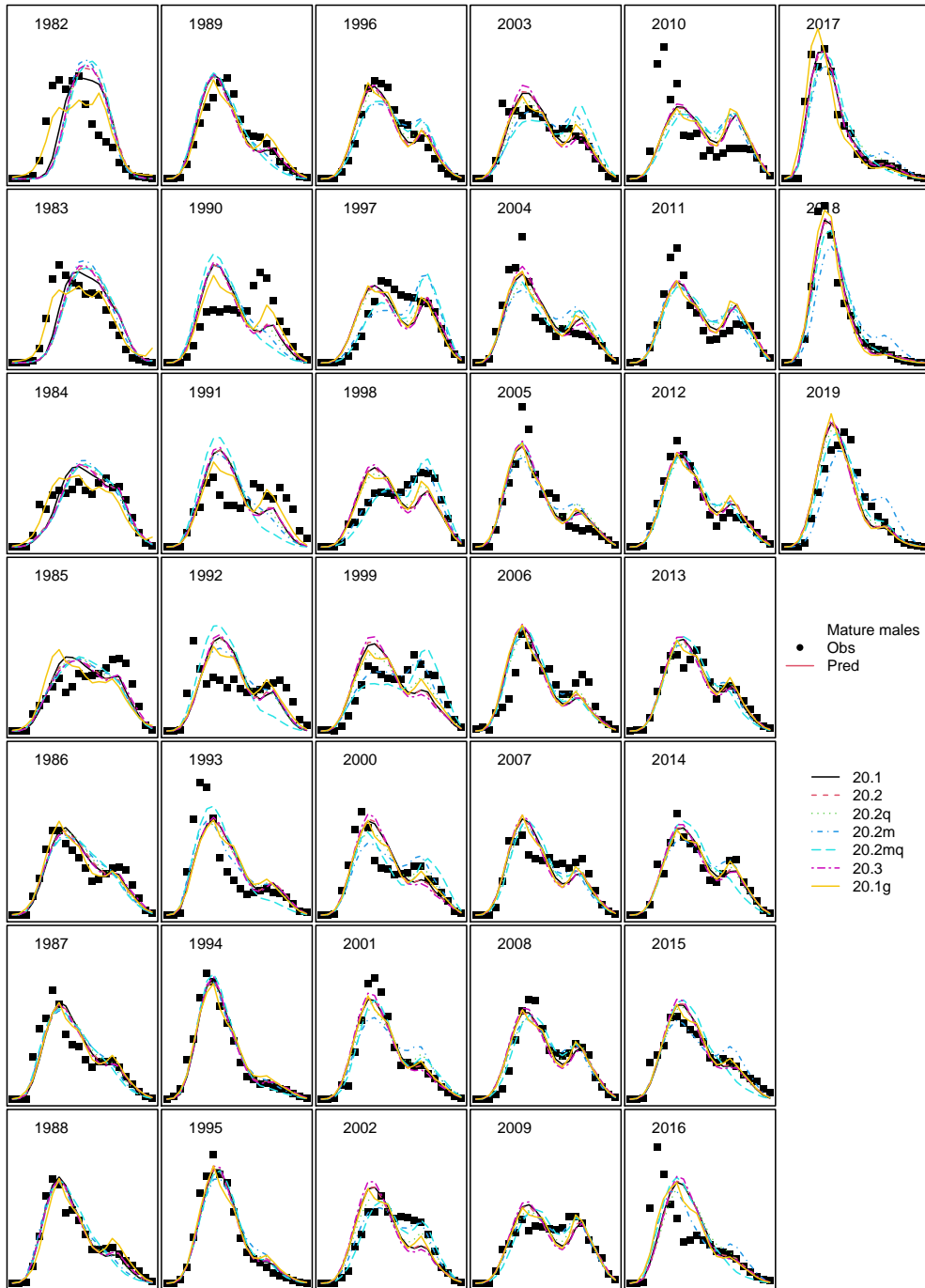
Figure 16: Model fits to mature male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.
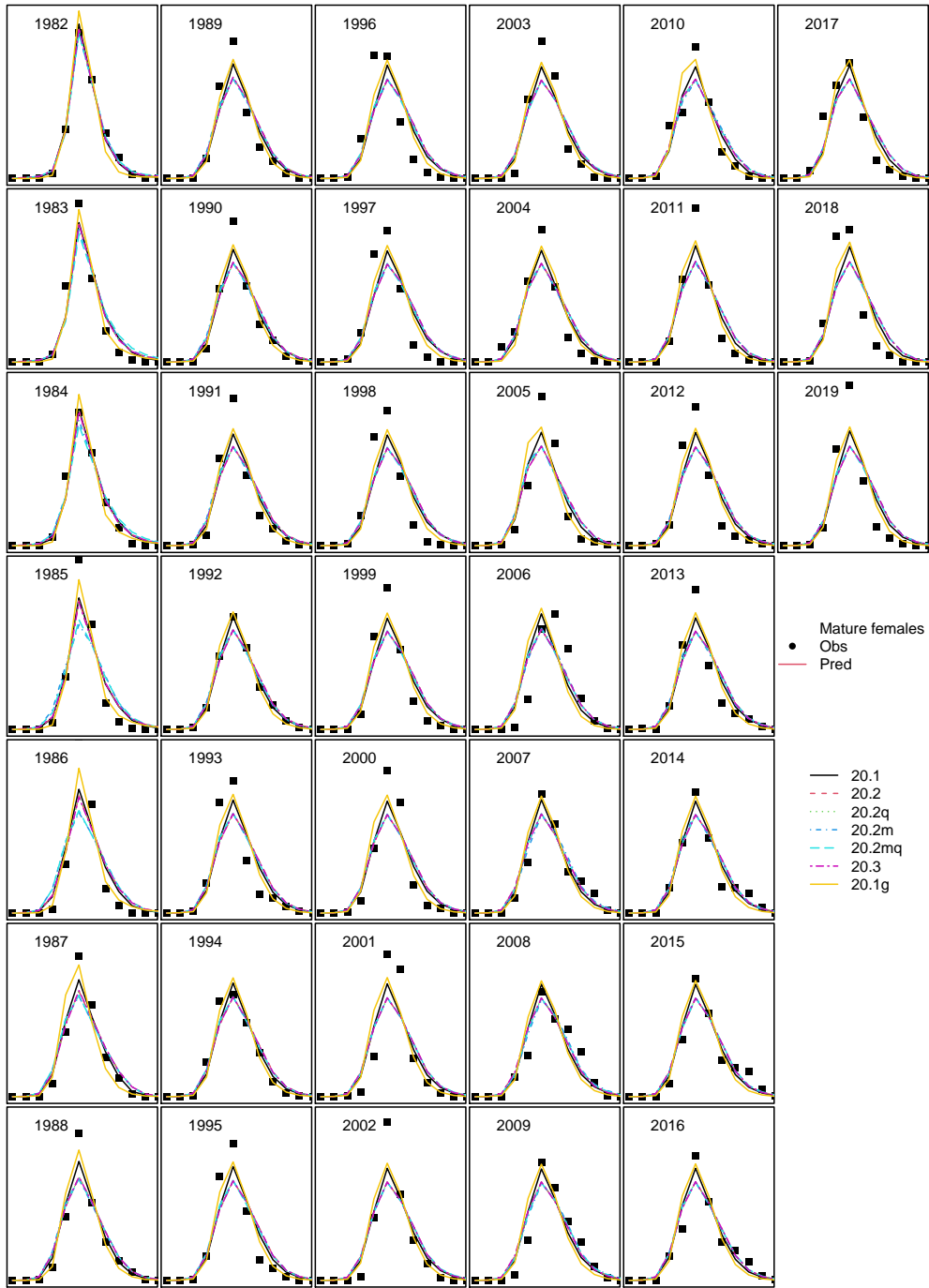
Figure 17: Model fits to mature female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.
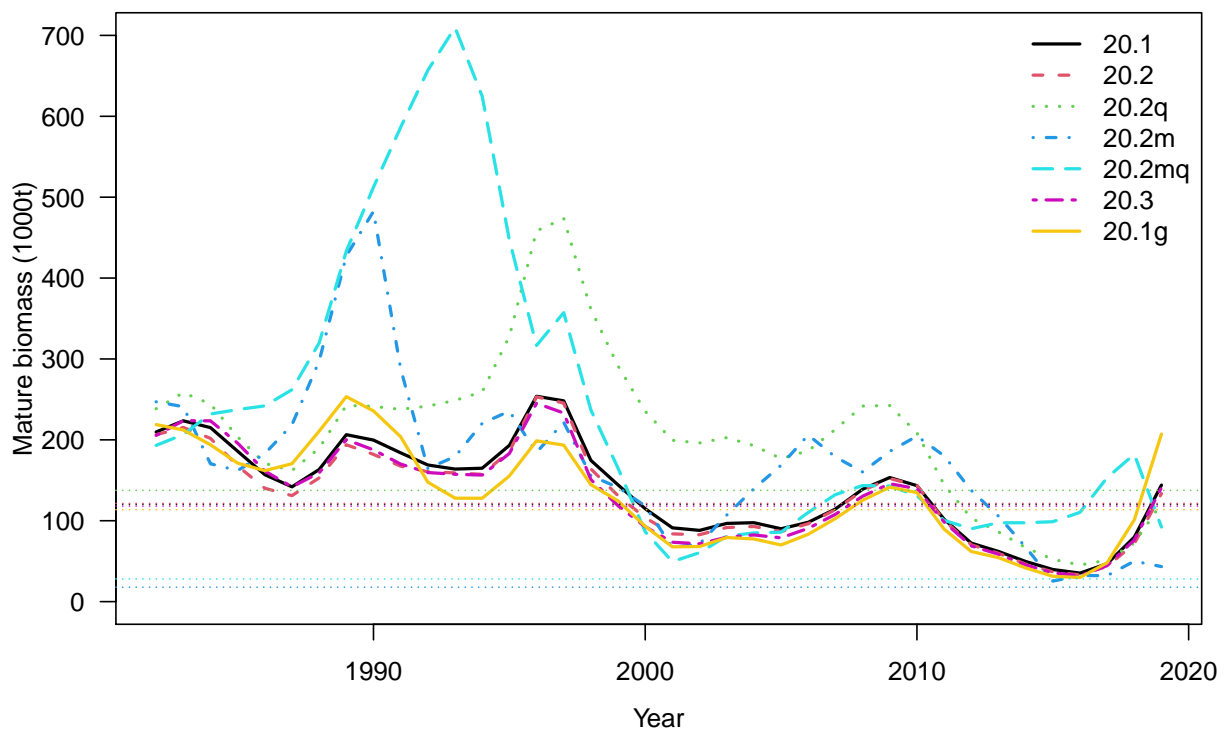
Figure 18: Model predicted mature biomass at mating time. Dotted horizontal lines are target biomasses.
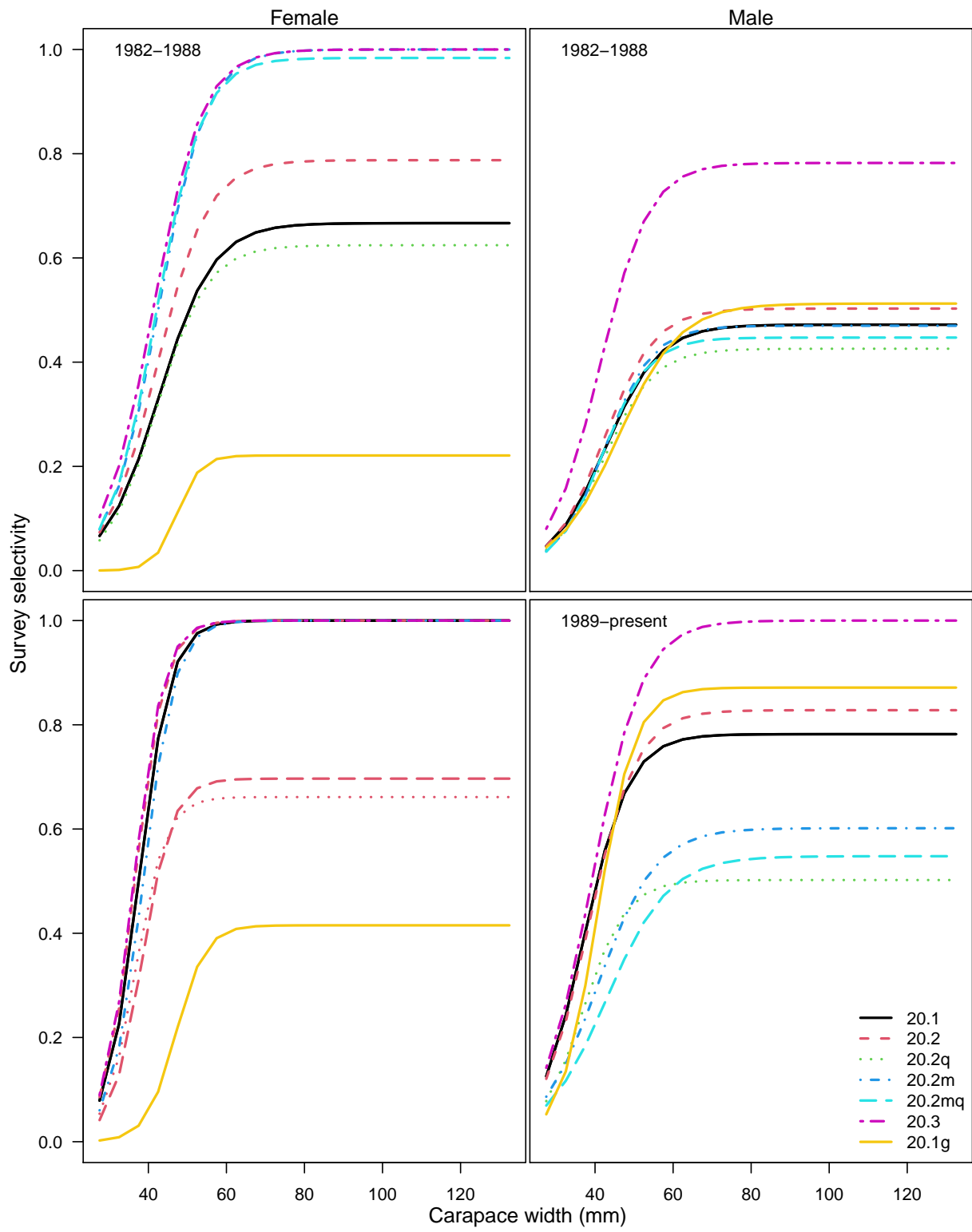
Figure 19: Estimated survey selectivity
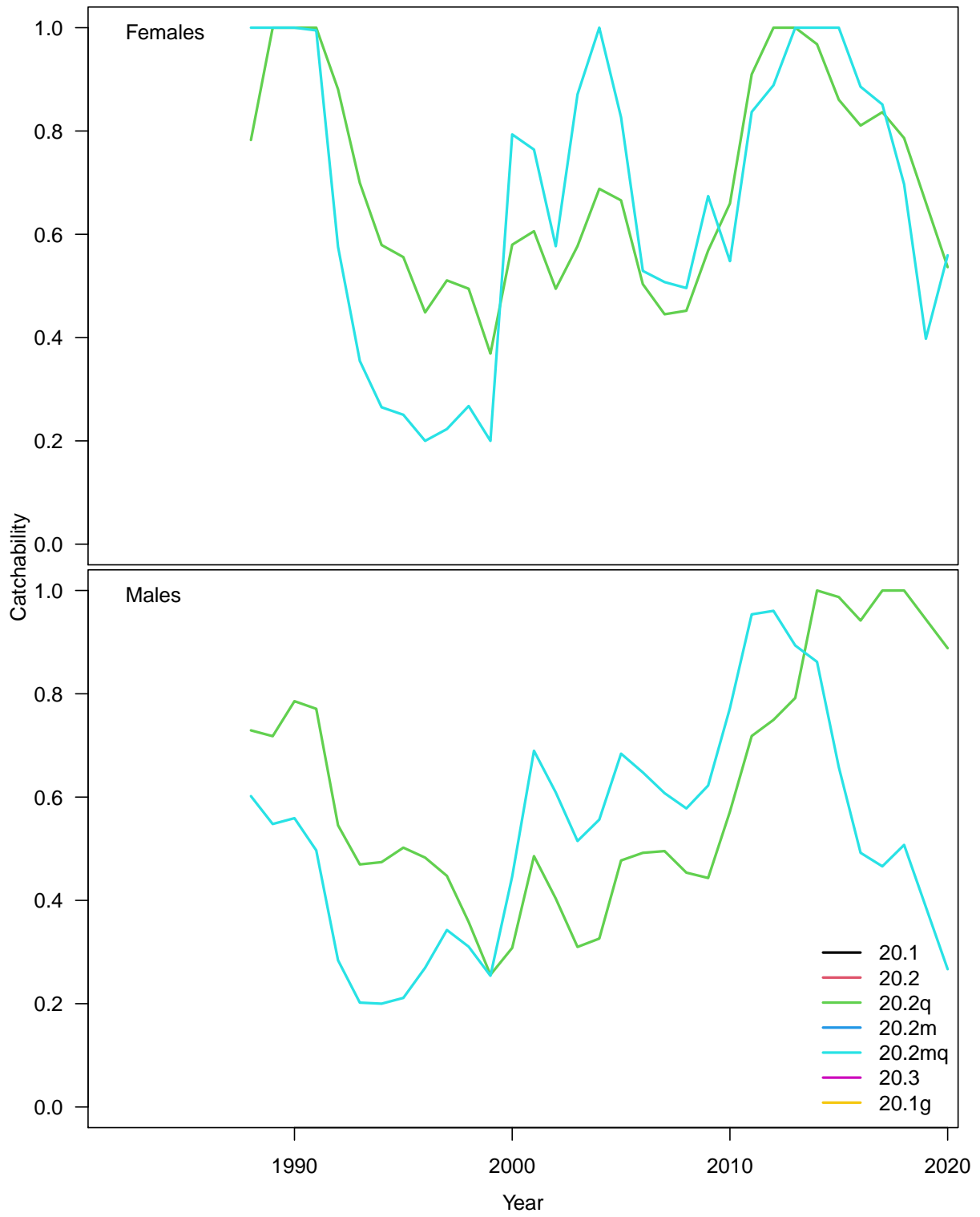
Figure 20: Estimated time-varying survey catchability (era 3).
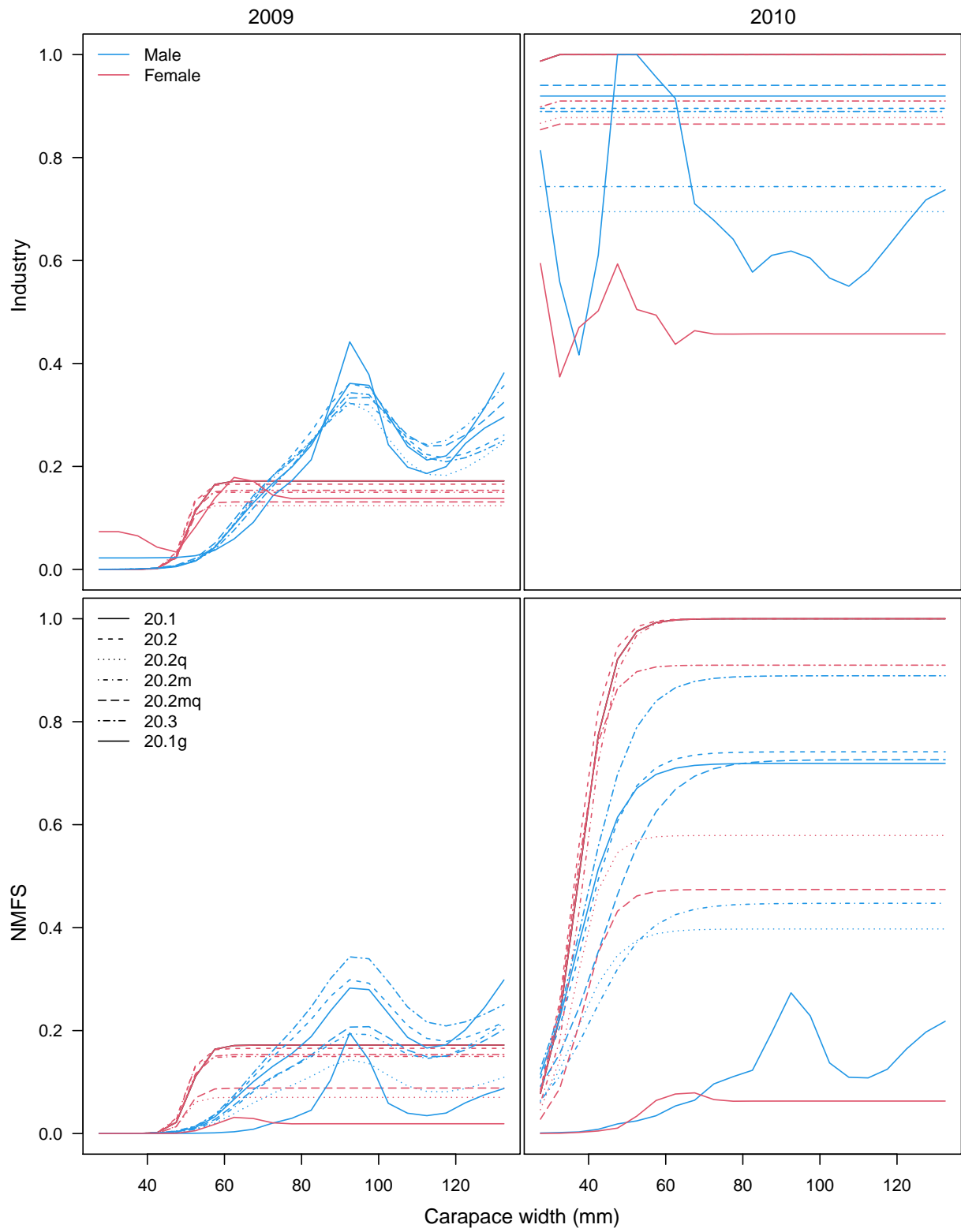
Figure 21: Estimated experimental survey selectivity (availability * survey selectivity)
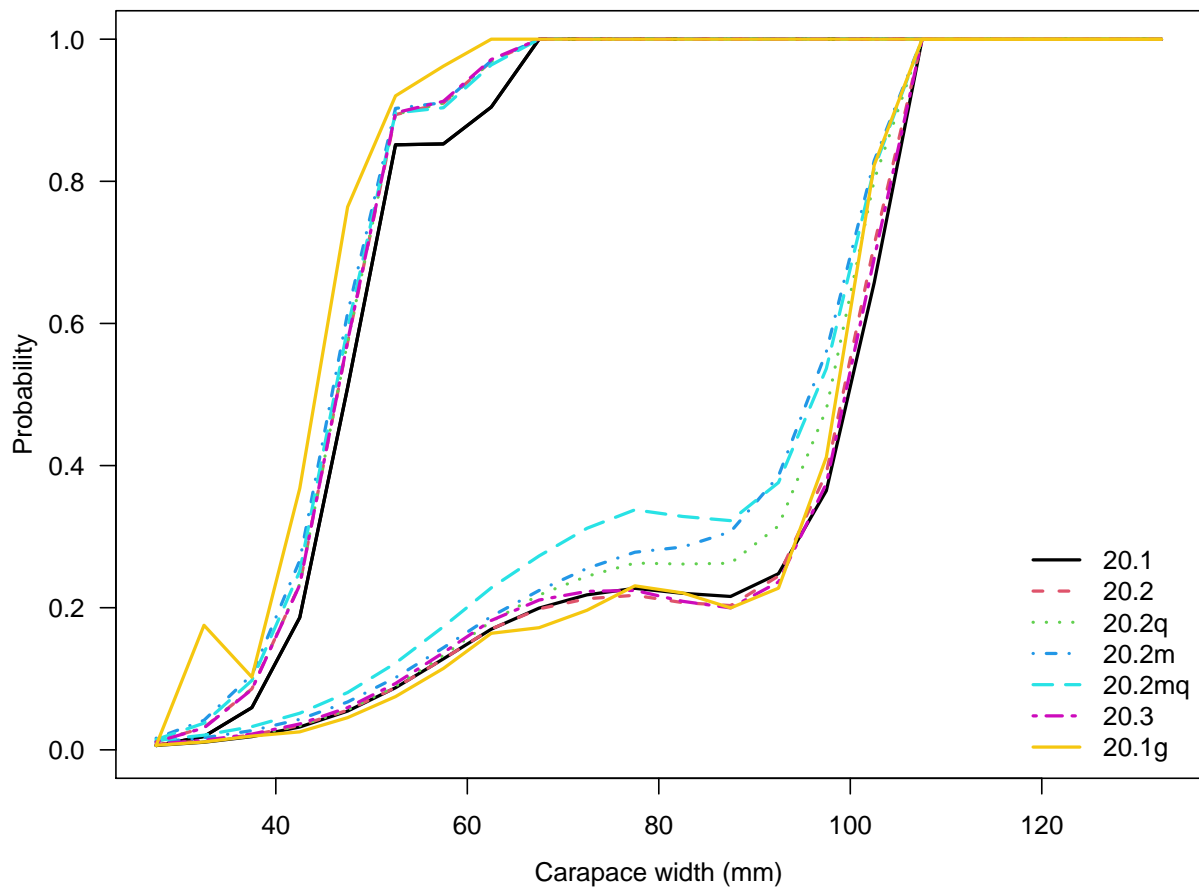
Figure 22: Estimated probability of maturing
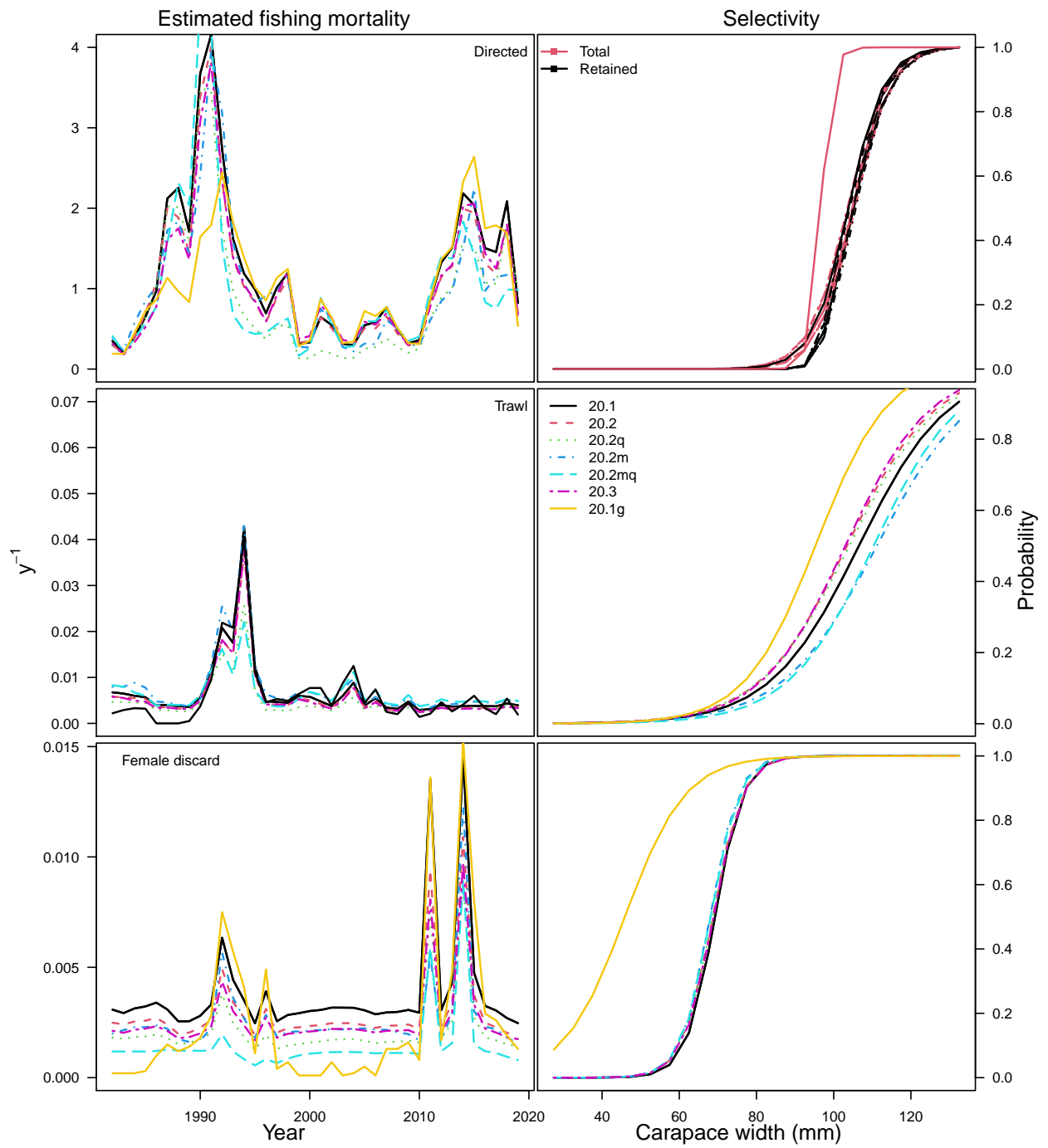
Figure 23: Model predicted fishing mortalities and selectivities for all sources of mortality
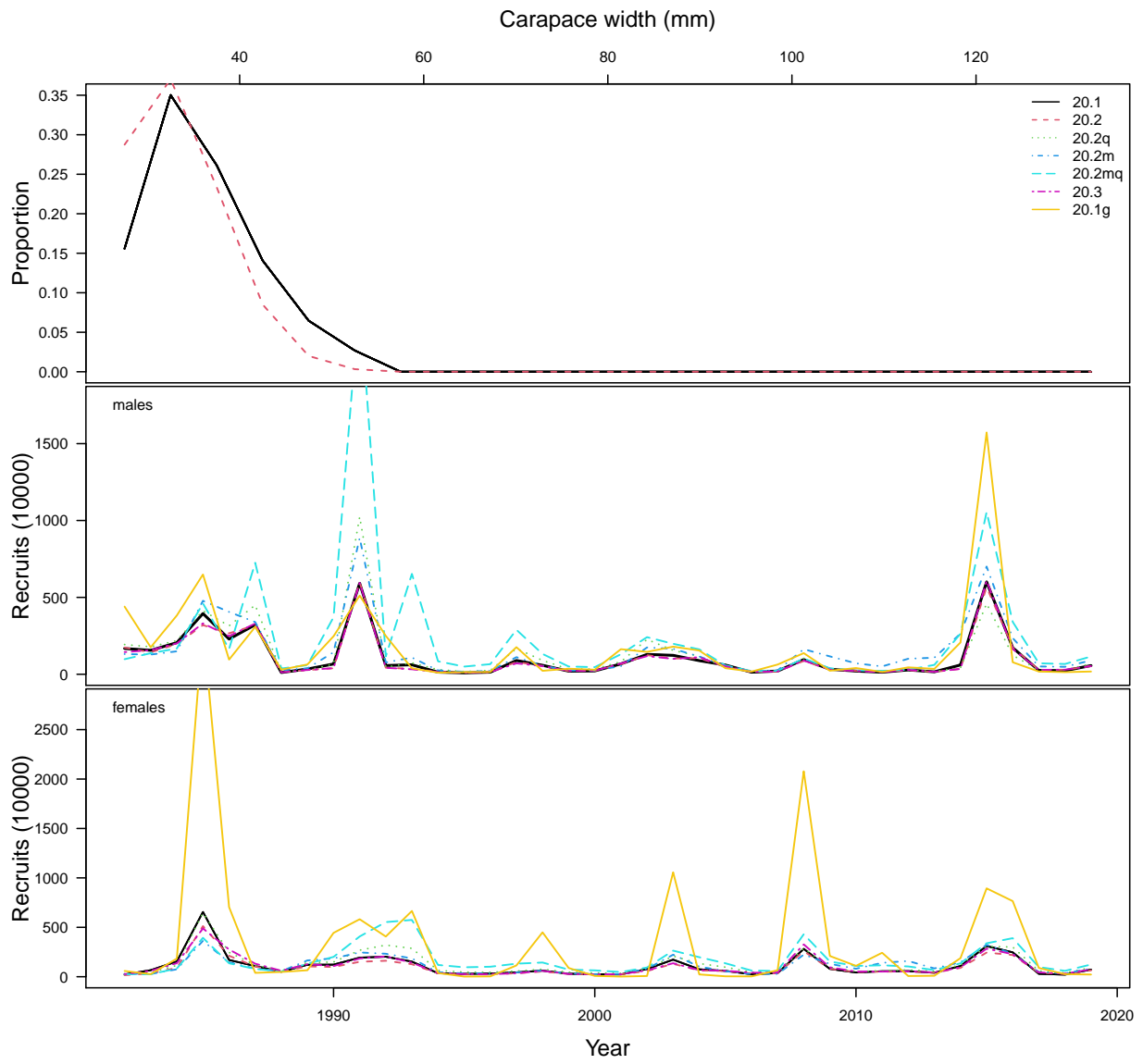
Figure 24: Estimated recruitment and proportions recruiting to length bin.
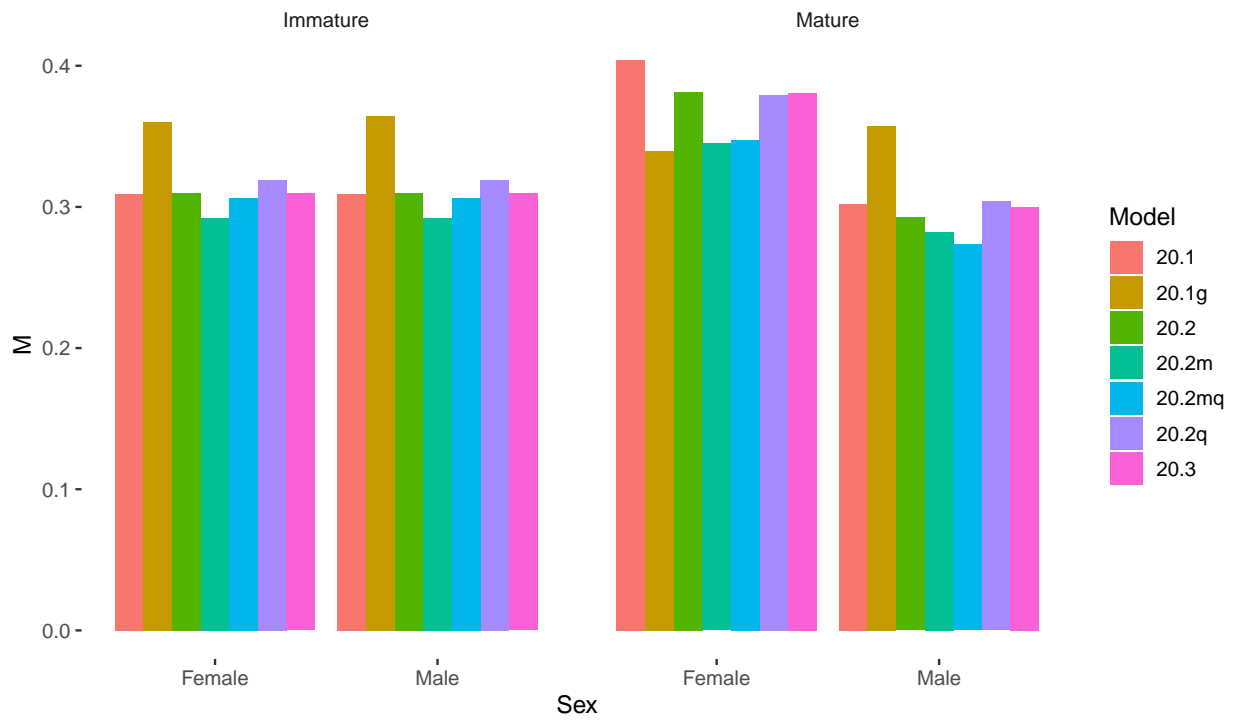
Figure 25: Estimated natural mortality by sex and maturity state.
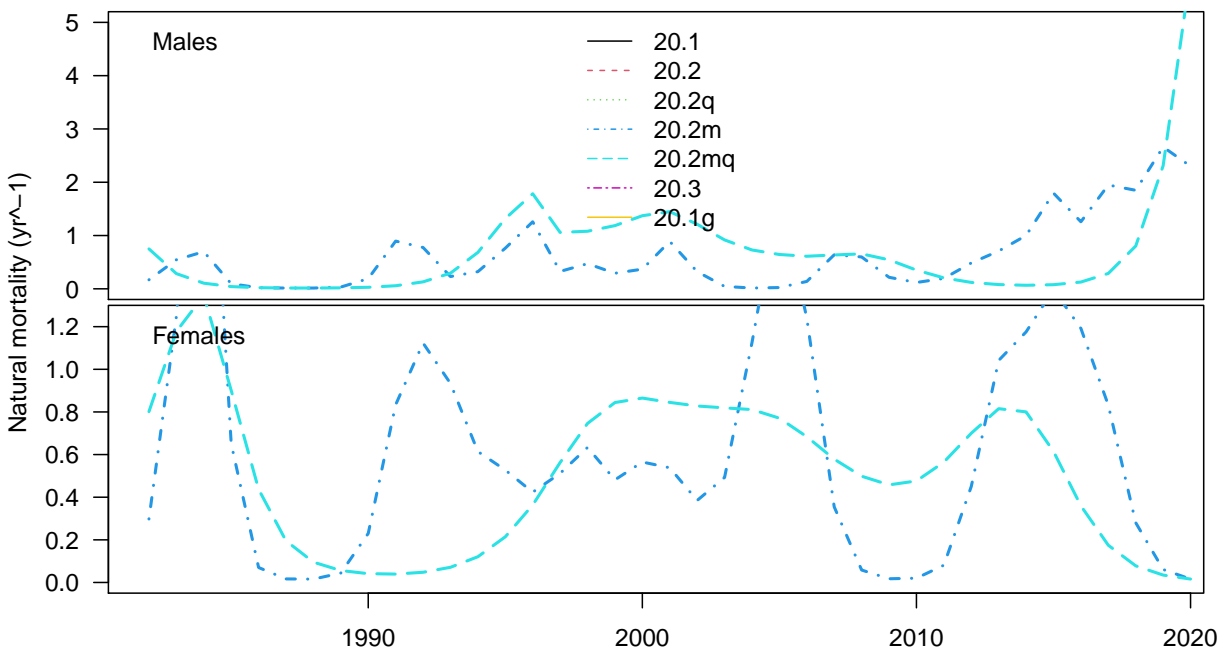
Figure 26: Estimated time varying natural mortality by sex and maturity state. Note different scales between sexes.
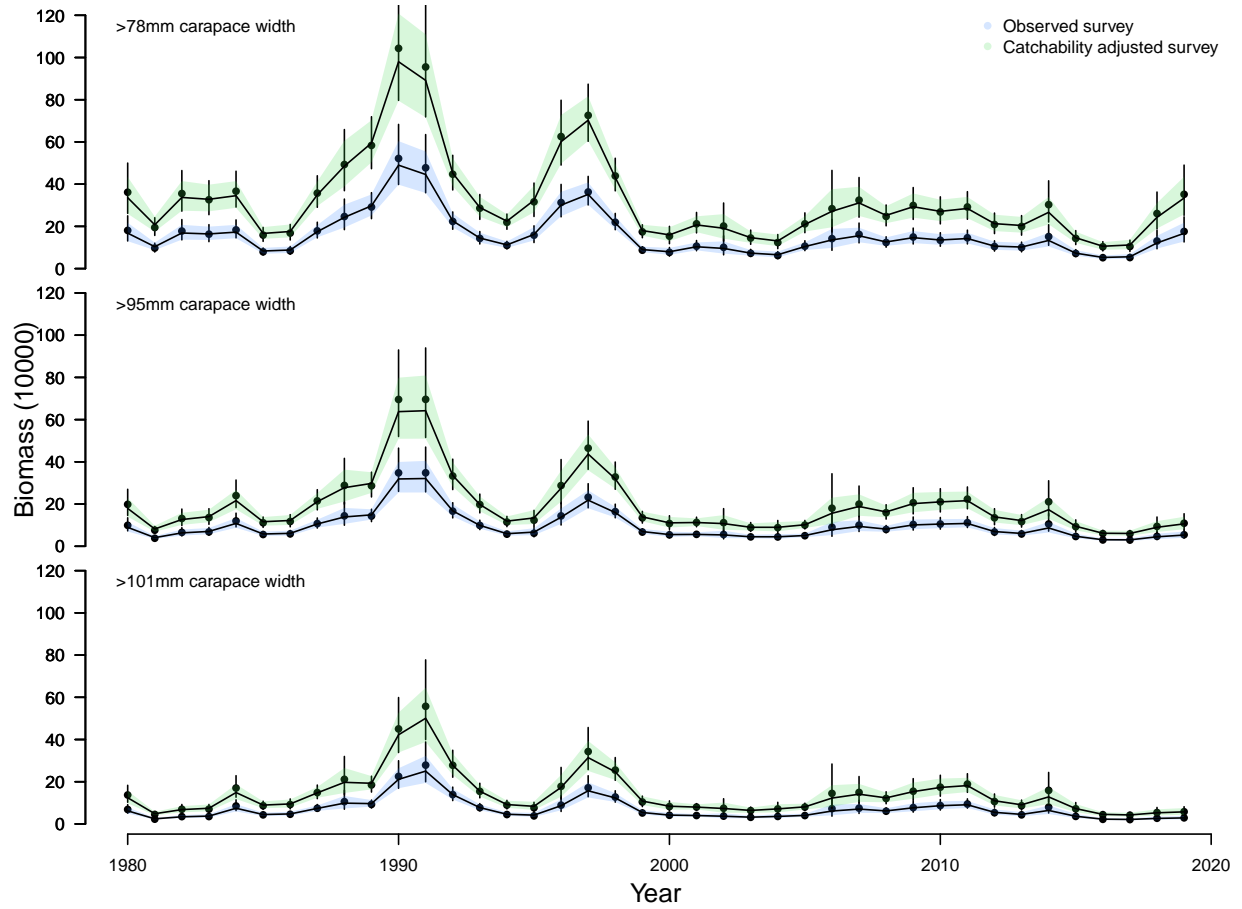
Figure 27: Output of random effects model for three different measures of large male biomass (>78mm, >95mm, and >101mm carapace width).
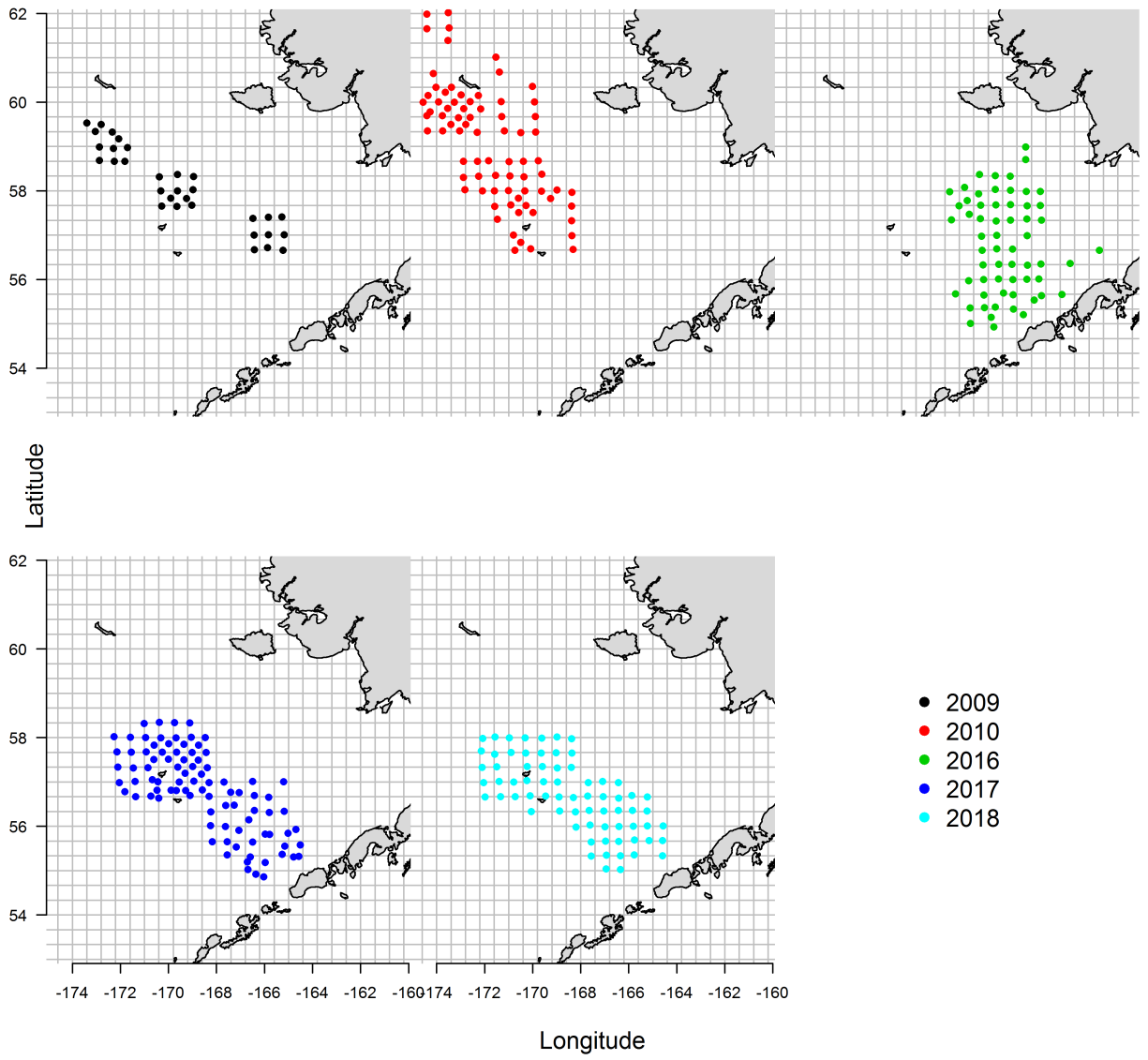
Figure 28: Location of BSFRF survey selectivity experiments.
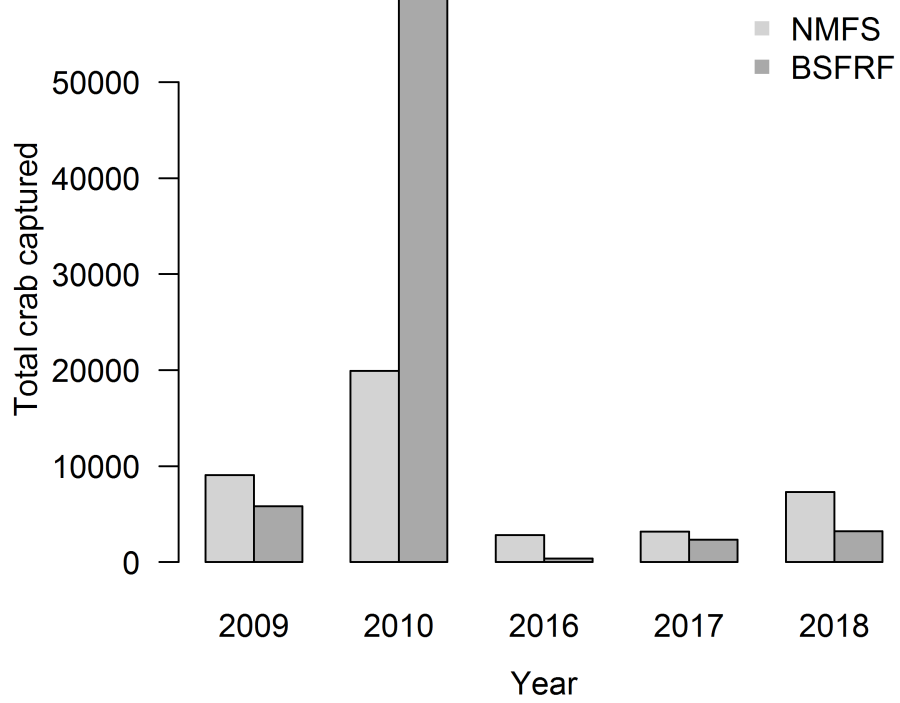
Figure 29: Number of crab from which estimates of biomass and length composition data were inferred within the survey selectivity experimental area.
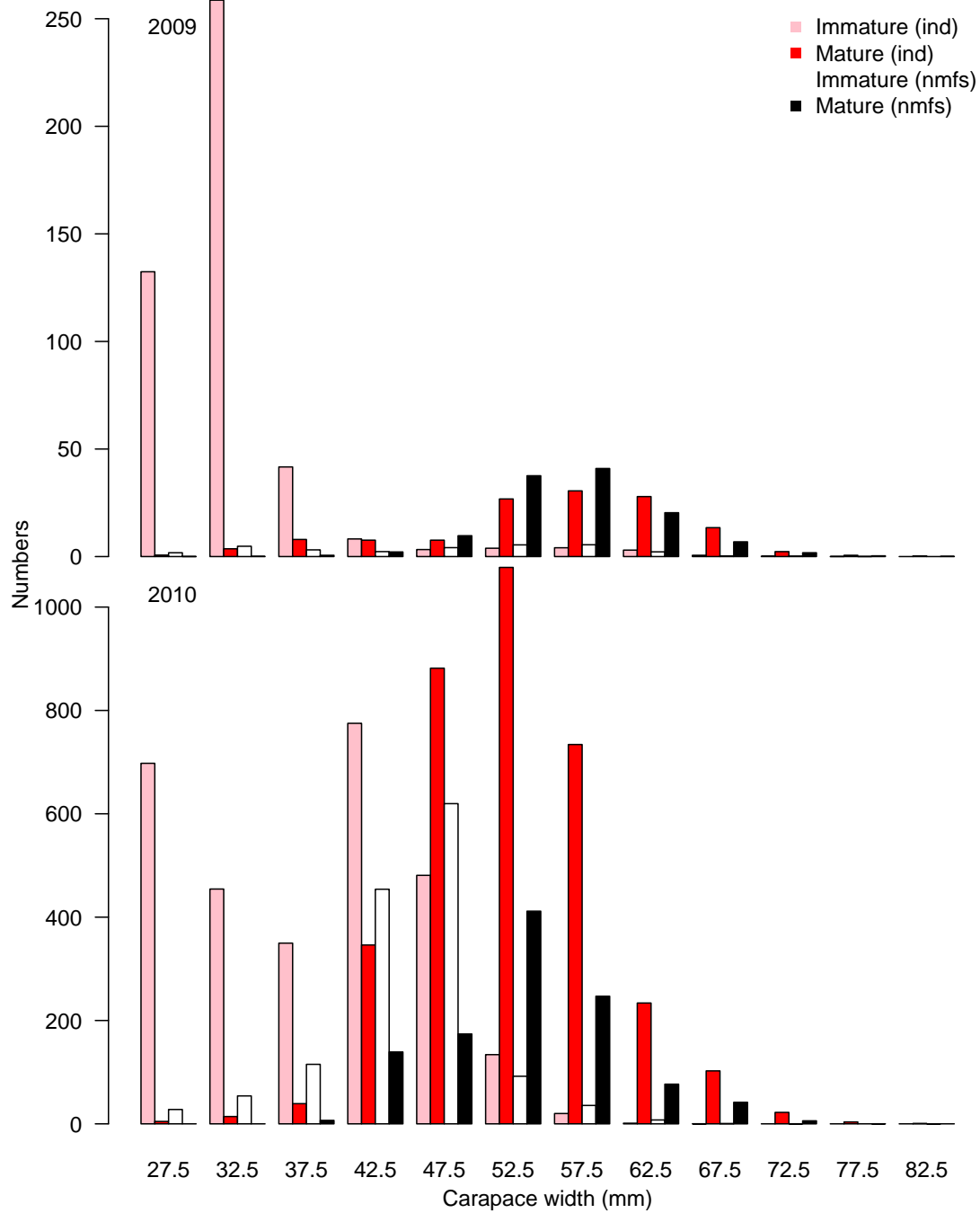
Figure 30: Raw female numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale on the y-axis from 2009 to 2010
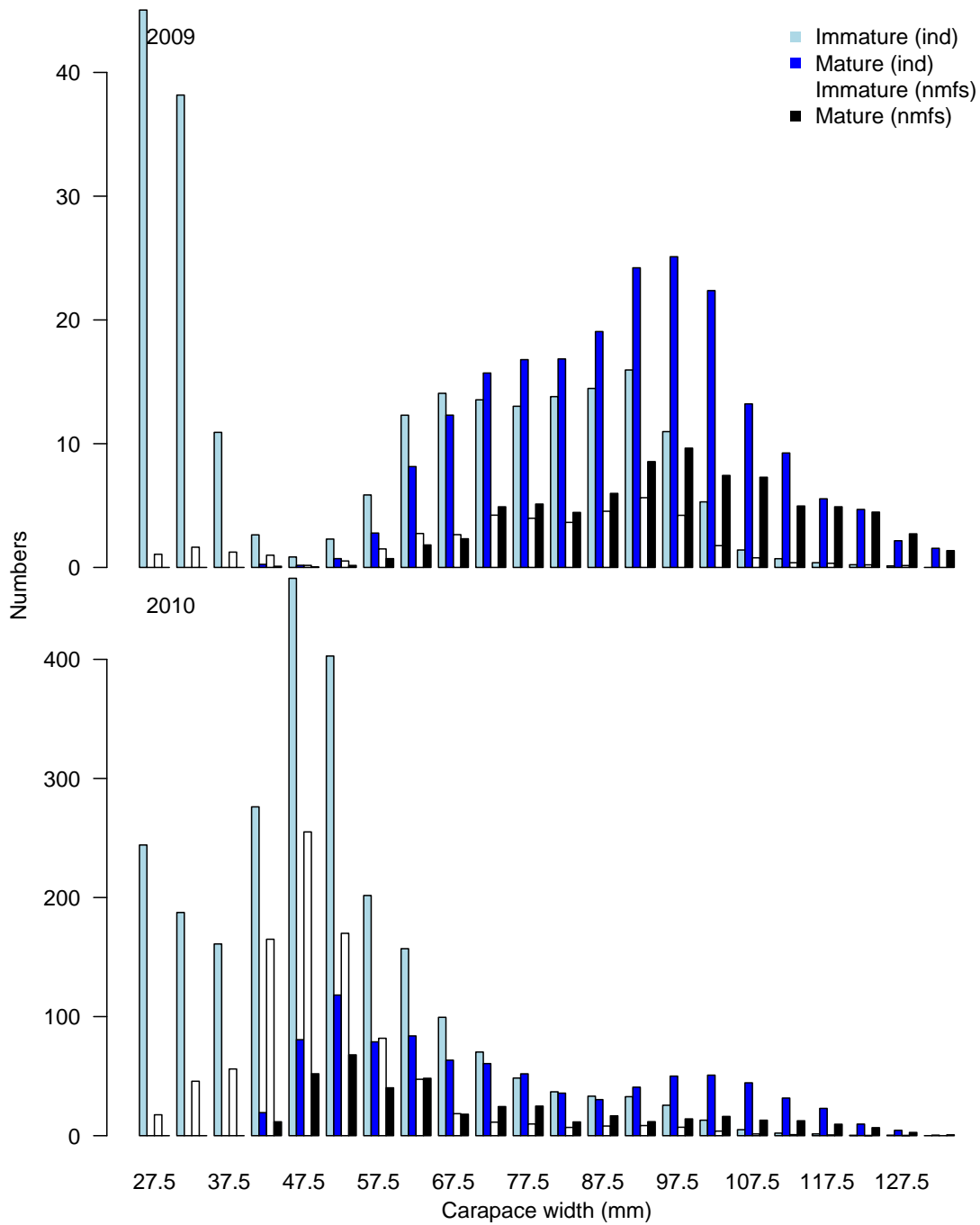
Figure 31: Raw male numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale from 2009 to 2010 on the y-axis.
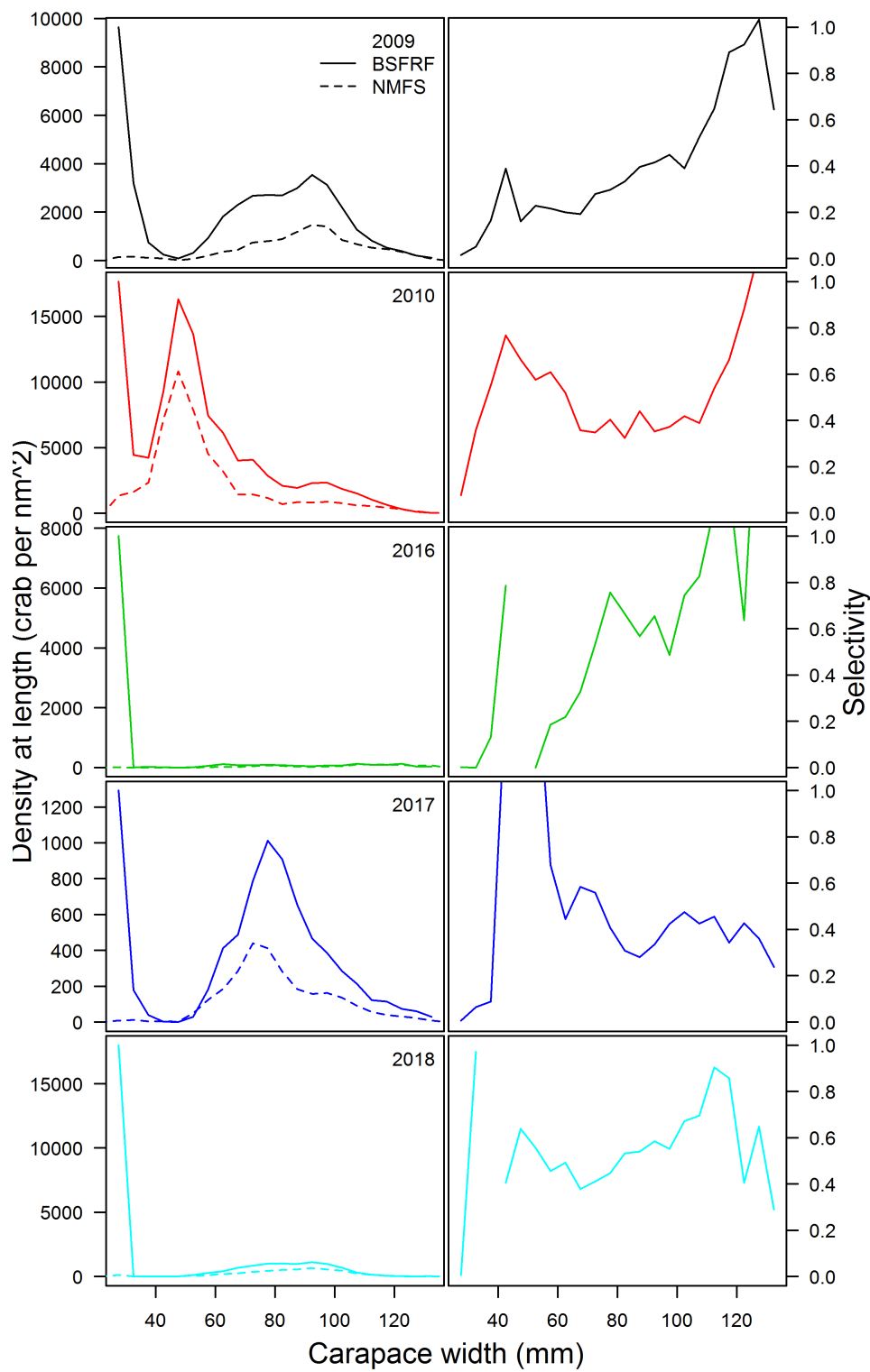
Figure 32: Observed numbers at length extrapolated from length composition data and estimates of total numbers within the survey selectivity experimental areas by year (left). Inferred selectivity (i.e. the ratio of crab at length in the NMFS gear to crab at length in the BSFRF gear.
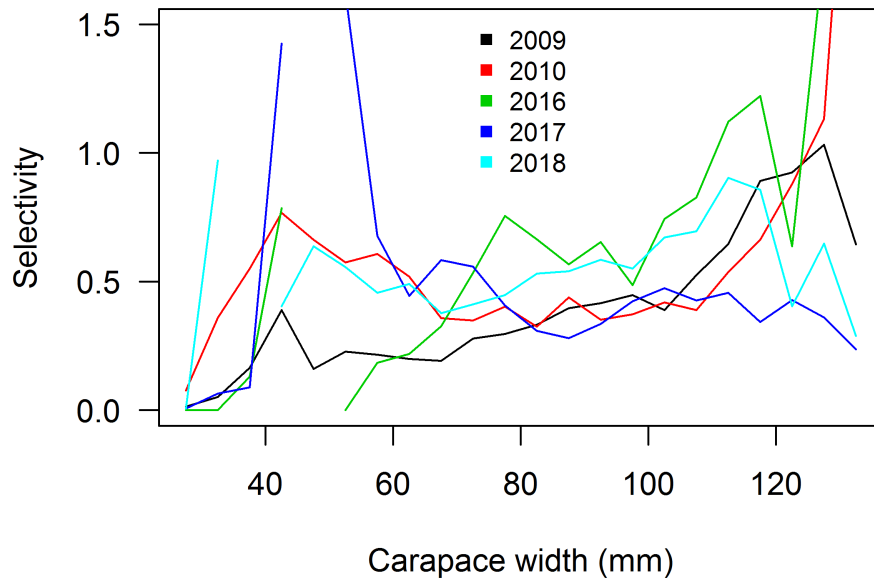
Figure 33: Inferred selectivity for all available years of BSFRF data.

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 34:   Radiometric estimates of shell age in male snow and tanner crabs collected during the NMFS survey of 1992. Reproduced from Ernst et al. 2005's presentation of Nevissi et al. 1995.
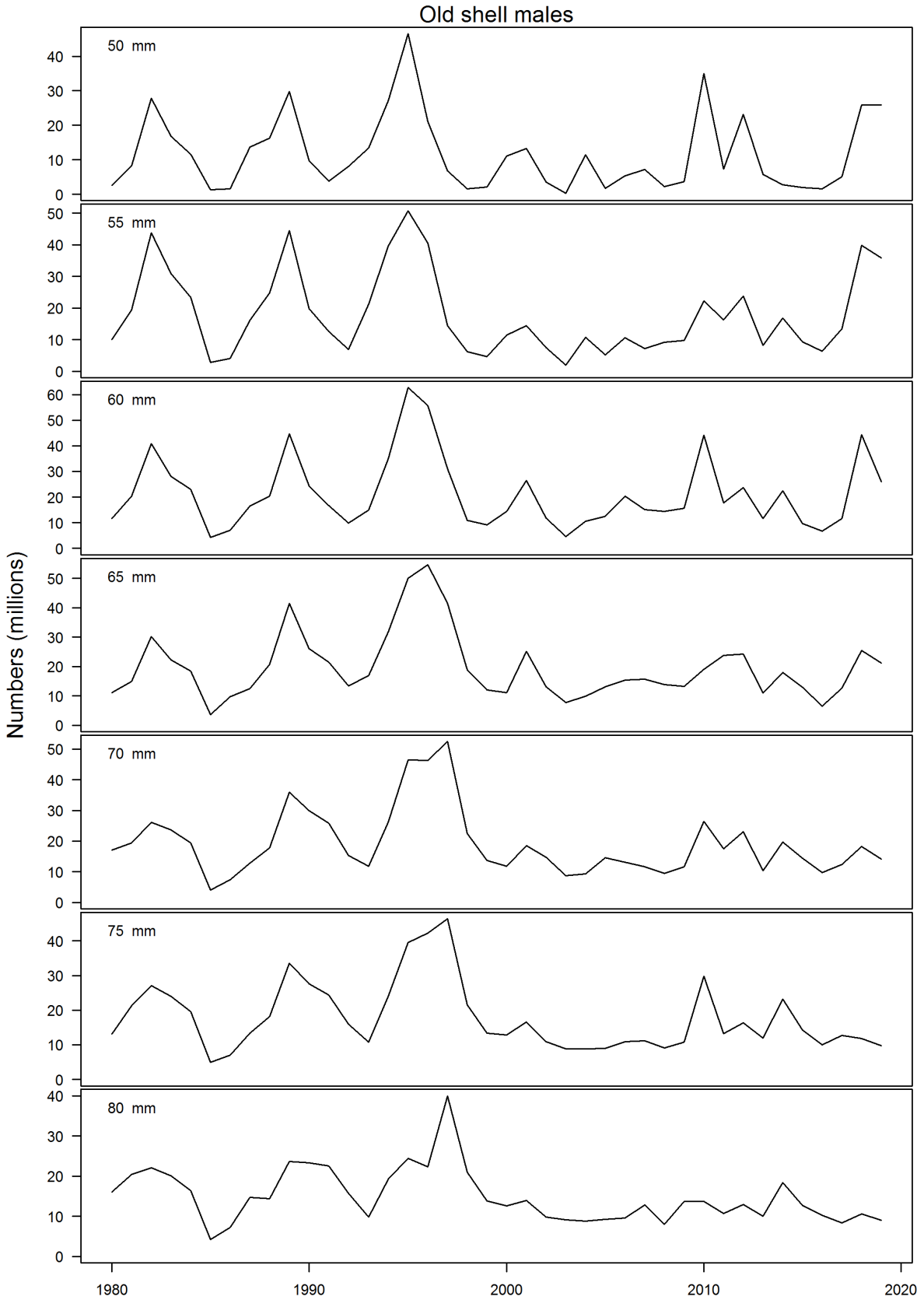
Figure 35: Observed numbers at length of old shell mature males by size class. The presented size bins are not vulnerable to the fishery, so all mortality is 'natural'. The decline in numbers in a size class after the recruitment collapse in the early 1990s demonstrates expected natural mortality for mature male individuals.
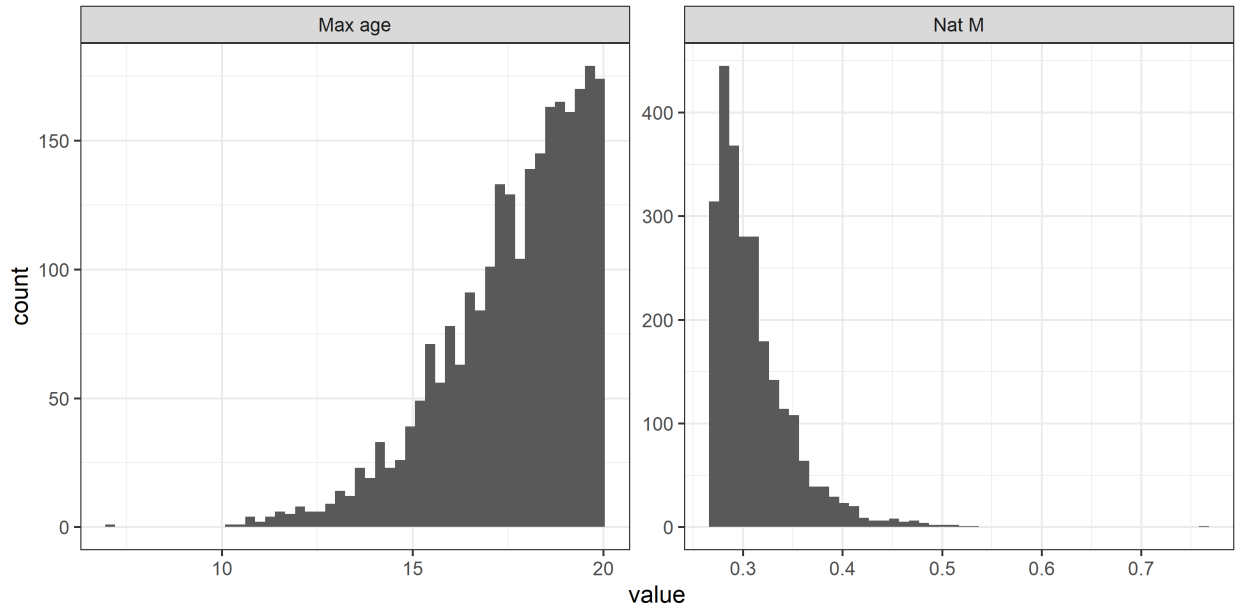
Figure 36: Input distribution of maximum age and resulting distribution of natural mortality calculating using Then et al. 2016's methodology.
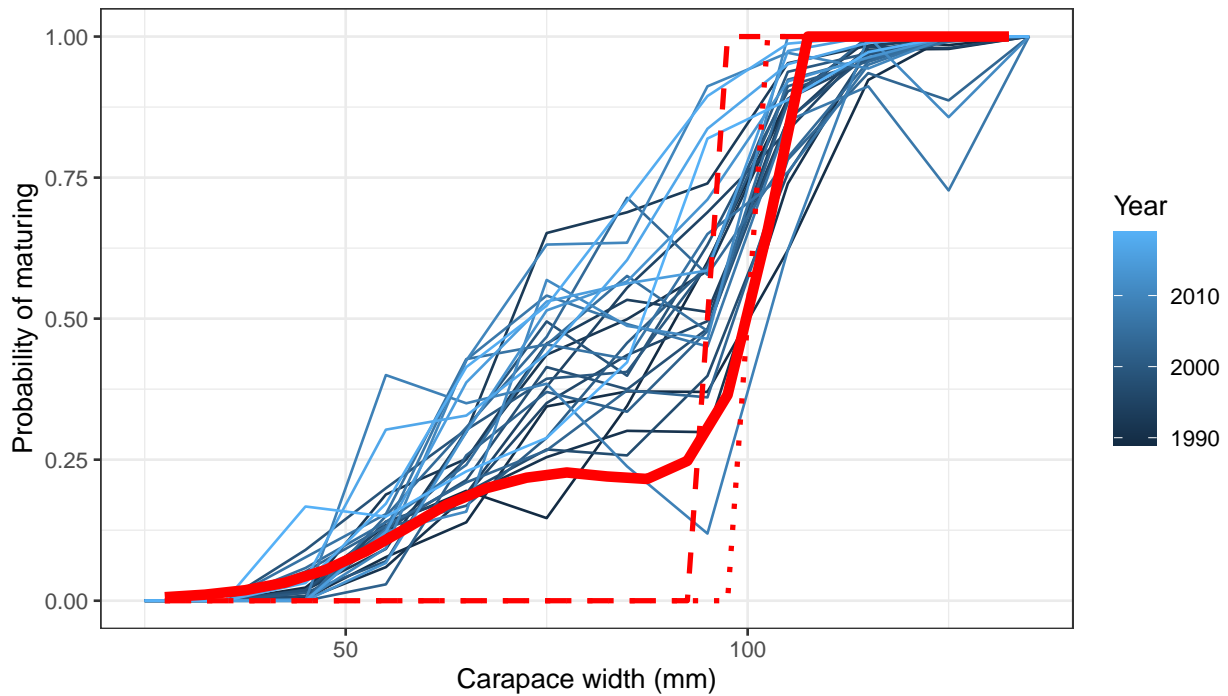

Figure 37: Comparison of estimated and empirically derived proportion maturing by size class. Blue lines are derived from observation of proportions of mature new shell males at a given size in a given year. Red dashed lines represent other hypotheses for the contribution to reproduction of different sized crab.
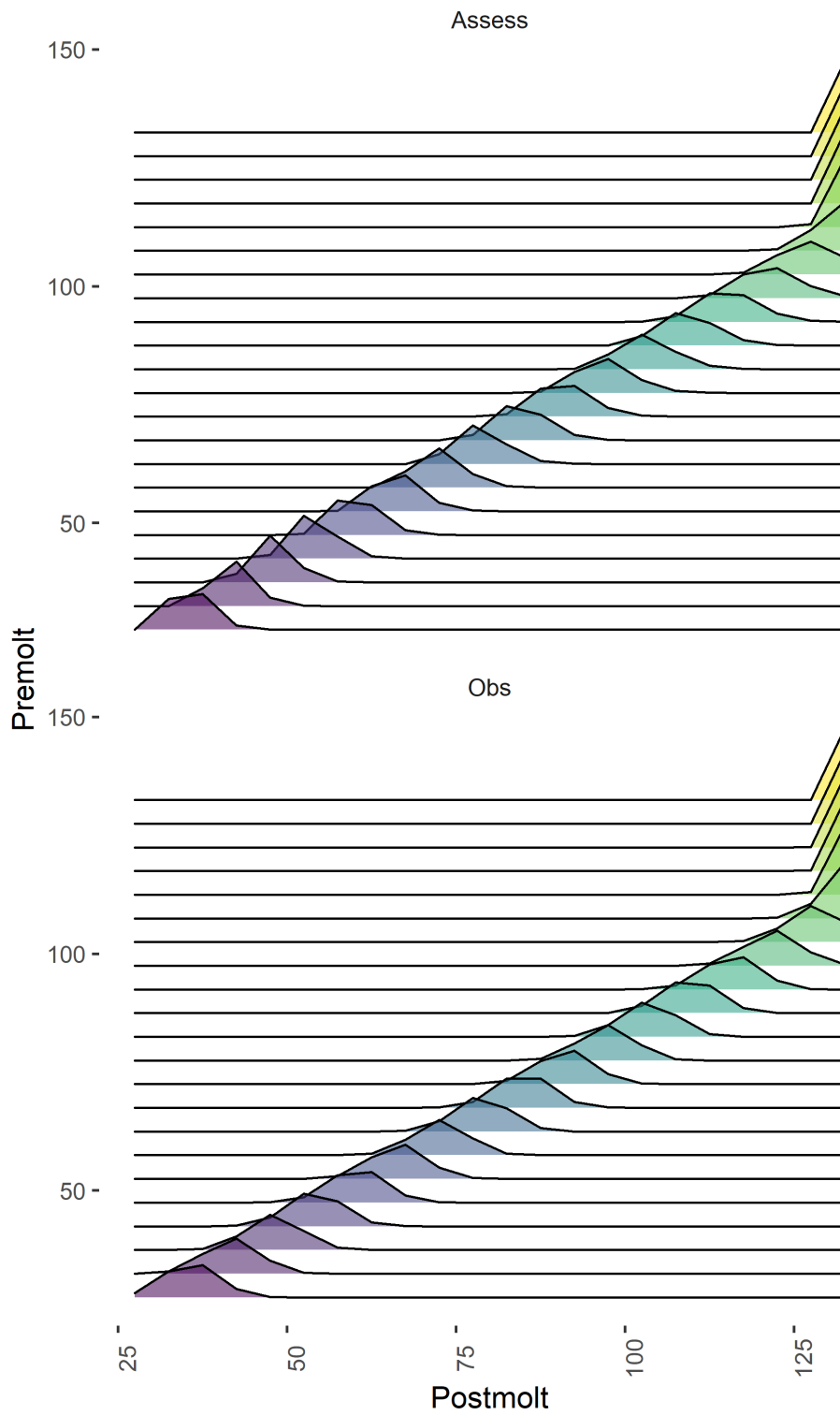
Figure 38: A comparison of size transition matrices from the assessment (left) and based on the empirical estimates. Units on each axis are width of carapace in mm.
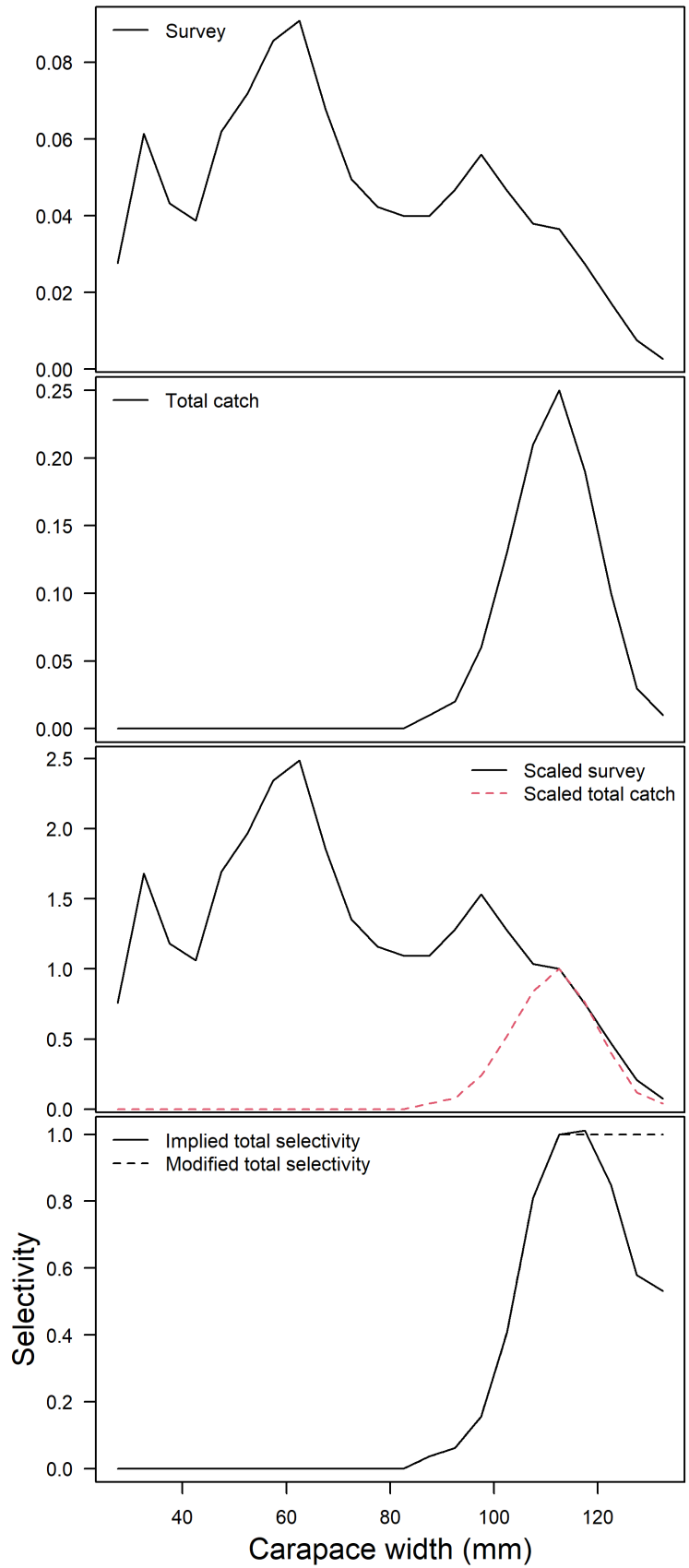
Figure 39: Methodology for calculating 'empirical' selectivity from total male survey size composition data, total fishery selectivity size composition data, and retained fishery selectivity size composition data. Units for top two panels are densities; units for third down panel are not defined because of the scaling.
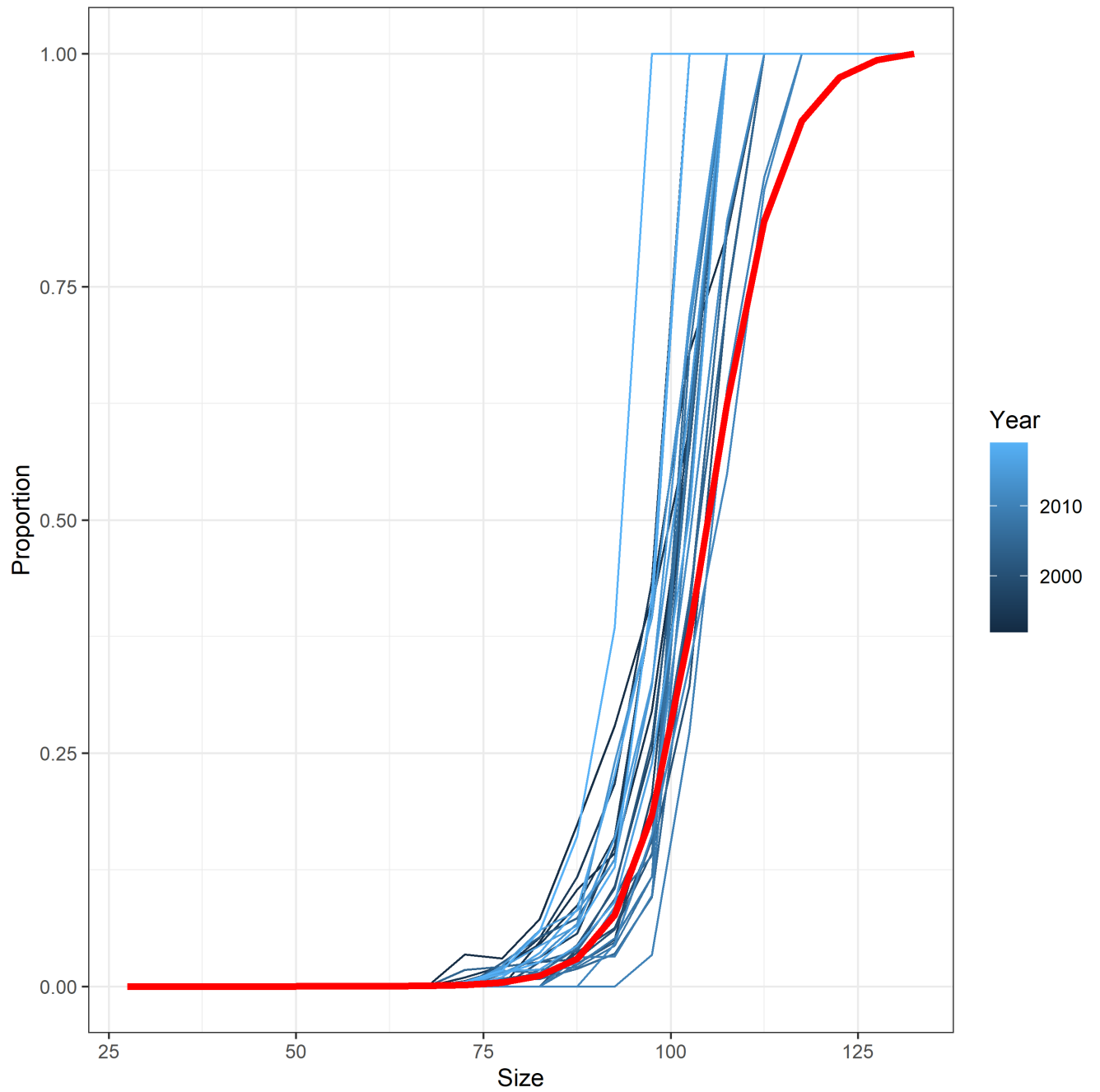
Figure 40: Comparison of estimated and empirically derived total fishery selectivity. Blue lines are yearly empirically derived selectivities. Red line is the 2020 status quo model's estimate of selectivity. Size is width of carapace in mm.
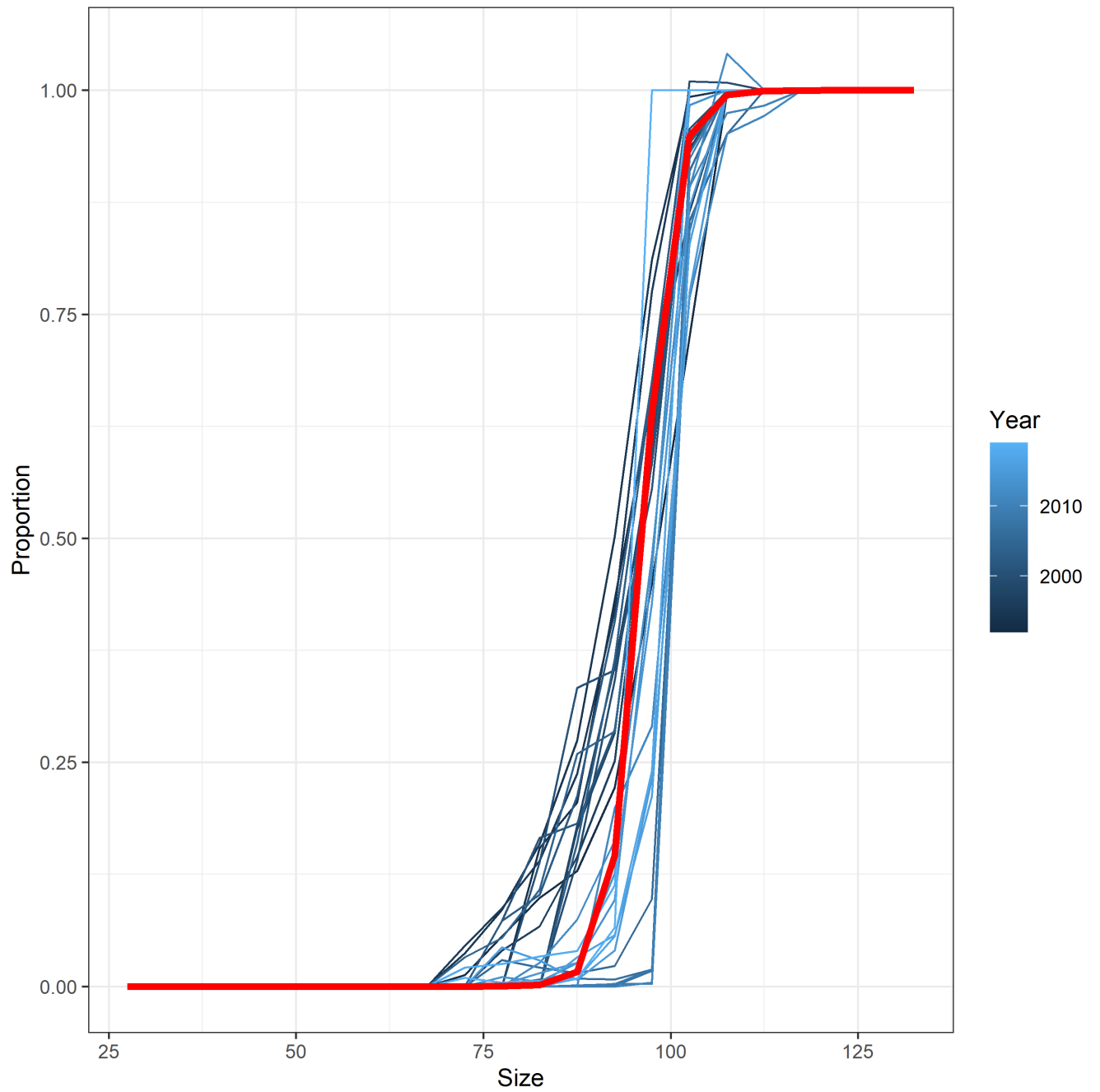
Figure 41: Comparison of estimated and empirically derived retained fishery selectivity. Blue lines are yearly empirically derived selectivities. Red line is the 2020 status quo model's estimate of selectivity. Size is width of carapace in mm.
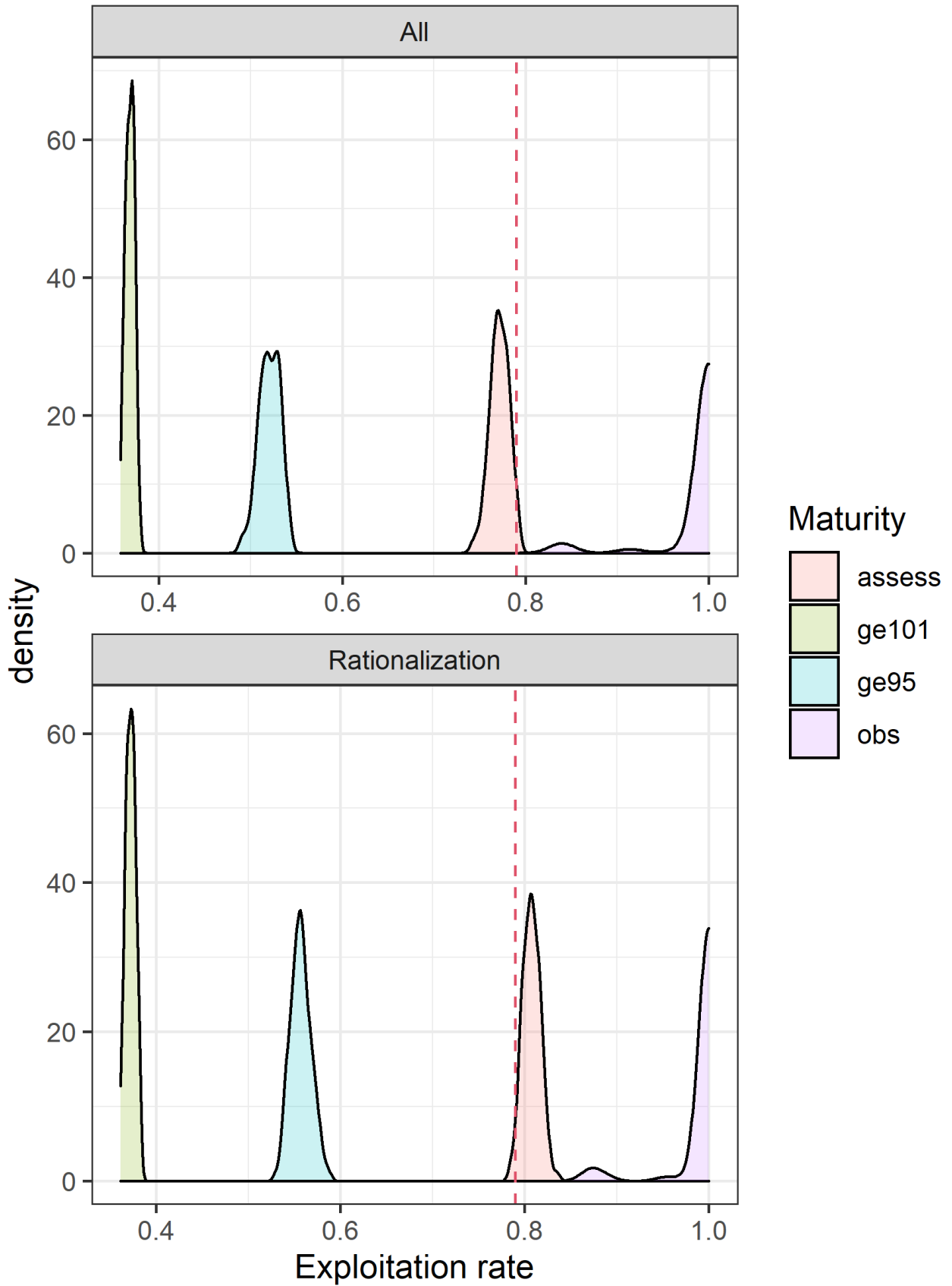
Figure 42: Distributions of exploitation rates associated with F35 for a range of assumptions about fishery selectivity and reproductive contribution of different sizes of crab. Vertical dashed red line indicates the exploitation rate associated with the F35 estimated in the assessment. The All panel uses all years of empirical fishery selectivity to calculate F35. The Rationalization panel uses only post rationalization years.