Snow crab: History and status of transition to GMACS

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Summary

This document summarizes the attempts at moving eastern Bering Sea (EBS) snow crab to an assessment using the Generalized Model for Assessing Crustacean Stocks (GMACS) to date, describes the differences between GMACS and the status quo model, and compares the fits and management advice produced by GMACS and the status quo model. The ultimate goal of this document is to provide the rationale for finally accepting GMACS as the new model for assessing EBS snow crab.

A GMACS model for snow crab was first presented in May 2020 and the CPT recommended it for use in September of 2020 based on better model fits, a confirmation that GMACS could reproduce the status quo numbers at size matrix for males with the same input parameters, improved model structure, assumptions, and stability, and the utility of working towards a common code base for all EBS stocks. However, the SSC rejected that implementation of GMACS for snow crab based on concerns around estimates of recruitment, fishing mortality, retrospective patterns, and the resulting overfishing levels. The SSC seemed most concerned with estimates of recruitment and the resulting management quantities. The differences in recruitment and management advice between GMACS and the status quo stemmed primarily from the fact that GMACS split the difference between the final years of survey biomass data and the status quo model fit only the lowest year (2019). It is difficult to pinpoint the reason that GMACS split the difference by estimating a larger recruitment in 2015 and the status quo model ignored the large survey biomass in 2018, but several differences exist between GMACS and the status quo that could contribute. (Currently, the question is mostly academic because the most recent status quo model incorporates time-varying natural mortality and now fits the survey MMB very similarly to GMACS.)

Some of the differences between GMACS and the status quo model include estimated linear growth models in GMACS, differences in the way fishing mortality is modeled, freely estimated availability curves for males and females in GMACS (instead of just males as in the status quo), an additional estimated parameter in GMACS so that immature male and female natural mortality are differentiated, and an estimated time series for both recruitment deviations and sex ratio (rather than just two time series of deviations as in the status quo). GMACS excludes some of the extra weight on data sources present in the status quo model (e.g. additional weight on the small size classes in the size composition data for mature males) and some GMACS likelihoods have different formulations than in the status quo (e.g. catch biomasses and growth increment data are fit with log-normal likelihoods instead of normal likelihoods).

These differences in model formulation and assumptions resulted in differences in fit, estimated population processes, and quantities used in management for the models presented here. For example, GMACS estimated a higher natural mortality for mature males (0.36 vs 0.27) which then resulted in differences in management quantities (e.g. GMACS' $B_{35\%}$ was 135 kt vs. the status quo 153 kt). Furthermore, differences in fits to the size composition data and estimated recruitments between GMACS and the status quo model would have resulted in a closure of the directed fishery in 2021 had GMACS been used in the presented format.

The salient issues raised to this point related to the adoption of GMACS for snow crab have been addressed. GMACS provides superior convergence characteristics and improves transparency and reproducibility for the snow crab assessment. Adopting GMACS for snow crab would also benefit other Bering Sea crab stocks because any improvements made to the snow crab assessment model and documentation could be used for other stocks. Based on the reasons outlined in this document, I conclude that GMACS is a superior assessment platform compared to the status quo model and recommend that the CPT and SSC adopt GMACS for snow crab in the eastern Bering Sea.

In spite of this recommendation, there are several issues facing snow crab assessment and management that transitioning to GMACS do not address. These issues include identifying an appropriate currency of management, addressing how the Bering Sea Fisheries Research Foundations' (BSFRF) experimental trawl selectivity data and the yearly maturity data from the National Marine Fisheries Service (NMFS) survey are incorporated into the assessment, identifying appropriate priors for and time-variation in natural mortality, establishing how to define reference points in a changing environment, and addressing potentially shifting spatial distributions. Transitioning to GMACS will not solve any of these problems, but it will provide a shared platform to explore these questions and allow time to focus on developing solutions rather than maintaining and modifying two code bases for snow crab.

GMACS abilities and expectations

Attempting to move snow crab to the Generalized Model for Assessing Crustacean Stocks (GMACS) has been one of the central assessment activities undertaken in the last three years. A move to GMACS will support the Crab Plan Team (CPT) goals of transparency and reproducibility of assessments for eastern Bering Sea (EBS) crab assessments by using the open-source code developed by a team of National Oceanic and Atmospheric Administration (NOAA) and University of Washington researchers. Using the same code base for EBS crab stocks will allow the CPT to immediately understand the underlying dynamics of a model without having to sift through the numerous bespoke assessment models currently used.

A key driver of the need to move to GMACS for snow crab is model stability. Improved model stability does not mean that estimates of natural mortality, catchability, or other population processes will not change from year to year. A 'stable' model also does not mean that biomass and fishing mortality reference points will not changes from year to year. Model stability in this context means that with a given data set, with a given set of assumptions, the model will converge to an answer and that this answer will be relatively insensitive to the starting values of parameters. Improved stability has already been seen with linear growth assumptions and the addition of the 2021 data that include a large drop in survey biomass. GMACS was able to fit models to the 2021 data with linear growth increment assumptions with no clear indicators of a lack of convergence when the status quo model was not able to do so.

Several on-going challenges in the snow crab stock assessment will not be solved by moving to GMACS. For example, persistent retrospective patterns cannot be solved by a move to GMACS. Retrospective patterns are a function of the data and model assumptions and are present in both the status quo and GMACS models when the same data and assumptions are made. Moving to GMACS will not allow us to identify the appropriate processes in the model to allow to vary over time (e.g. natural mortality or catchability); data will need to be collected and focused analyses performed. GMACS does not solve the problem of defining reference points in a changing environment or identifying an appropriate currency of management (e.g. morphometrically mature males vs. functionally mature males vs. a metric that includes female spawning biomass and considers sperm limitation). GMACS will, however, make it easier for the CPT to explore these questions with a common understanding of the code used to perform the analyses.

Summary of previous transition efforts

CPT accepts GMACS (May/September 2020)

GMACS was first adopted for use in the assessment of a Bering Sea crab stock for Saint Matthew's blue king crab by the CPT in 2018 and GMACS models have been implemented or adopted for four other stocks since then. These were king crab stocks that do not perform a terminal molt to maturity beyond which no further growth occurs like snow crab. The code for GMACS was modified to allow for this life history trait in 2020, in addition to several other modifications to accommodate the transition of the snow crab assessment to GMACS. The bar for adoption of GMACS in other assessments has historically been the reproduction of the numbers at size matrices, given the same input parameters. Making this comparison for snow crab was an involved process because some processes are not modeled the same way in the status quo and GMACS models, necessitating a 'translation' of parameters or modification of the one of the code bases to make the comparison possible.

One of the key differences was related to how fishing mortality was treated. The status quo model removes assumed discard mortality directly from the catches before estimating selectivity and fishing mortality. GMACS inputs the total catches and specifies a discard mortality rate which is incorporated into the vulnerability of crab to a given fishing gear (see May 2020 CPT presentation for code and details). After allowing for these differences, the numbers at size matrix for males was almost perfectly reproduced (Figure 1). The numbers at size matrix for females was reproduced less perfectly, but still close (Figure 2). The differences in numbers at size matrices followed from differences in the way discard fishing mortality was calculated for males and females. Changing this difference would require modification of the status quo or GMACS code for which the benefits were not directly obvious. Ultimately, the CPT recommended GMACS for use as the model to assess snow crab in September 2020 based on better model fits, improved structure and assumptions, improved model stability, and the utility of having a common code base. See an in depth write up of this exercise at https://www.npfmc.org/fishery-management-plan-team/bsai-crab-plan-team/ under the "Past Crab Plan Team Meetings" section in the eAgenda for the May meeting in 2020.

SSC rejects GMACS (October 2020)

The SSC rejected GMACS in September 2020, citing concerns about changes in stock size, estimates of recruitment and fishing mortality, and retrospective patterns. Each of these concerns were addressed in the May 2021 meeting and are summarized below.

From the SSC report: "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 projected biomass for 2020/21 from the author preferred model was 276.7 kt; the estimated biomass from 2019/20 was 167.3 kt (Figure 3). This was a 65% increase, not '4x'. However, the OFL did increase more than 65%, increasing from 54.9 kt to 184.9 kt (a 237% increase). This difference in OFL was a combined result of the largest pseudocohort (i.e. a group of crab of the same size, but not necessarily the same age) ever observed entering the population after a period in which MMB was the lowest on record.

From the SSC report: "The GMACS model 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."

The status quo model appeared to ignore the 2018 data point for survey MMB and fit only the 2019 data point in the 2020 assessment. GMAC split the difference between the two data points. The reason GMACS could split the difference was that it estimated a larger recruitment in 2015 than the status quo model. This recruitment was supported by several years of data in which the pseudocohort developed as one would expect given NMFS survey selectivity (Figure 4). Comparing the relative sizes of the scaled estimated and raw recruitment numbers shows that the survey numbers indicate that the 2015 pseudocohort was roughly twice the size of the previous largest pseudocohort (1991) and this relative magnitude of the recruitments was captured best by GMACS (Figure 5; these figures are made with output from assessment with the data updated to 2021 and time-varying natural mortality, which produced larger estimates of recruitment from the status quo model). The large estimates of the pseudocohort was not driven by large observations at a few stations–there were high densities of small crab over a large portion of the northern eastern Bering Sea shelf (Figure 6). Simply put, the survey data strongly indicate that there was a strong recruitment event that occurred around 2010 and began being seen by the survey gear in 2015. The only way to fit the survey data was to estimate a large recruitment and only GMACS was able to do that in 2020.

Although the available evidence strongly suggest that the 2015 pseudocohort was the largest that has ever been observed in the EBS bottom trawl survey, the strong declines in the survey index in 2019 and 2021 also suggest a that mortality events occurred. This issue will be discussed in another document.

From the SSC report: "…there is still a very large positive retrospective pattern which is puzzling…"

Retrospective patterns exist in both the status quo model and in GMACS (see the 2019 SAFE in which the status quo model had a Mohn's rho of 0.48-0.54). Retrospective patterns can result from unmodelled variation in population processes like natural mortality or from incomplete data sets (e.g. missing catch data). So, given the same data and population dynamics model, two different models (like the status quo and GMACS) would be expected to produce similar retrospective patterns. They would not, however, be expected to produce identical retrospective patterns. Difference in likelihood formats and weighting of data sets (as exist between the status quo model and GMACS, discussed more below) would influence the relative sizes of retrospective patterns.

From the SSC report: "Another feature of the author-preferred GMACS model is extremely high fully-selected fishing mortality in some years…"

This is actually a ‘feature’ of the status quo model. GMACS estimates more reasonable (though still high) fishing mortalities in the early period of the assessment (see a comparison below).

Each of the problems identified by the SSC were actually important ‘features’ of GMACS that addressed failings of the status quo model (e.g. the estimated recruitment), misidentified problems (e.g. high fishing mortality for GMACS), or were shared problems of GMACS and the status quo (e.g. retrospective patterns).

A problem arises (September 2021)

After addressing the SSC comments in May 2021, GMACS runs were planned for September 2021, but the 2021 survey data showed a large reduction in survey numbers. The status quo model was unable to fit to these data and mortality events were introduced into the status quo model to allow the model to fit the data. GMACS did not have the functionality to allow time-varying natural mortality for animals with a terminally molting life history at that time, so no GMACS models were brought forward for consideration in 2021. Time-varying natural mortality was implemented in GMACS for terminally molting life histories for the January 2022 CPT meeting. The models presented below are a result of these efforts and are the candidate models for consideration in September.

Differences between GMACS and the status quo model

The population dynamics of GMACS and the status quo model are very similar, except for how fishing mortality is modeled (described above). This was made clear by the reproduction of the status quo numbers at size matrix by GMACS with identical input parameters and modification of fishing mortality parameters. The largest remaining differences between GMACS and the status quo exist in the likelihood formulation and the weighting of data components and are described below.

Likelihoods and weightings

Models are fit to data by minimizing the objective function value which is a sum of negative log likelihoods. Likelihoods compare the observed data to model predictions given a vector of estimated parameters. The estimation process finds vectors of estimated parameters that makes the difference between the observations and the predictions from the model as small as possible. Even when the same data are being fit using predictions from models that have the same underlying population dynamics, differences can arise in the model output when different assumptions are made about the form of the likelihoods or the weights assigned to different data sources. Many of the likelihoods are shared between GMACS and the status quo model (Table 1). For example, multinomial likelihoods are used for all of the size composition data in both GMACS and the status quo model. However, the status quo model adds additional components to the objective function that place extra weight on specific years or sizes in the size composition data. This is often done in response to an unexpected or undesirable lack of fit. An example of this can be seen in the large sizes for the first three years in the retained catch size composition data which are poorly fit by the GMACS models. The status quo model does not have this problem, but it also has extra weighting on these data (Table 1).

In addition to supplementary likelihoods that only exist in the status quo model, the form of some of the shared likelihoods are different (Table 1). The priors on natural mortality are a good example of this. In the status quo model, a mean value of natural mortality is input with a variance. A multiplier on this input mean value of natural mortality is then estimated using a normal likelihood and the input variance. The initial value of the multiplier is 1 and the variance (and weighting of other data sources) determines how much from 1 the multiplier can differ. In contrast, GMACS directly estimates natural mortality using a normal prior and does not employ a multiplier. So, in spite of the same input parameters, the influence of the prior on natural mortality on model outcomes can be different between the status quo and GMACS models because the variance means different things as a result of the difference in formulation.

Finally, even when likelihoods are identical, differences in weighting of the likelihoods can affect the estimation process and the resulting management advice (Table 1). GMACS uses coefficients of variation or standard deviations for all lognormal and normal likelihood components, but the status quo model mixes coefficients of variation, standard deviations, and 'weights'. Weights are user-input numbers that multiply the likelihood value. Larger weights result in a likelihood component being fit more precisely. Weights can be translated to standard deviations by taking the square root of the inverse of twice the weight for normal likelihoods. An example of this can be seen in the translated weights for the retained catch time series. The status quo model assigned weights of 1000 to this likelihood which translates to a standard deviation of 0.02 in the normal likelihoods used. The GMACS model used an input coefficient of variation equal to 0.04 used in the lognormal likelihoods. This slight difference in both the weights and the likelihood formulation contributes to the differences in the fits to the retained catch time series seen between the models.

The form of a likelihood used in a model is one of the many choices that is made in development. Oftentimes, quantities that cannot be less than zero (e.g. catch or survey biomass) are modeled using lognormal likelihoods as GMACS does. Although this is an often-seen practice, it does not necessarily mean that using normal likelihoods for the catch is 'wrong'–it is just an alternative assumption that can have ramifications in how the data are fit and ultimately the output of the model. Further, some of the weights and coefficients of variation that are assumed in the status quo and GMACS models are choices for which we currently have little data. Differences in the input weightings for the catch biomass time series resulted in differences in fit. The GMACS weightings were chosen because they seemed more reasonable than the status quo weights because retained catch, total catch, female discards, and bycatch should be known with decreasing certainty. However, this was not the case in the status quo model (Table 1).

Ultimately, decisions around likelihoods to be included in the model, formulation of those likelihoods, and the relative weighting of those likelihoods should be a topic of discussion at CPT meetings. Moving assessments to GMACS will facilitate a common vocabulary and model understanding for that discussion.

Comparison of the most recent status quo and GMACS models

Three models are presented for comparison here: the status quo model (21.sq), a similarly (though not identically) configured GMACS model (21.g), a version of 21.g in which natural mortality is fixed at the value estimated in 21.sq (21.g.m), and a version of 21.g.m in which growth parameters are fixed at the value estimated in 21.sq (21.g.mg). Each of these models are fit to the data presented at the September 2021 Crab Plan Team meeting and incorporate additional mortality events in 2018 and 2019.

In addition to the differences in likelihoods and weightings described above (Table 1), there are several differences between the parameters that are estimated and the assumed form of some populations processes in model 21.sq and 21.g. These differences include:

- Linear growth models for males and females are estimated in GMACS, but the parameters associated with growth are estimated outside of the status quo model and specified because the model will not converge linear growth models
- Availability curves in the status quo were freely estimated vectors of parameters with smoothing components for males, but logistic curves for females. Empirical availability curves were adopted last year. In GMACS, both sexes have freely estimated vectors of parameters estimated for the availability of the population to the BSFRF experiments. A better method for incorporating these data will be implemented after the adoption of GMACS.
- The status quo model estimates 3 natural mortality parameters for mature males, mature females and immature crab of both sexes. GMACS estimates 4 natural mortality parameters for mature males, mature females, immature males, and immature females.
- The status quo model estimates an average recruitment and yearly deviations for both sexes. GMACS estimates a single average recruitment and yearly deviations, then another time series of sex ratios to divide the recruitment between the sexes.

Model convergence

Maximum gradient components were 0.18, 0.002, 0.0004, and 0.0006 for models 21.sq, 21.g, 21.g.m, and 21.g.mg, respectively. In a basic sense, gradient components represent how close a parameter is to the value that minimizes the objective function. When the gradient is very small, this means that changing the parameter incrementally does not improve the objective function. Generally a cutoff is set sufficiently close to 0 to demonstrate a lack of non-convergence and subsequent acceptance of a model.

The maximum gradient component for 21.sq was associated with the recruitment deviation in the year 1991 (value of 0.18). Gradients for 9 other parameters in the status quo model exceeded 0.01, including other recruitment deviations, fishing mortality deviations, and the multiplier for immature natural mortality. While 0.01 is 'close' to zero, it is sufficiently large to potentially warrant further exploration with respect to model convergence. The status quo model was accepted in 2021 in spite of the potential issues with convergence (e.g. maximum gradient component of 0.18) because there was no clear alternative. A similarly configured GMACS model (21.g) did not have these potential convergence issues.

A comparison of likelihood component contributions to the objective function between GMACS and the status quo model is not appropriate because of differences in the likelihood forms and weightings, so tables providing these metrics are not provided. That said, most of the differences in the fits observed between GMACS are large enough that visual inspection is sufficient to see which model fits the data better.

Fits to data

Survey, growth, and catch data

GMACS fits to the survey mature male biomass were visually superior to the status quo model during the period from 1989 to 1995 and fairly similar elsewhere in the the time series (Figure 7). GMACS fits the female spawning biomass much better than the status quo model (Figure 7). All models were able to fit the recent increase and decline from 2018-2021 by estimating mortality events in 2018 and 2019 (see below).

Growth parameters have been fixed to values estimated outside of the model for the status quo for the past few assessments because models estimating linear growth increment models would not converge (Figure 8). GMACS, however, is capable of estimating the parameters associated with the linear growth model, but the estimates are somewhat different than those resulting from fitting the a model to the increment data outside of the assessment. This is likely related to both the action of fitting the growth data simultaneously with many other data sets and the use of a lognormal likelihood in GMACS for fitting the linear model. The regression used to specify the parameters for the status quo model used a normal likelihood.

GMACS fit some years of retained catch data more poorly than the status quo model and this is likely related to the differences in the relative weights of data sets in GMACS and the status quo. Discards of both sexes and aggregated bycatch were better fit by GMACS (Figure 9).

Size composition data

Retained catch size composition data were visually well fit by all models in most years (Figure 10); total catch size composition data were similarly well fit (Figure 11). The most obvious difference among models occurred in the years in which mortality events were implemented (2018 and 2019) and the initial years (1982-1984). GMACS estimated more large males than observed in the fishery size composition data, but the status quo did not. This is likely related to the extra weight placed on the initial year of size composition data in the status quo model that is not present in GMACS. More variability was seen among the fits to the bycatch size composition data, but the general shapes of the predicted size compositions were largely similar within years (Figure 12).

Fits to size composition data for the BSFRF survey selectivity experiments produced some notable runs of positive and negative residuals, but GMACS fit each of these data set better than the status quo (Figure 13).

Male size composition data for the NMFS survey were generally well fit and fits were visually similar for most models (Figure 14, Figure 15, Figure 16 & Figure 17). Larger differences in the fits to the female size composition data occurred between GMACS and the status quo. GMACS fit the data much better for the immature females and was able to capture the peaks of the mature female size data better than the status quo model.

Estimated population processes and derived quantities

Estimated population processes and derived quantities varied among models. Trajectories of estimated MMB from GMACS models had a more pronounced downward trend (Figure 18). This is likely related to both the better fits to survey MMB by GMACS and the relative differences in estimated survey catchability in 1982-1988 and 1989-present between models (Figure 19). Male catchability estimated in GMACS was lower than the status quo for both eras, and the decline in 1982-1988 was larger than the decline in the second period. This implies that, in relative terms, for the same observation of survey MMB, GMACS would estimate a larger MMB in the earlier period than the status quo model. The GMACS estimates of catchability were more similar to the status quo when natural mortality and growth parameters in GMACS were fixed to those estimated in the status quo model, but still smaller. Estimated female catchability was much lower from GMACS models, which is more inline with the implied catchability from the BSFRF selectivity experiments (~0.45).

The status quo availability curves were fixed to the empirically derived availability curves (Figure 20; see September 2021 snow crab assessment document for details). GMACS estimated availability curves with free vectors of parameters. Neither of these methods satisfactorily addresses the question of the appropriate shape and scale of the selectivity curve for the NMFS summer survey, but this issue will be revisited after adoption of GMACS.

Slight differences in the estimated probability of having undergone terminal molt existed among models. GMACS models estimated higher probabilities of having undergone terminal molt at a given size for females than the status quo model. However, the biggest departures from the status quo estimates of the probability of male crab having undergone terminal molt at size were negative and occurred in animals of carapace width ~90-100 mm (Figure 21).

Estimated trends in fully-selected fishing mortality in the directed fishery differed between GMACS and the status quo model (Figure 22). The status quo model estimated very high fishing mortality (>4) in the early 1990s, but GMACS estimates were <2. An estimated fishing mortality of 4 and 2 are equivalent to survival rates of of 1.8% and 13.5%, respectively. All models estimated directed fishing mortality near 3 in 2019 and 2020 (~5% survival rate). Estimated bycatch mortality and female discard mortality were on a similar scale for the status quo and GMACS models, but somewhat more variable for GMACS. All estimated selectivities differed somewhat, likely as a result of the differences in the ways in which fishing mortality is modeled between GMACS and the status quo.

Patterns in recruitment by sex varied among models, particularly with respect to the size of the recent large pseudocohort (Figure 23). Generally, the models estimated a period of higher recruitment for males during the 1980s and early 1990s. Following that, a period of low recruitment persisted from the early 1990s to 2013, then a large pseudocohort recruited to the survey gear in 2015. The GMACS model estimates for this male recruitment was more than twice the size of the previous largest recruitment in 1985.

GMACS estimates of natural mortality were 0.36, 0.34, 0.35, and 0.38 for mature males, mature females, immature males, and immature females, respectively (Figure 24). Status quo estimates of natural mortality were 0.27, 0.28, 0.27, and 0.27 for mature males, mature females, immature males, and immature females, respectively. Additional mortalities estimated in 2018 and 2019 were highest for immature females (up to ~4 for the status quo model), followed by mature males (status quo estimates were slightly lower than GMACS estimates, both ~2). Hamel (2015) and Then et al. (2014) associate a natural mortality of 0.27 and 0.36 with a longevity of 20 years and 15 years, respectively. Maximum age for snow crab is poorly known in the Bering Sea because relatively few studies have been undertaken to determine it. In the best of these studies, Nevissi, et al. (1995) used radiometric techniques to estimate shell age from last molt. 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). Coupled with an assumed time to terminal molt of 7-9 years, that provides a range of maximum ages from ~13-17 years. Given the small sample size, this range is likely lower than the true maximum age.

Reference points and management advice

In spite of sometimes large differences in fits to data sources and estimated population processes, the resulting quantities used in management were fairly similar between the status quo model and GMACS model (Table 2). Estimates of the terminal year of MMB ranged from 22.6-26.7 kt. Somewhat higher estimates of natural mortality for mature males from GMACS than the status quo estimate resulted in a lower $B_{35\%}$ from GMACS than the status quo model (135 kt vs 153 kt). This is a result of the interaction of a scaling up of recruitment (if natural mortality increases, recruitment also has to increase to fit the data) and fewer animals surviving to maturity because of higher natural mortality. The higher natural mortality also resulted in a higher $F_{35\%}$ than the status quo (2.31 vs 1.43) because, all other things equal, more of the mature biomass concentrates in smaller size classes under higher natural mortality. Higher concentrations of mature biomass in smaller size classes allows for higher exploitation on large animals while still maintaining 35% of unfished mature biomass in the population. Fixing natural mortality in GMACS to the estimates from the status quo model (21.g.m) resulted in more similar reference points ($B_{35\%}$: 155.94 kt vs. 153.42 kt and $F_{35\%}$: 1.51 and 1.43). Fixing growth (21.g.mg) changed the reference point very little from model 21.g.m.

All of the estimated overfishing levels (OFL) from GMACS were 0.1 and the F_{OFL}s were 0.00, meaning there would have been no directed fishery had the GMACS model been used in 2021. The reason this occurs stems from differences in the fits to the size composition data between GMACS and the status quo. The status quo model estimated more immature crab in the size classes that would molt to >101 mm carapace width in the projected year (Figure 25). Since the OFL is based on projected MMB, these incoming crab maintained the population above the size at which directed fishing is prohibited, whereas GMACS did not. GMACS fits the survey size composition data for the immature males in the terminal year markedly better than the status quo model did (Figure 14).

Projections

A final compelling reason for adopting GMACS is the existence of code to perform projections under different fishing mortality, recruitment, and/or natural mortality scenarios. The status quo code does not currently have this functionality. Projections are particularly important for overfished stocks that require a rebuilding plan, like snow crab. This functionality is demonstrated here under three different recruitment scenarios corresponding to a 'high', 'medium', and 'low' recruitment. In the high recruitment scenario, future recruitments are drawn from the estimated recruitment from 1982-2019 (the currently used time period for reference points). The medium recruitment scenario corresponds to draws from the estimated recruitment for years 1994-2019, which roughly corresponds to the period of time since the collapse of recruitment that precipitated the overfished declaration in 1999. The low recruitment scenario corresponds to the same period, but excludes the recent period (2015-present) during which the largest recruitment ever observed occurred.

Two scenarios were also explored in which the natural mortality applied during the projection period corresponded either to the average natural mortality (i.e. that applied in the GMACS model from 1982-2017 and 2020) or to the natural mortality in 2018, during which an additional mortality was estimated. An additional mortality was also estimated in 2019, but the difference between the projections under 2018 vs. 2019 natural mortality were minimal. Finally, three directed fishing mortality scenarios were implemented: zero directed fishing, half of $F_{35\%}$, and $F_{35\%}$. All scenarios had bycatch mortality equal to the average of the last eight years applied. Each scenario was projected to the year 2040 and 100 replicates were performed.

The time to rebuilding under no directed fishing (t_{min}) is one of the key pieces of information in developing a rebuilding plan. The t_{min} for these scenarios ranged from ~7 years to infinity (Figure 26). If the mortality events estimated in 2018 and 2019 have not concluded, the median projected stock will never rebuild to $B_{35\%}$. However, the median projected stock under all recruitment scenarios with natural mortality that has returned to pre-2018 levels rebuilt in less than 10 years.

Recommendations

Adopt GMACS

GMACS provides superior convergence characteristics and improves transparency and reproducibility for the snow crab assessment. The changes in the number parameters and the functional forms of estimated processes (e.g. growth, natural mortality, availability) are conceptual improvements over the status quo model. The differences in the number, form, and weighting of likelihoods between GMACS (e.g. lognormal vs. normal, weights vs. coefficients of variation, excluding extra weightings) are improvements at best and lateral moves at worst over the status quo model. The fits to several data sources are markedly improved in GMACS. In addition to improving the snow crab assessment, adopting GMACS for snow crab would benefit other Bering Sea crab stocks because any improvements made to the snow crab assessment model and documentation could be used for other stocks. In light of all of these points, I recommend that the CPT and SSC adopt GMACS for snow crab in the eastern Bering Sea.

Many issues remain to be addressed beyond the transition to GMACS. Several population processes appear to vary over time (i.e. the probability of having undergone terminal molt, natural mortality, survey catchability), but these processes are time-invariant in the assessment. Data for the probability of having undergone terminal molt can be directly input into the assessment, but understanding the ability of a model to estimate time-varying natural mortality and catchability with the available data is an unanswered question. Revisiting the input standard deviations on the priors for natural mortality is needed before considering further time variation. With the introduction of time-variation in population processes, defining reference points in a changing environment becomes challenging. The complexity of time-variation in population processes may warrant supplementary assessments that are much simpler and more forward-looking than our current assessments (e.g. 'Tier 3.5' presented in May 2021).

Under small changes in modeling assumptions (e.g. the functional form of survey selectivity, data weights, maturity ogives), $F_{35\%}$ can increase dramatically, effectively allowing all large males to be harvested in a given year because of the large reserve of small mature males sheltered from harvest by the industry preferred size. Complete removal of large males does not seem like an appropriate management response for a longer lived organism like snow crab. Conversations need to continue about an appropriate currency of management (e.g. morphometrically mature biomass vs. functionally mature biomass vs. a metric that includes female biomass, a measure of sperm limitation, and spatial overlap).

A final note on transitions between assessments: if GMACS is accepted as the new model for snow crab, this does not mean the assessment will not continue to evolve as new information becomes available. Many unanswered questions still exist around snow crab biology (see above for a partial list) and science is an iterative process. Moving to GMACS will make our process of iteration more transparent and easier to reproduce for other stocks.

Table 1: Status quo likelihood components listed with a description of their form, an indication of whether or not they are present in GMACS (blanks indicate they are present), whether or not the form of the likelihood is the same in GMACS, the values of the status quo weightings on the likelihood component (‘cv’ is entered if it the input is a coefficient of variation), the ‘translated’ coefficients of variation from the input weights, and the weights used in GMACS.

Likelihood	Description	in.GMACS.	Same.form.	SQ.weight	Translated.CV	GMACS.wt
Smoothness for recruitment	norm2(devs)		No	1	0.71	1
Constraint on intial numbers of small old shell males	square(exp(numbers))	No		0.000001	707.1	
Retained fishery length comp	Multinomial			100	NA	100
Total fishery length comp	Multinomial			100	NA	100
Female length comp	Multinomial			100	NA	100
Survey length comp	fit to by sex and maturity state			100	NA	100
Trawl length comp	Multinomial			100	NA	100
2009 BSFRF length comp	Multinomial			100	NA	100
2009 NMFS length comp	Multinomial			100	NA	100
Prior on natural mortality	square(multiplier -1)/input_variance		No	0.0154	NA	0.0154
Prior and smoothness on maturity	norm2(second_diff(prob_molt))		No	50	0.1	60
Growth data (male)	sum of squares, no CV		No	1	0.71	0.03
Growth data (female)	sum of squares, no CV		No	1	0.71	0.03
2009 BSFRF mature biomass	log normal, no constants			cv	NA	cv
2009 NMFS mature biomass	log normal, no constants			cv	NA	cv
Fishery CPUE	normal with input ‘cv’	No		5	0.32	
Retained catch	normal with input weight, no constants		No	1000	0.02	0.04

Likelihood	Description	in.GMACS.	Same.form.	SQ.weight	Translated.CV	GMACS.wt
Total catch	normal with input weight, no constants		No	20	0.16	0.07
Trawl catch	normal with input weight, no constants		No	1000	0.02	0.1
Female discards	normal with input weight, no constants		No	30000	0	0.07
Survey mature biomass	lognormal with input cv			cv	NA	cv
Penalties on directed F	norm2(F-1.15)	No		10	0.22	
Penalties on trawl F	norm2(F)	No		2	0.5	
Penalties on all but last year of directed F	norm2(F)	No		0.1	2.24	
2010 BSFRF mature biomass	lognormal with input cv			cv	NA	cv
2010 NMFS mature biomass	lognormal with input cv			cv	NA	cv
First year survey length comp additional weight	Multinomial, adds if molt_prob>0.99	No		100	NA	
2010 BSFRF length comp	Multinomial			100	NA	100
2010 NMFS length comp	Multinomial			100	NA	100
Smoothness of selectivity experiment	normal with input SD, if used	No		1	0.71	
Smoothness of female discards	norm2 on first differences of predicted discard	No		10	0.22	
Smoothness of first year length comp	norm2 on first differences of initial year			20	0.16	15

Table 2: 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
21.sq	26.74	153.42	1.43	0.37	7.5	0.27	106.14
21.g	25.53	135.32	2.31	0.00	0.1	0.36	189.52
21.g.m	23.37	155.94	1.51	0.00	0.1	0.27	119.89
21.g.mg	22.55	155.66	1.52	0.00	0.1	0.27	117.36

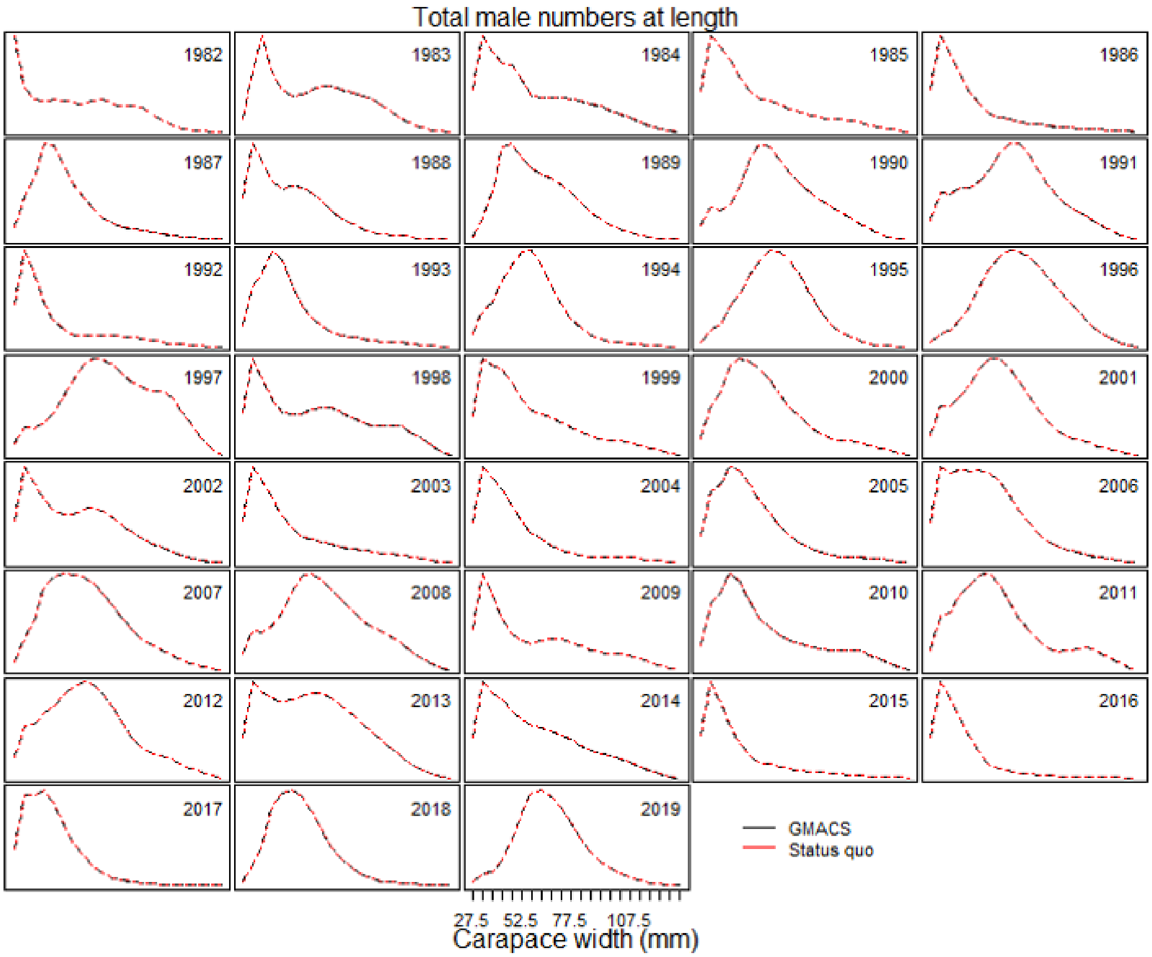


Figure 1: Comparison of the male numbers at size matrix from the status quo and GMACS with identical input parameters from the May 2020 snow crab document presented to the CPT. The GMACS model used to reproduce these numbers at size was modified based on different treatments of fishing mortality. See the full description in the May 2020 snow crab document.

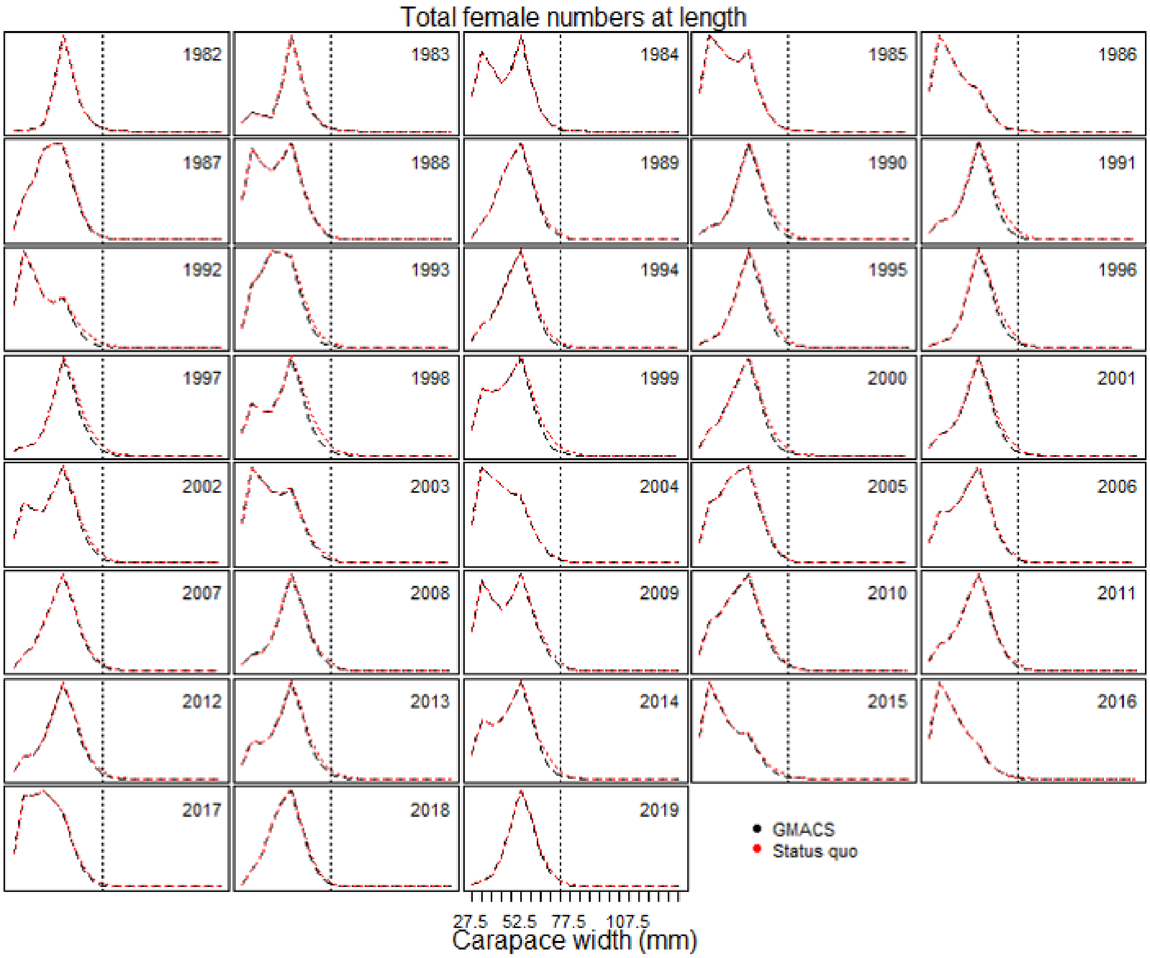
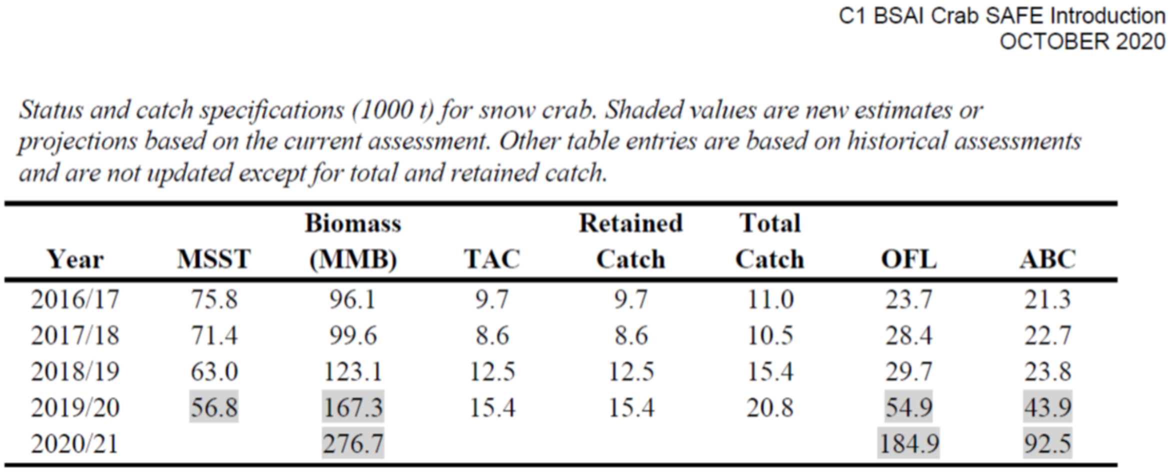


Figure 2: Comparison of the female numbers at size matrix from the status quo and GMACS with identical input parameters from the May 2020 snow crab document presented to the CPT.



C1 BSAI Crab SAFE Introduction
OCTOBER 2020

Status and catch specifications (1000 t) for snow crab. Shaded values are new estimates or projections based on the current assessment. Other table entries are based on historical assessments and are not updated except for total and retained catch.

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2016/17	75.8	96.1	9.7	9.7	11.0	23.7	21.3
2017/18	71.4	99.6	8.6	8.6	10.5	28.4	22.7
2018/19	63.0	123.1	12.5	12.5	15.4	29.7	23.8
2019/20	56.8	167.3	15.4	15.4	20.8	54.9	43.9
2020/21		276.7				184.9	92.5

Figure 3: A screen grab of the specifications from September 2020 BASED Crab SAFE Introduction in which GMACS was the author preferred model.

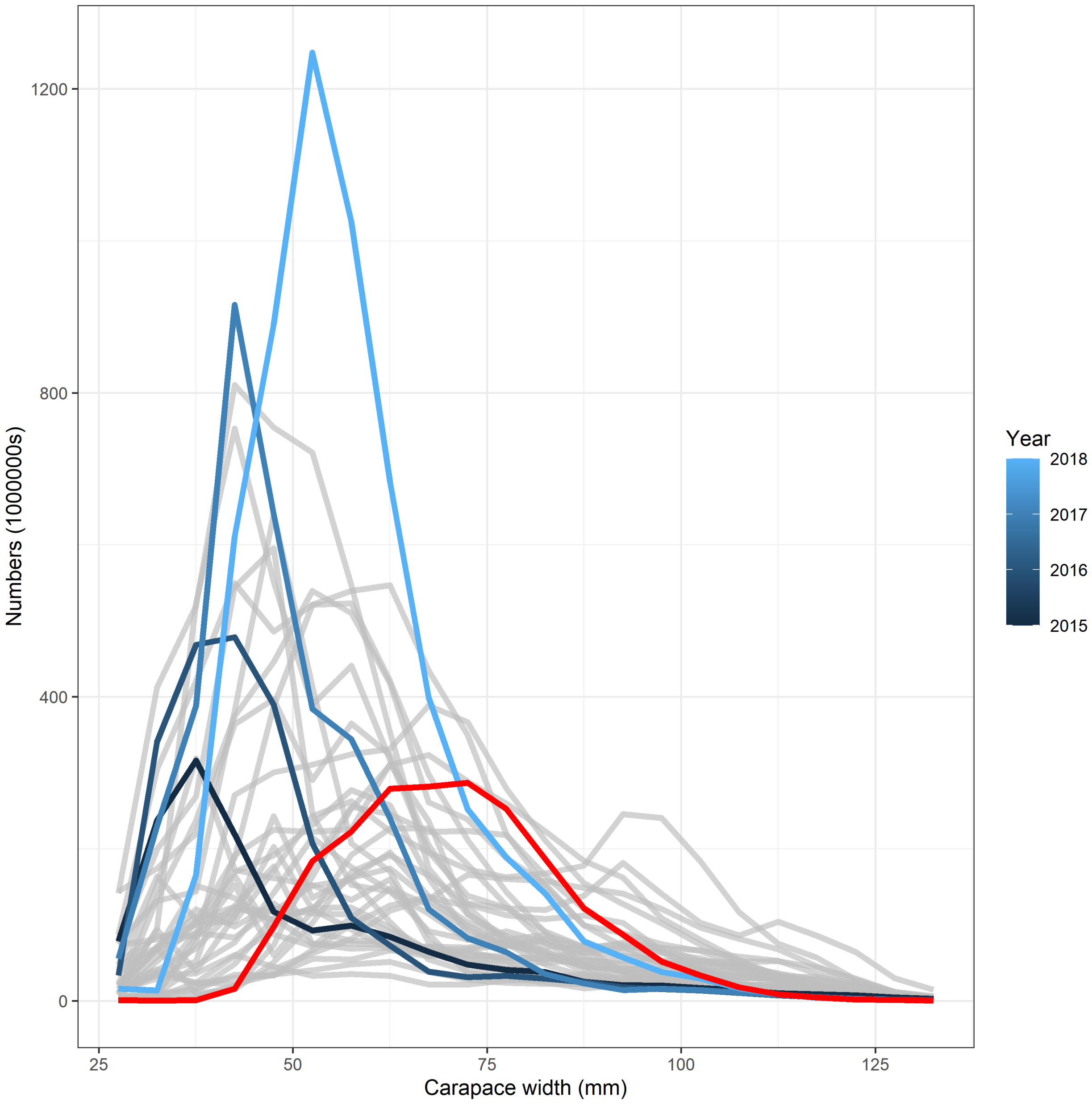


Figure 4: Progression of the numbers at size of the 2015 pseudocohort in the NMFS summer survey. Blue lines are the years 2015-2015, showing the large pseudocohort moving through the size classes. The red line is the 2019 data that demonstrate a much larger decline than would be otherwise expected by the assumed natural mortality.

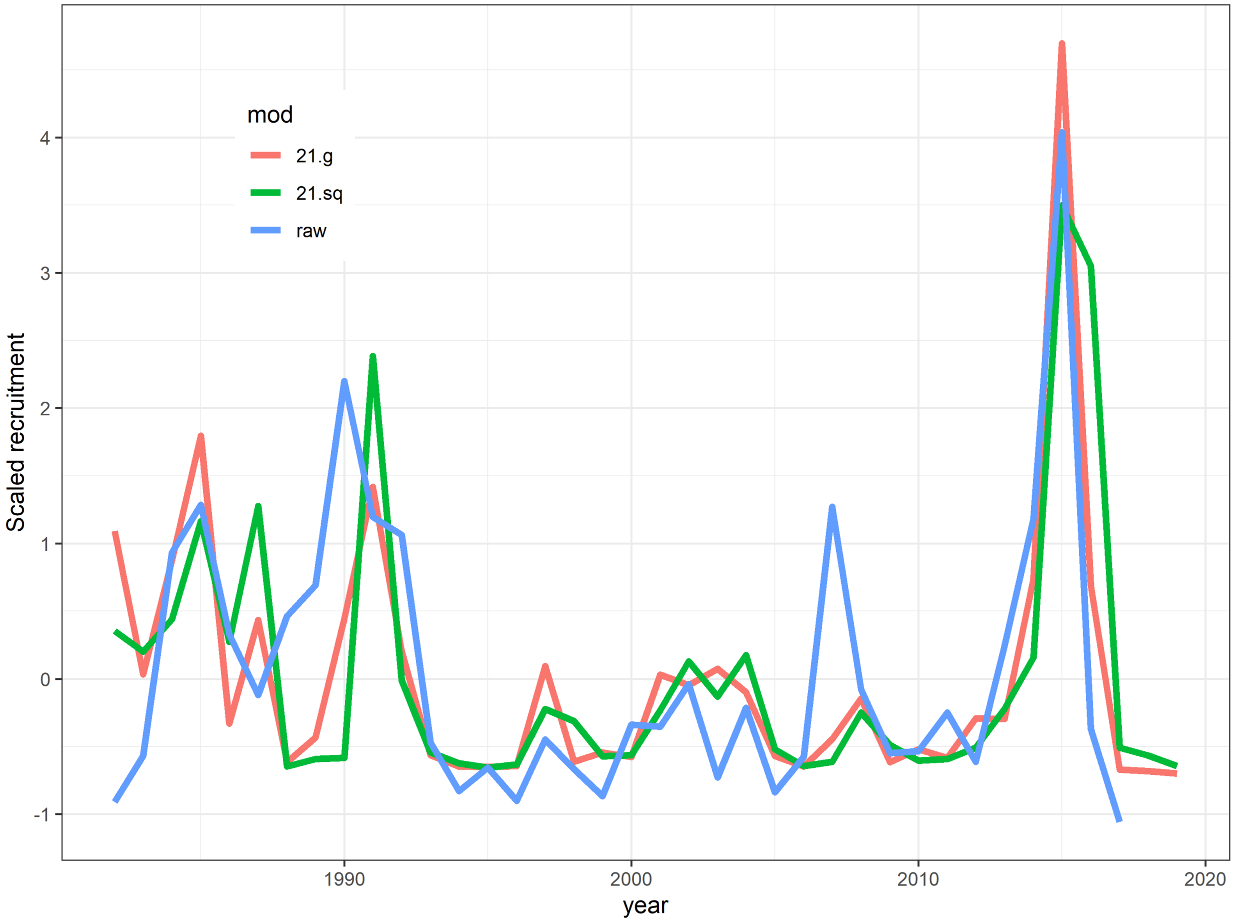


Figure 5: Estimated recruitments from the status quo model (21.sq) and GMACS (21.g) compared to the raw numbers of crab 45-55 mm carapace width in the NMFS summer survey (raw).

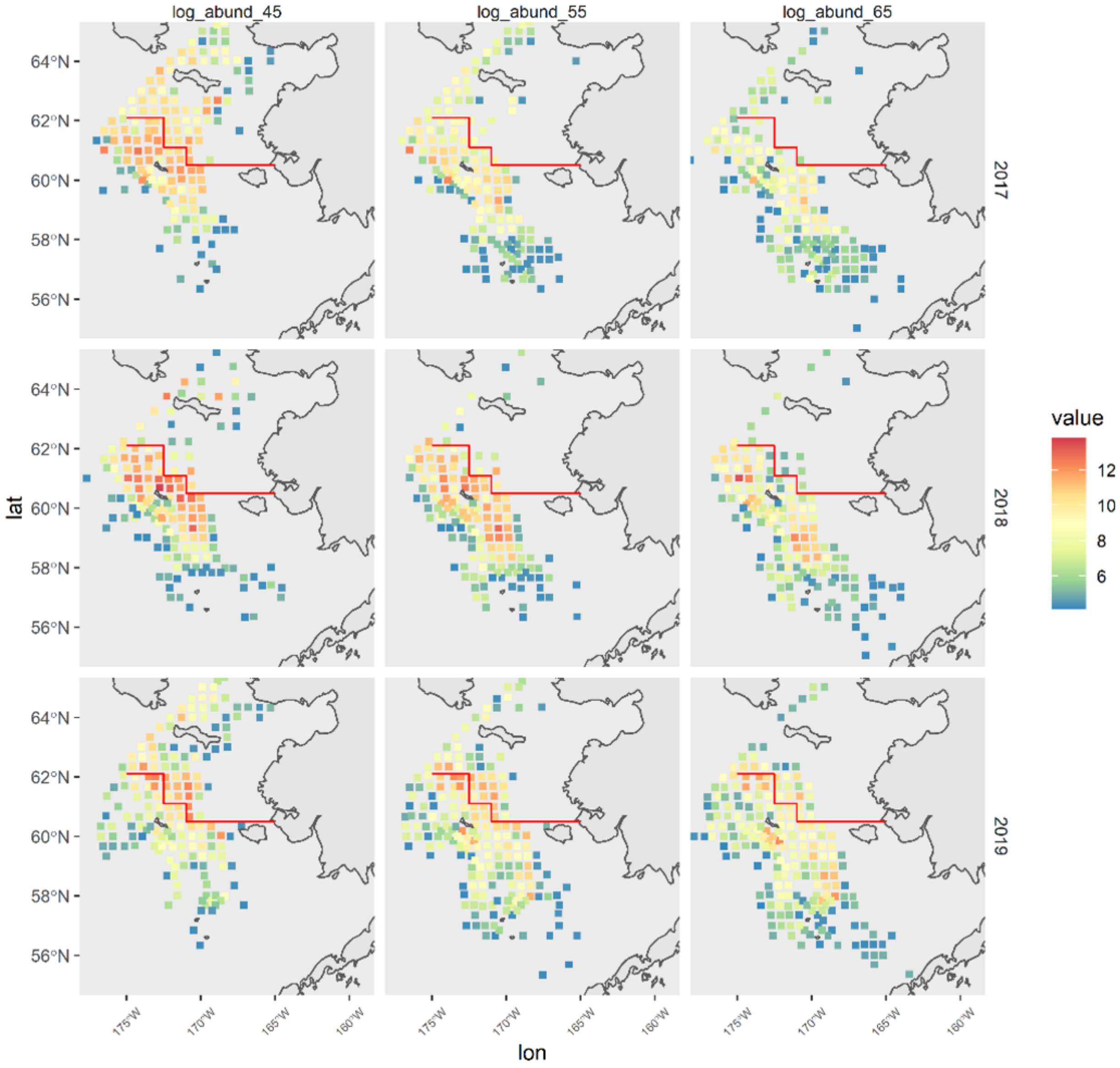


Figure 6: Maps of the densities of small crab for the years 2017, 2018, and 2019. Red line is the boundary between the northern Bering Sea survey station grid and the eastern Bering Sea survey grid. Size classes are from 40-49mm, 50-59 mm, and 60-69 mm carapace width by column.

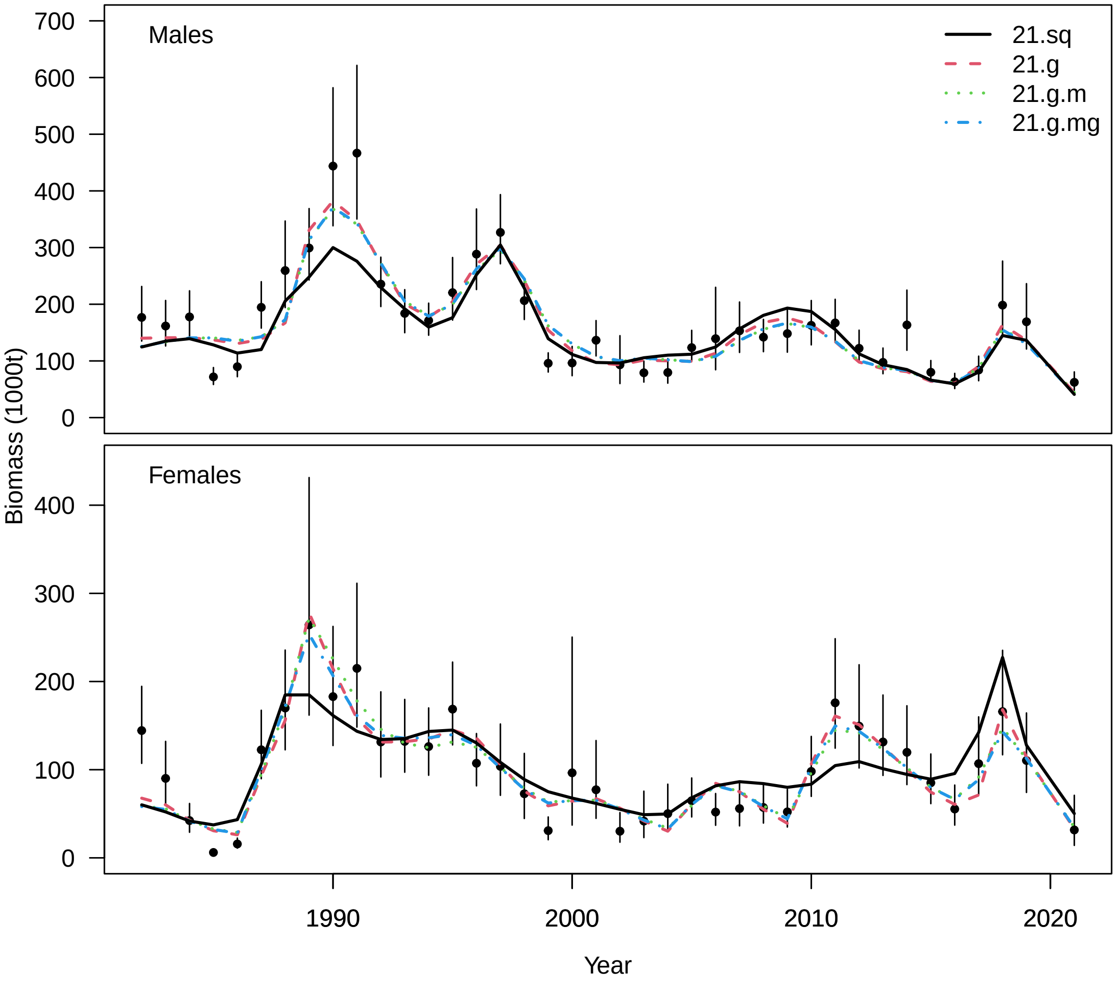


Figure 7: Model fits to the observed mature biomass at survey

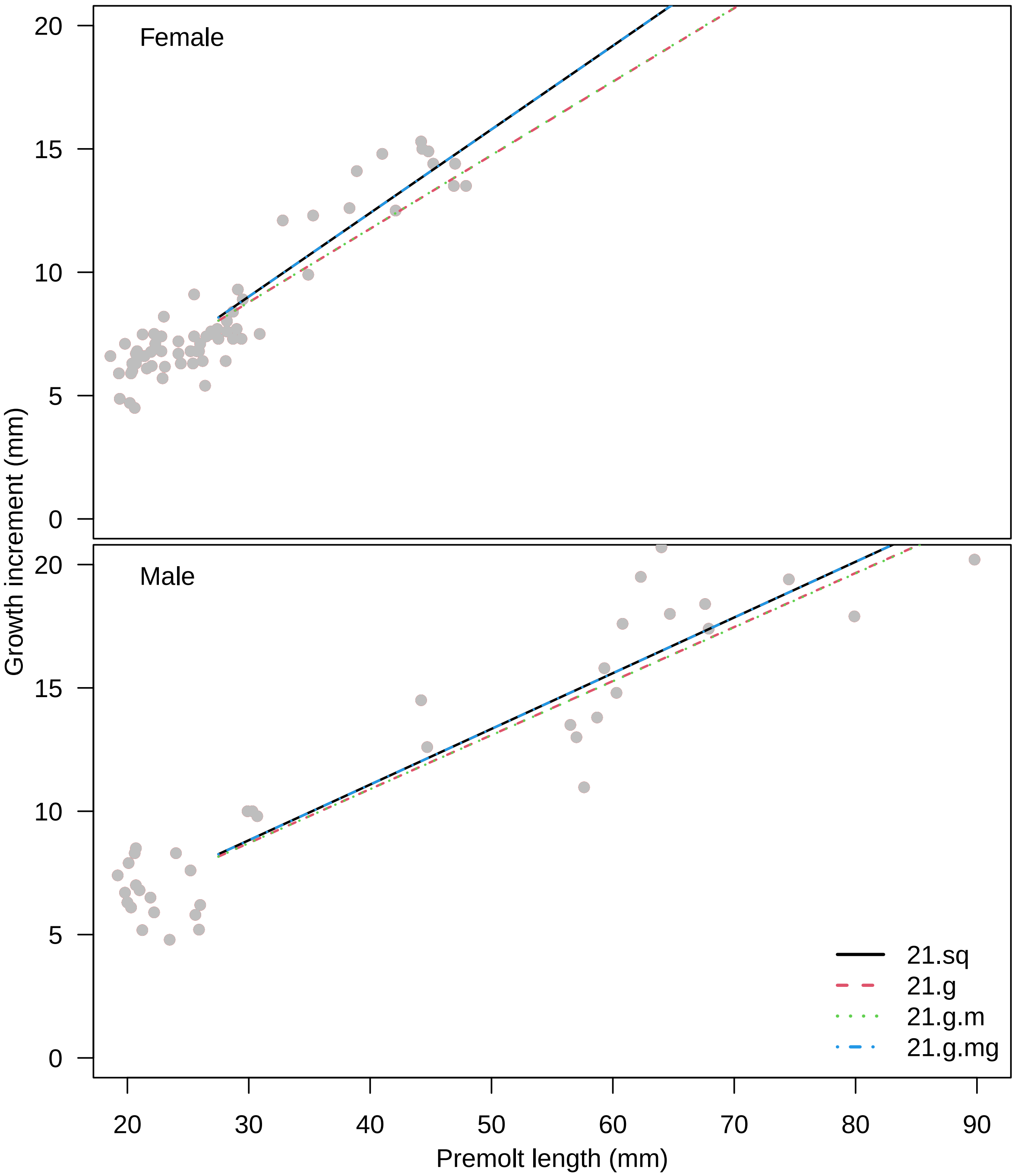


Figure 8: Model fits to the growth data

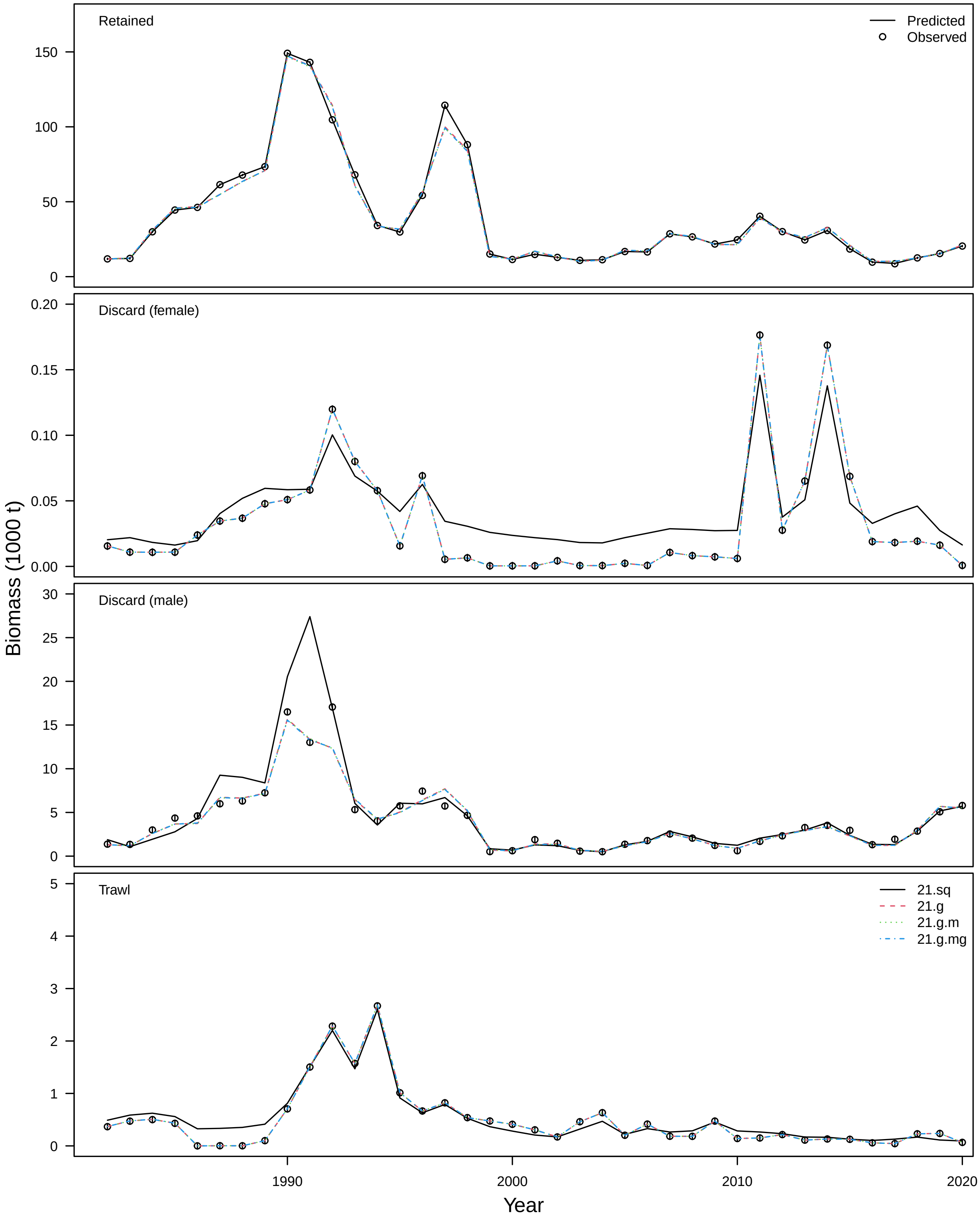


Figure 9: Model fits to catch data

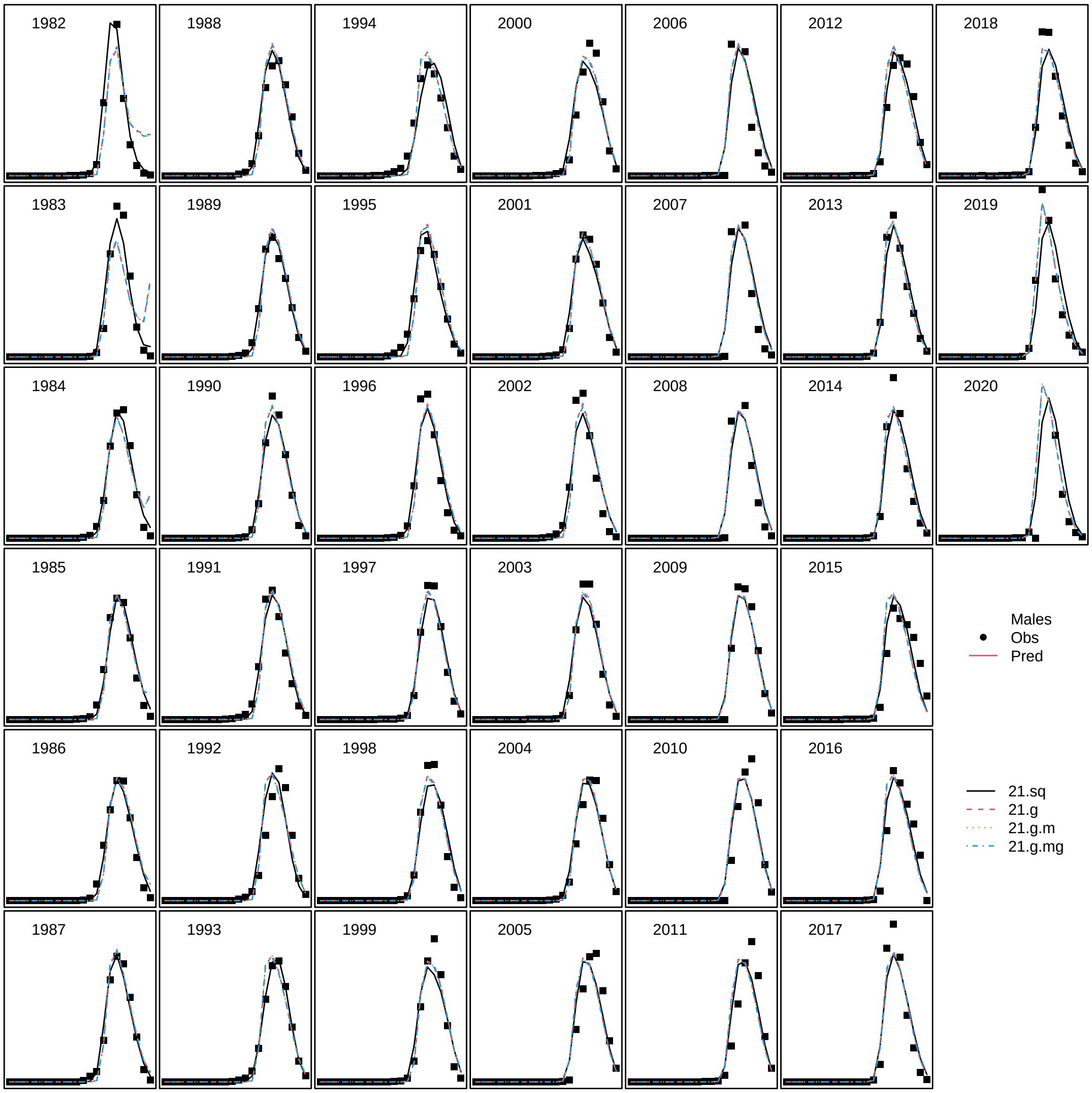


Figure 10: Model fits to retained catch size composition data

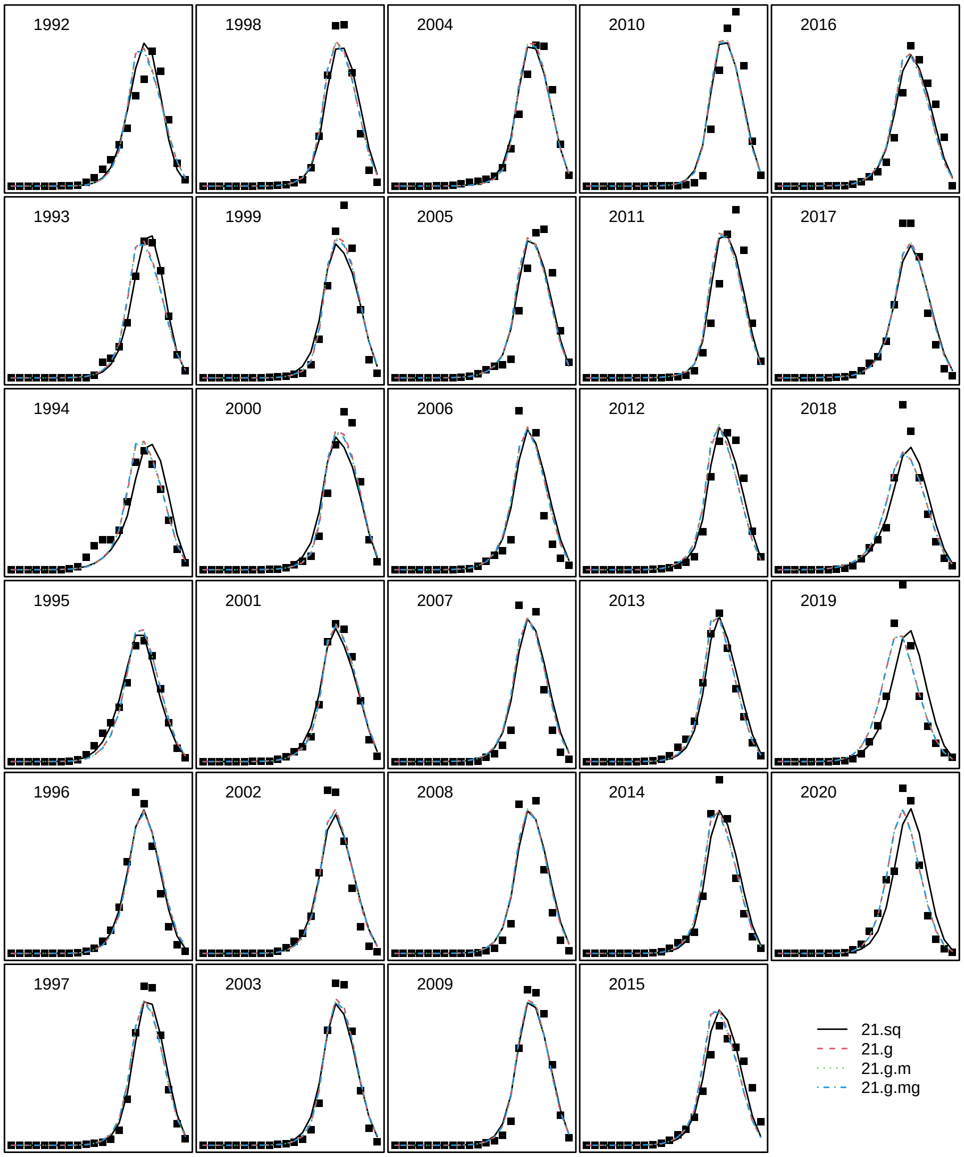


Figure 11: Model fits to total catch size composition data

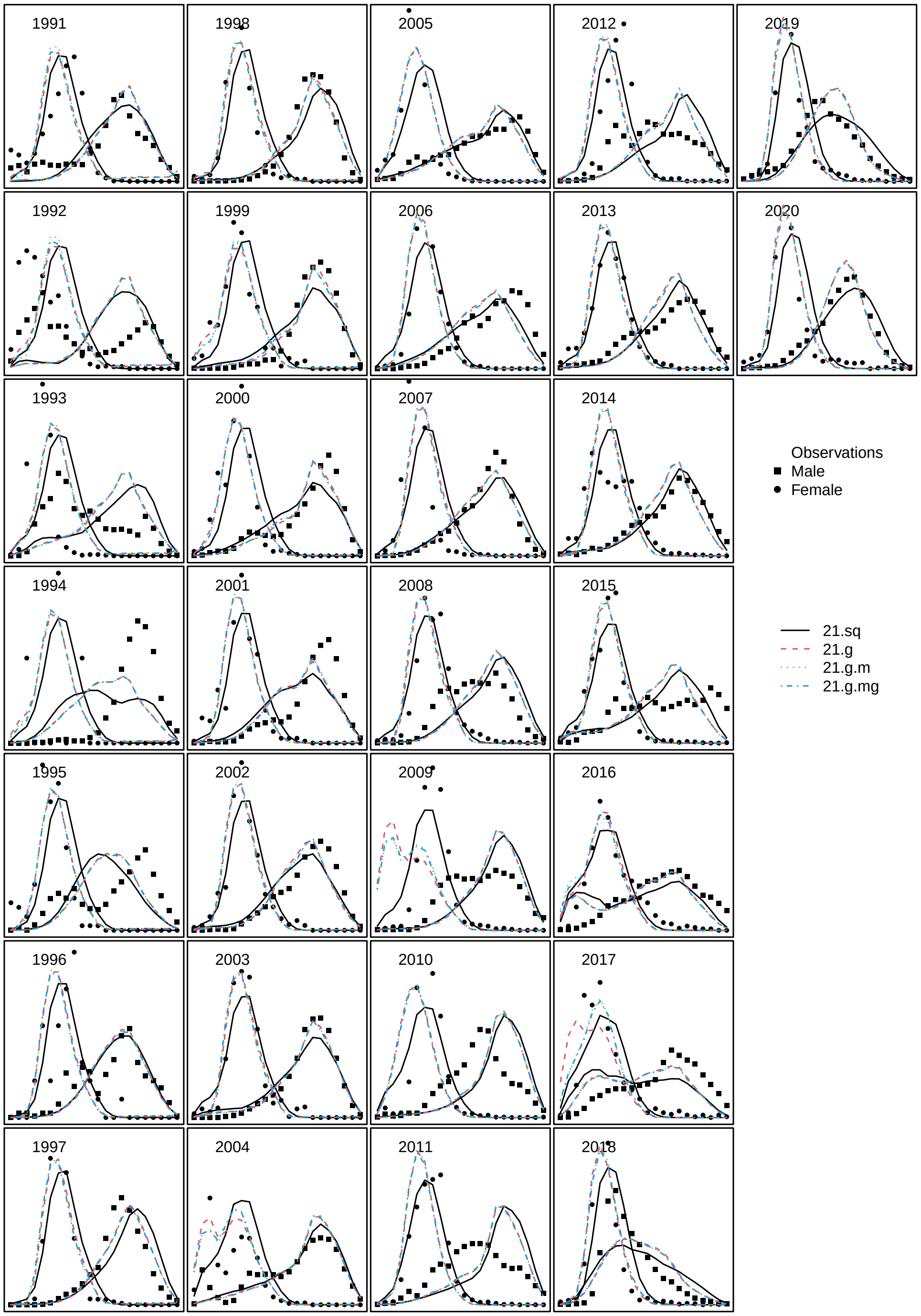


Figure 12: Model fits to trawl catch size composition data

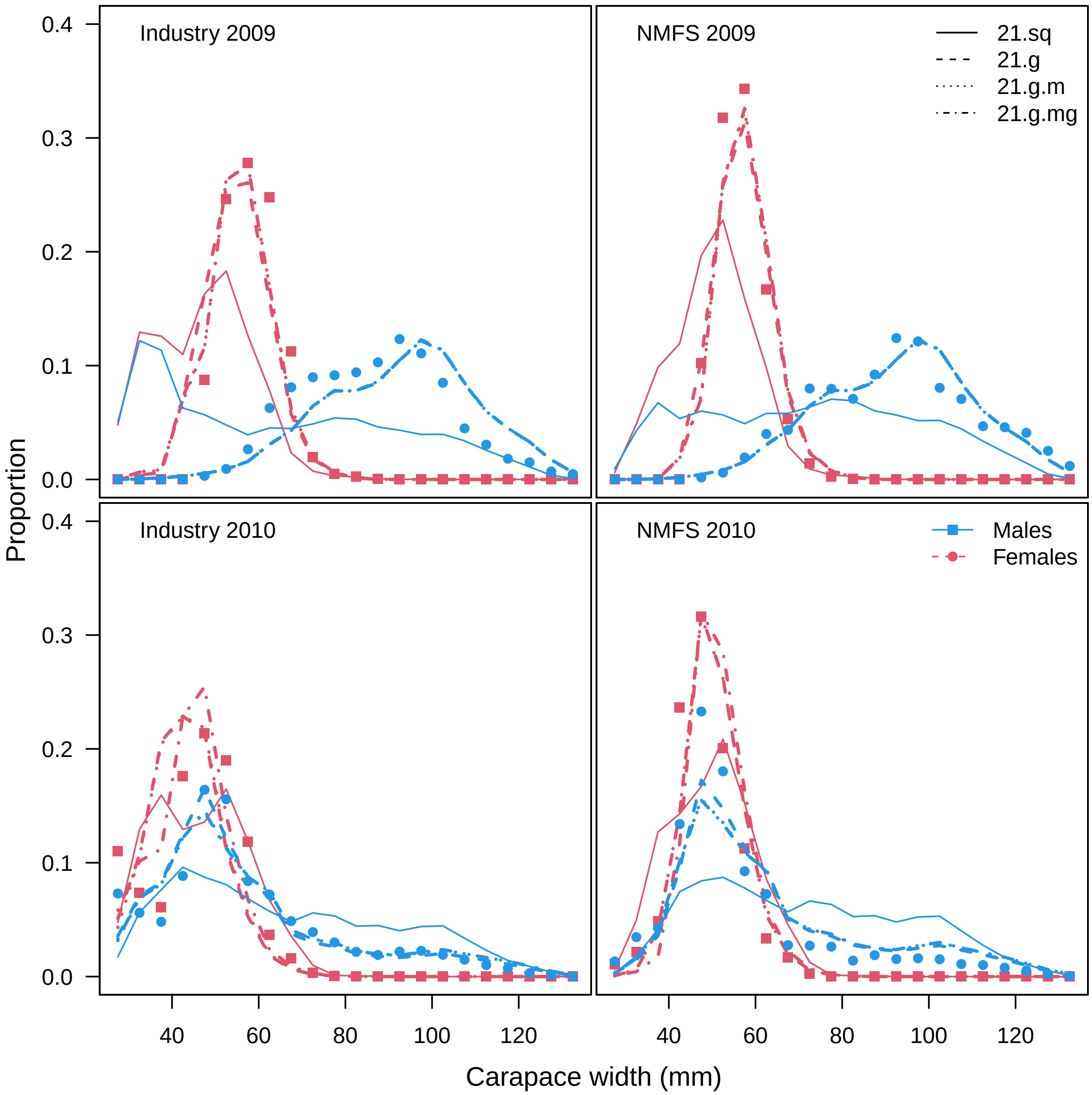


Figure 13: Model fits to size composition data from summer survey experiments (2009 & 2010)

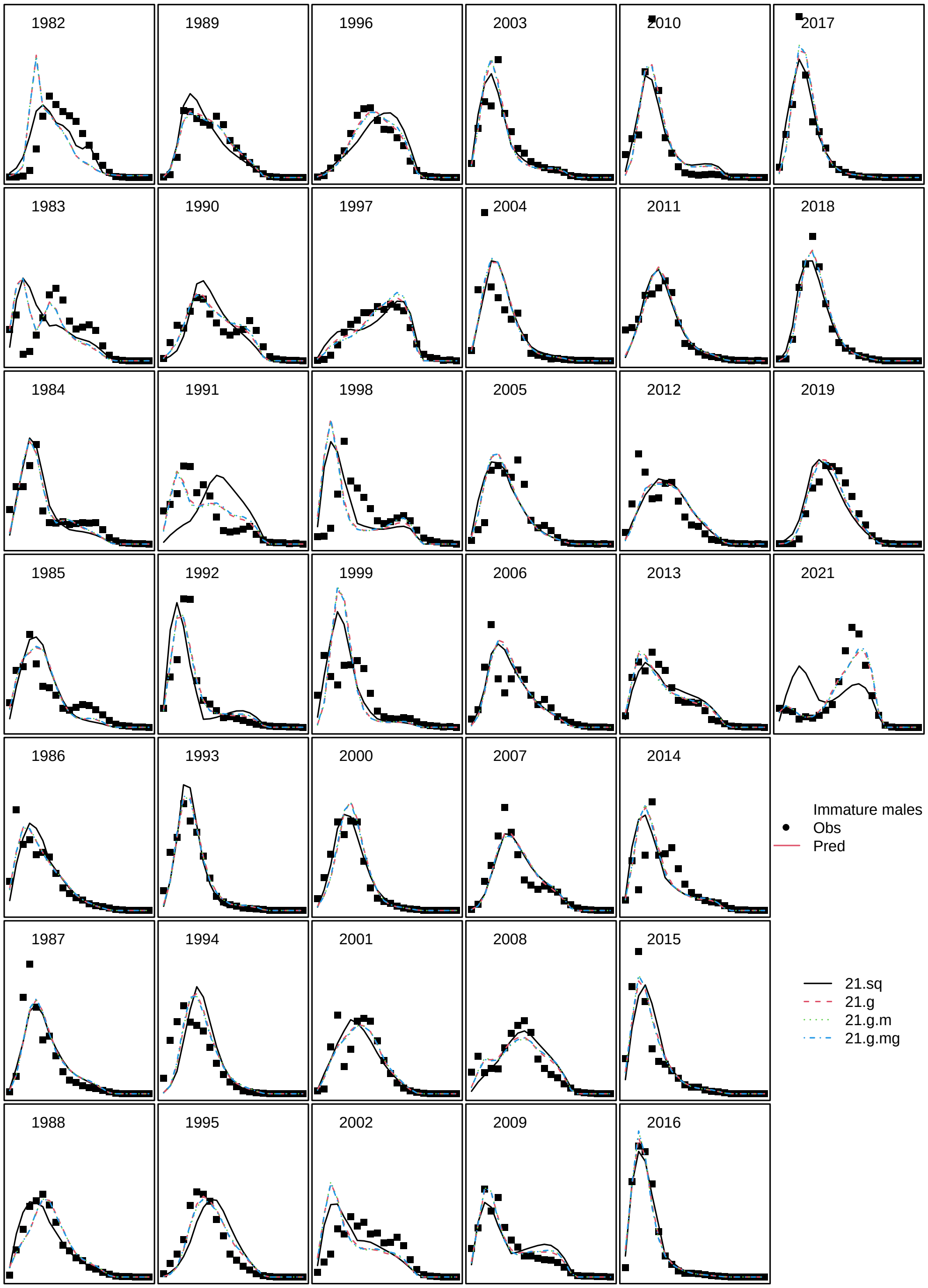


Figure 14: Model fits to immature male survey size composition data.

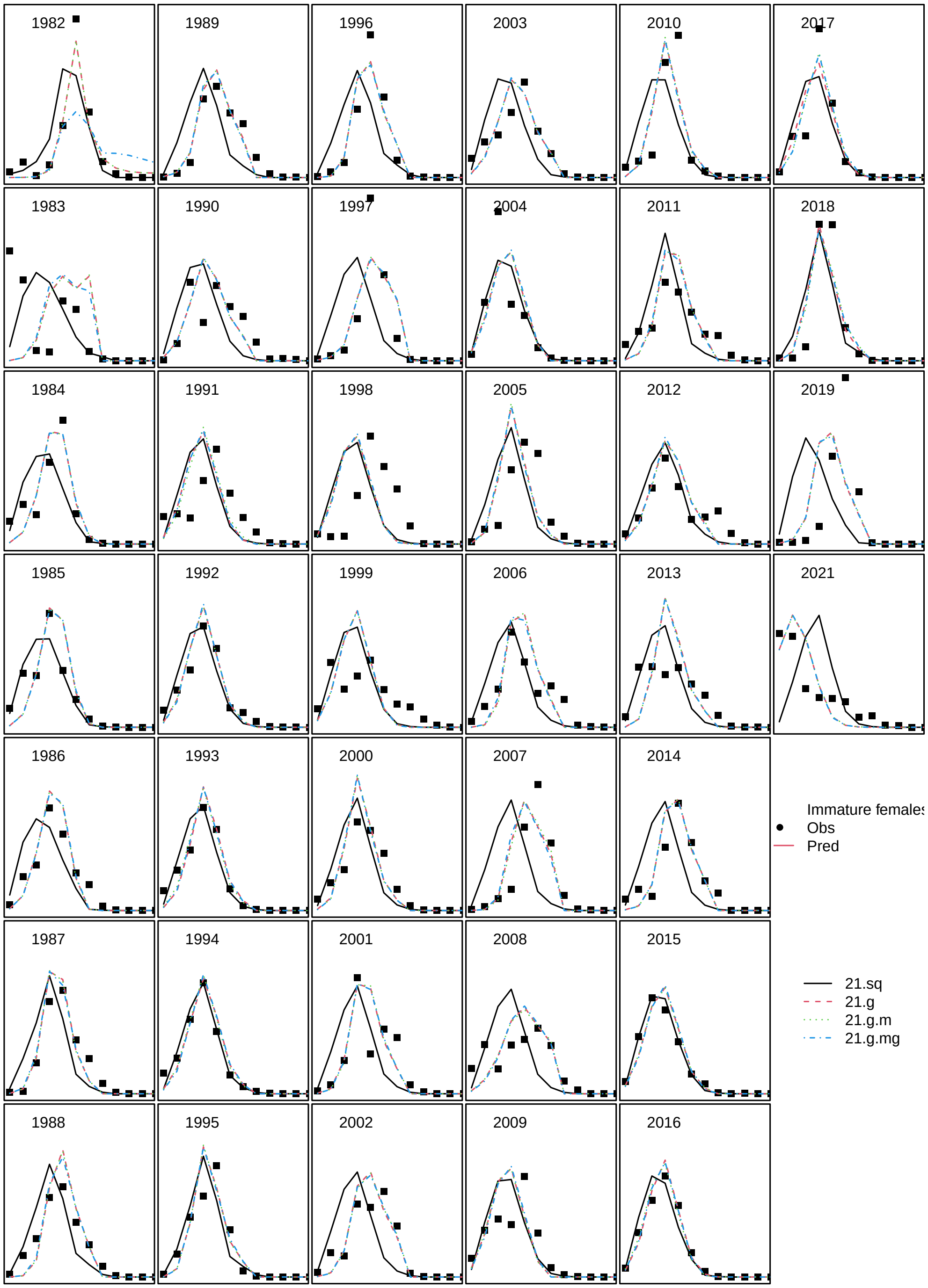


Figure 15: Model fits to immature female survey size composition data.

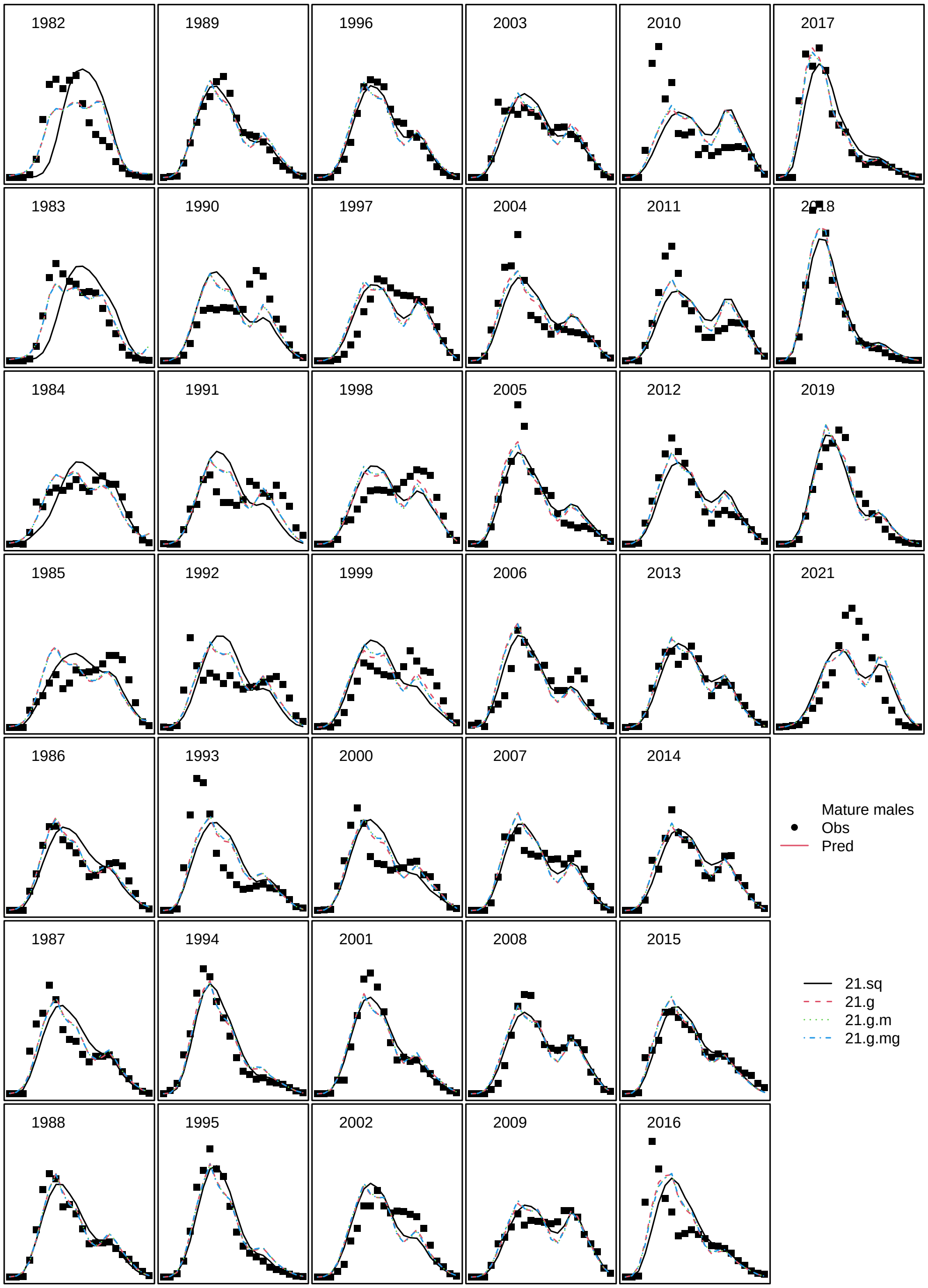


Figure 16: Model fits to mature male survey size composition data.

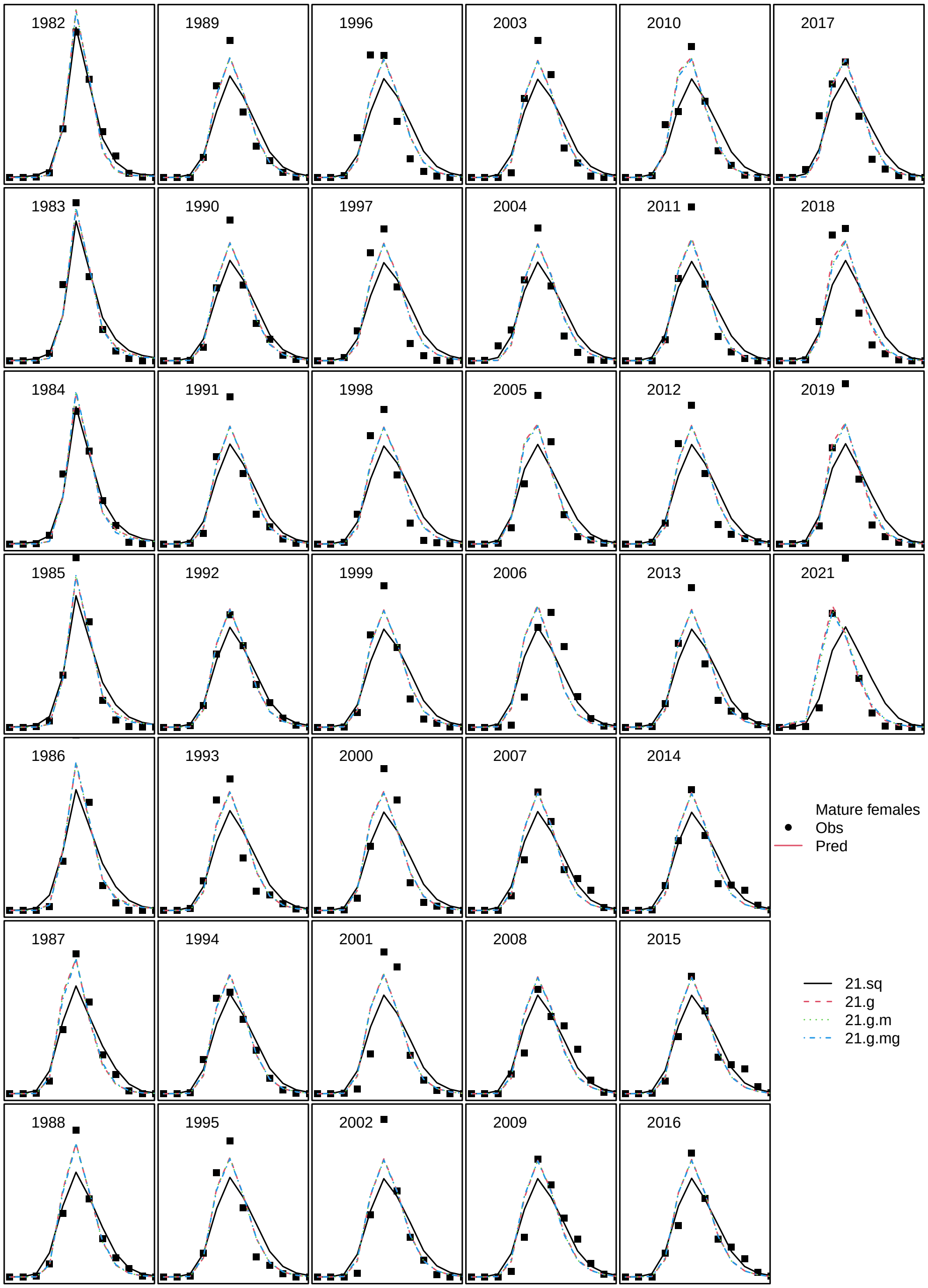


Figure 17: Model fits to mature female survey size composition data.

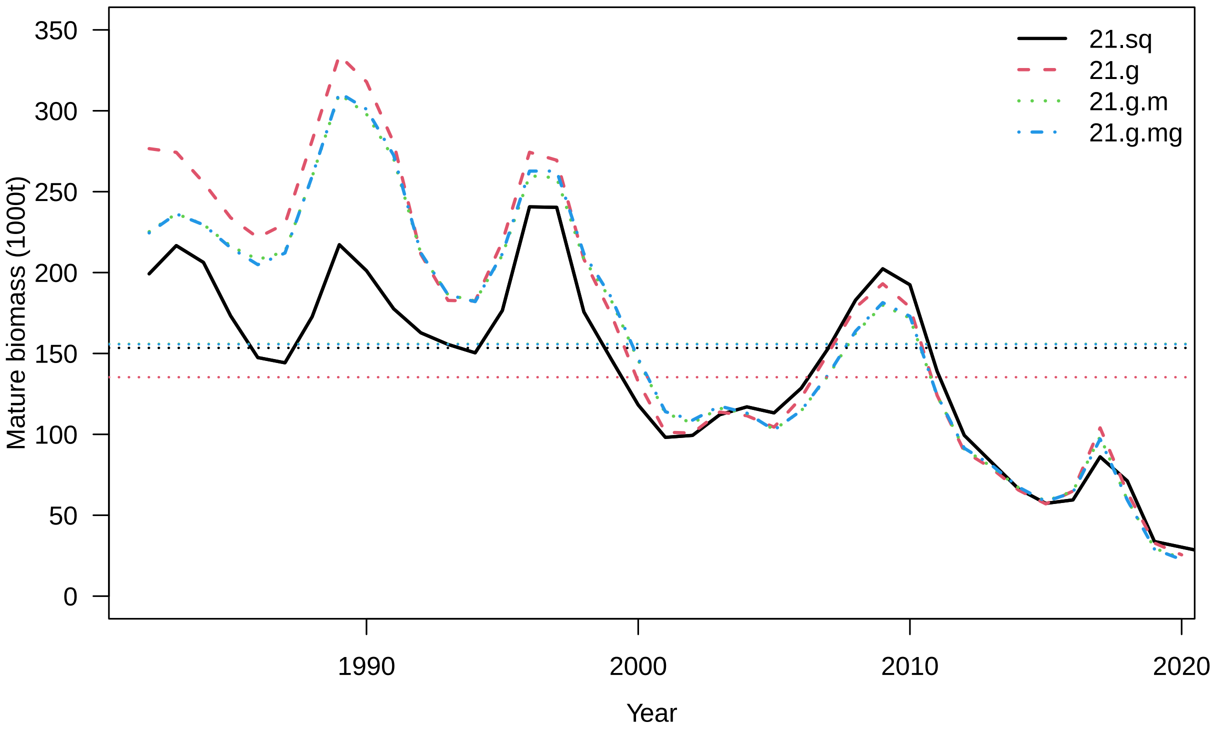


Figure 18: Model predicted mature biomass at mating time. Dotted horizontal lines are target biomasses.

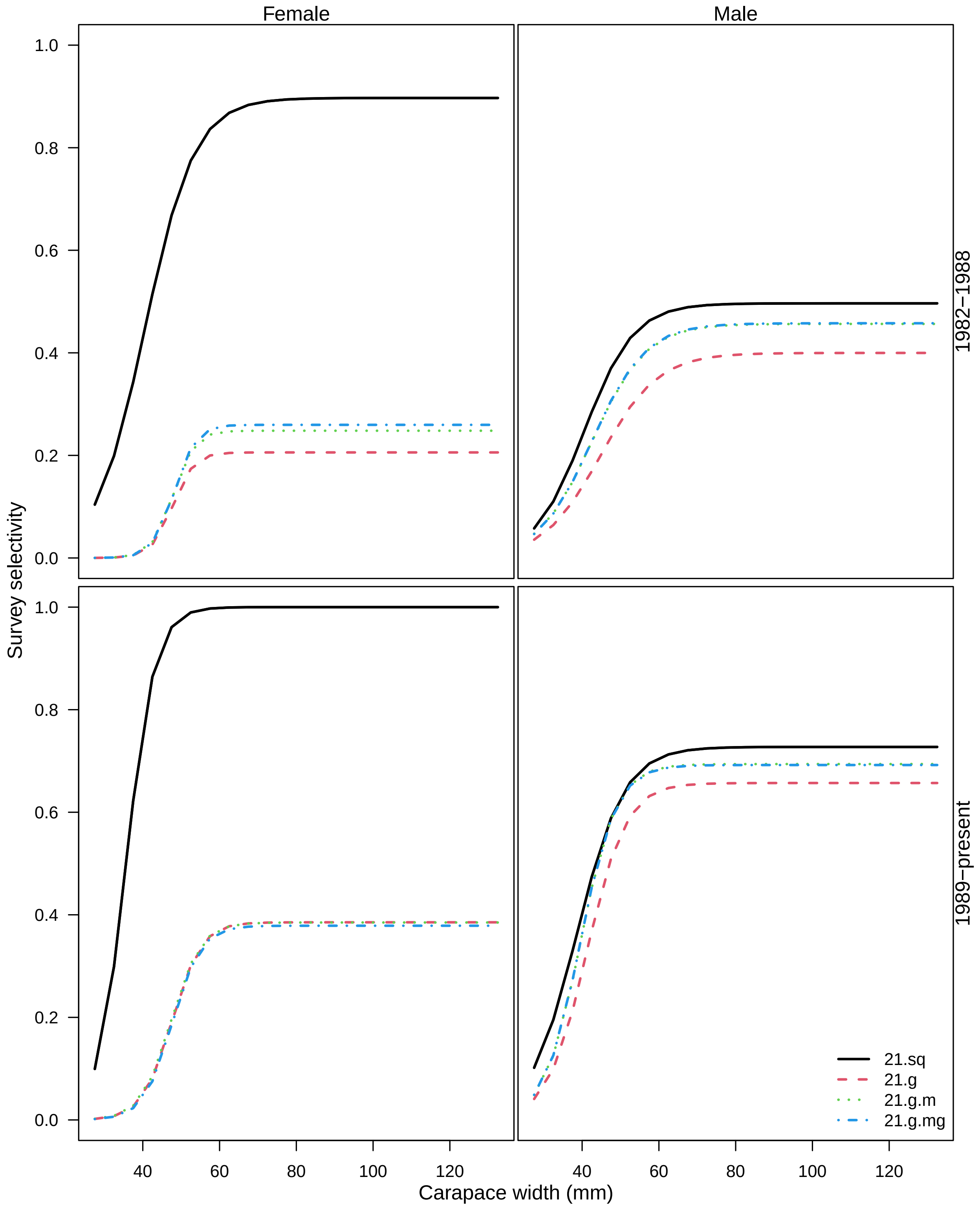


Figure 19: Estimated survey selectivity

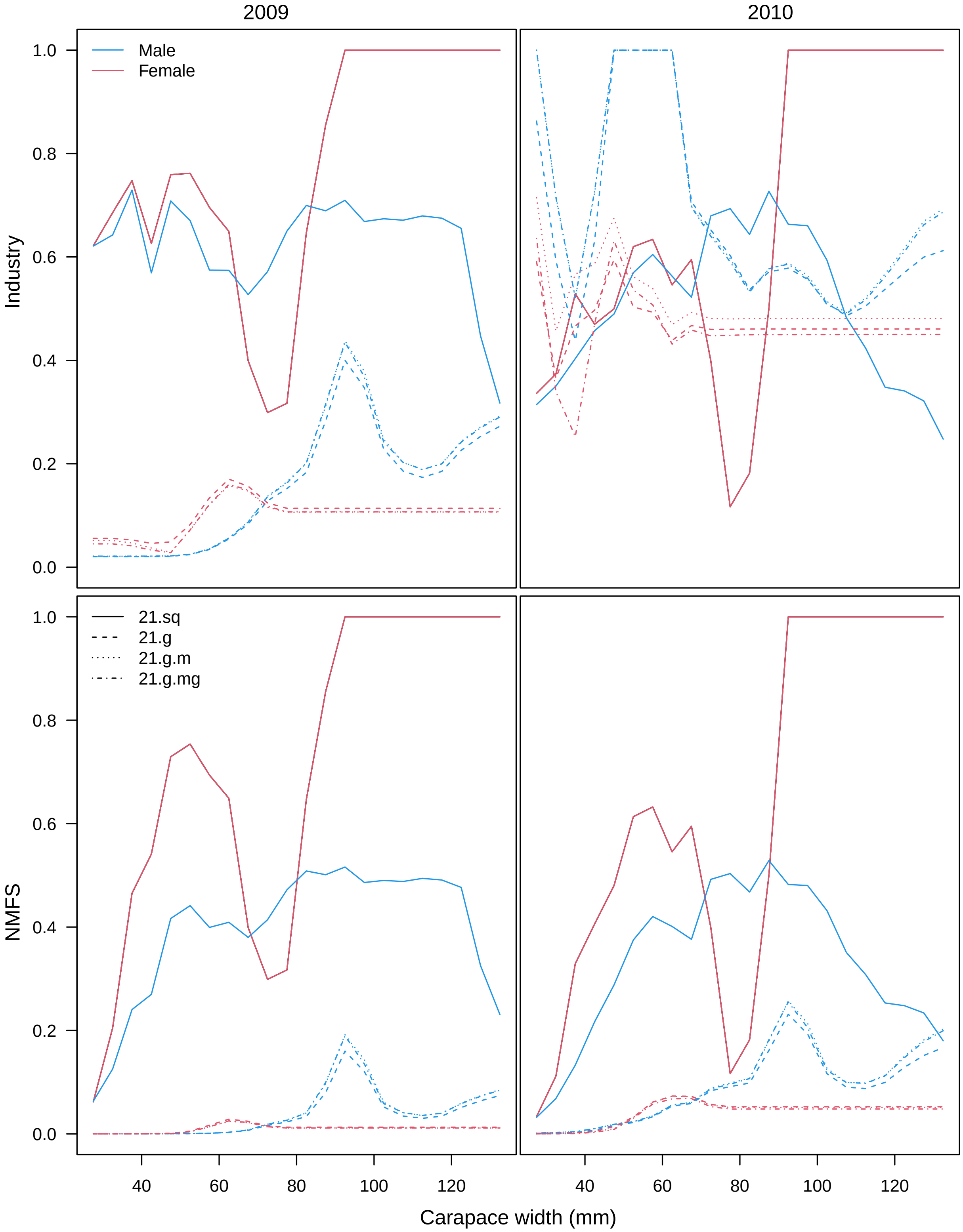


Figure 20: Estimated experimental survey selectivity (availability * survey selectivity)

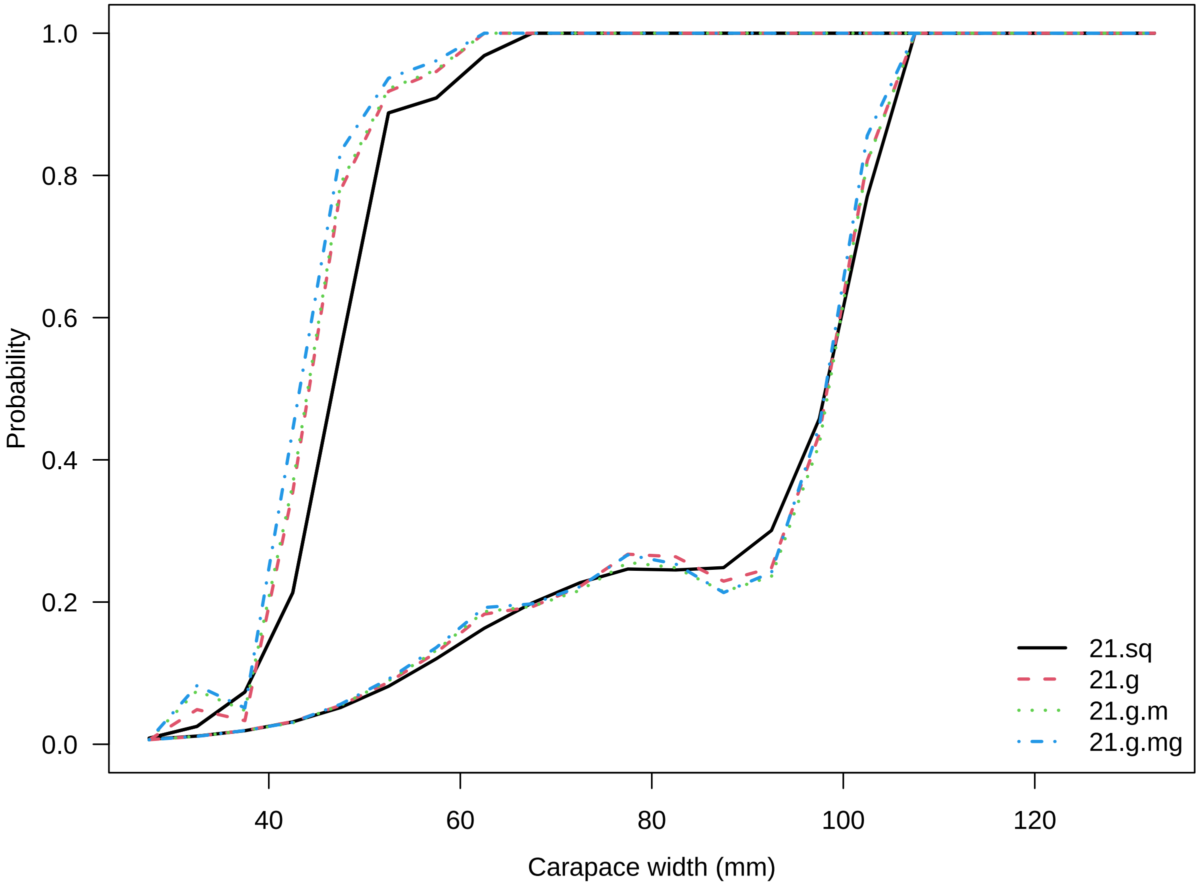


Figure 21: Estimated probability of maturing

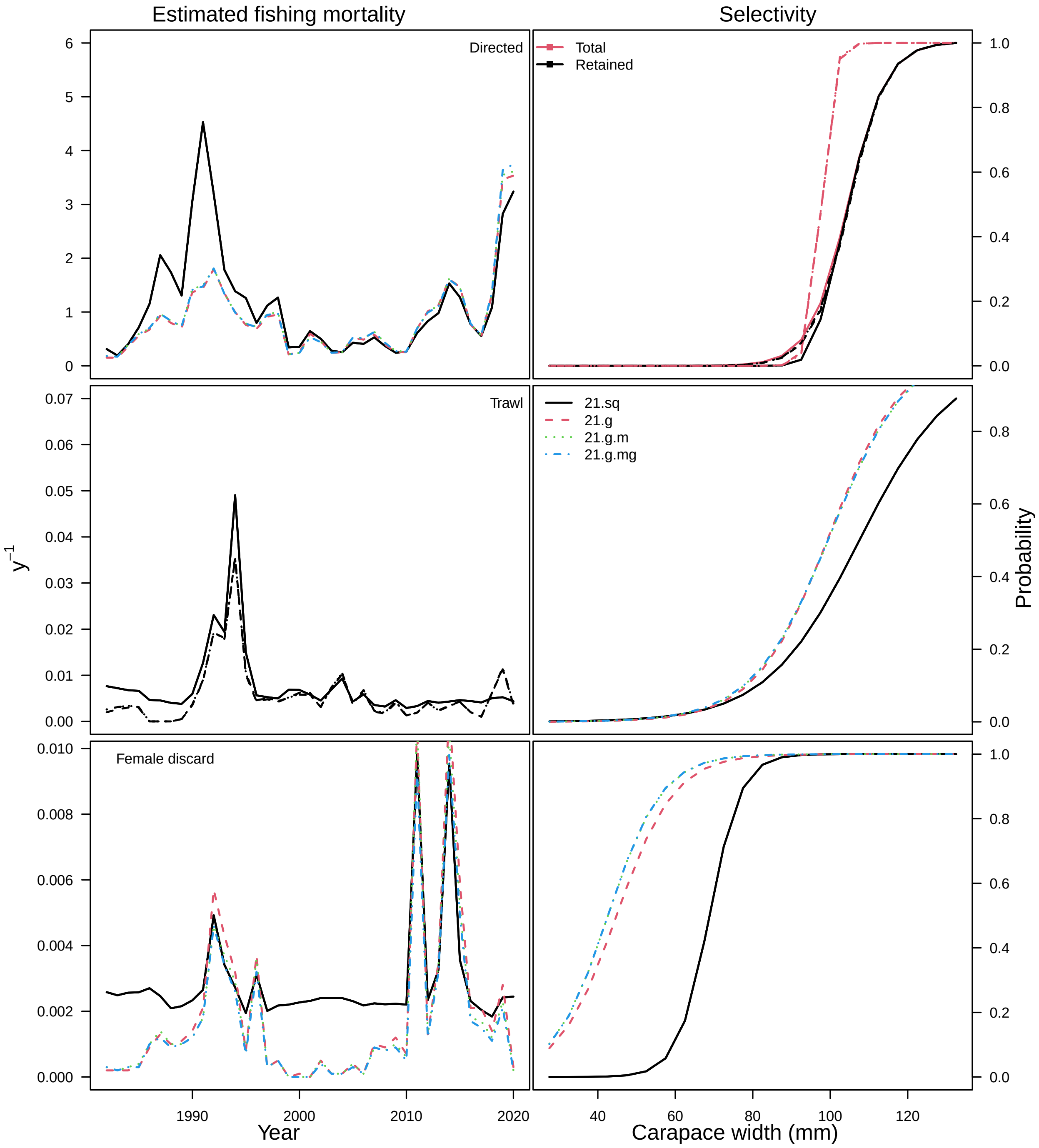


Figure 22: Model predicted fishing mortalities and selectivities for all sources of mortality

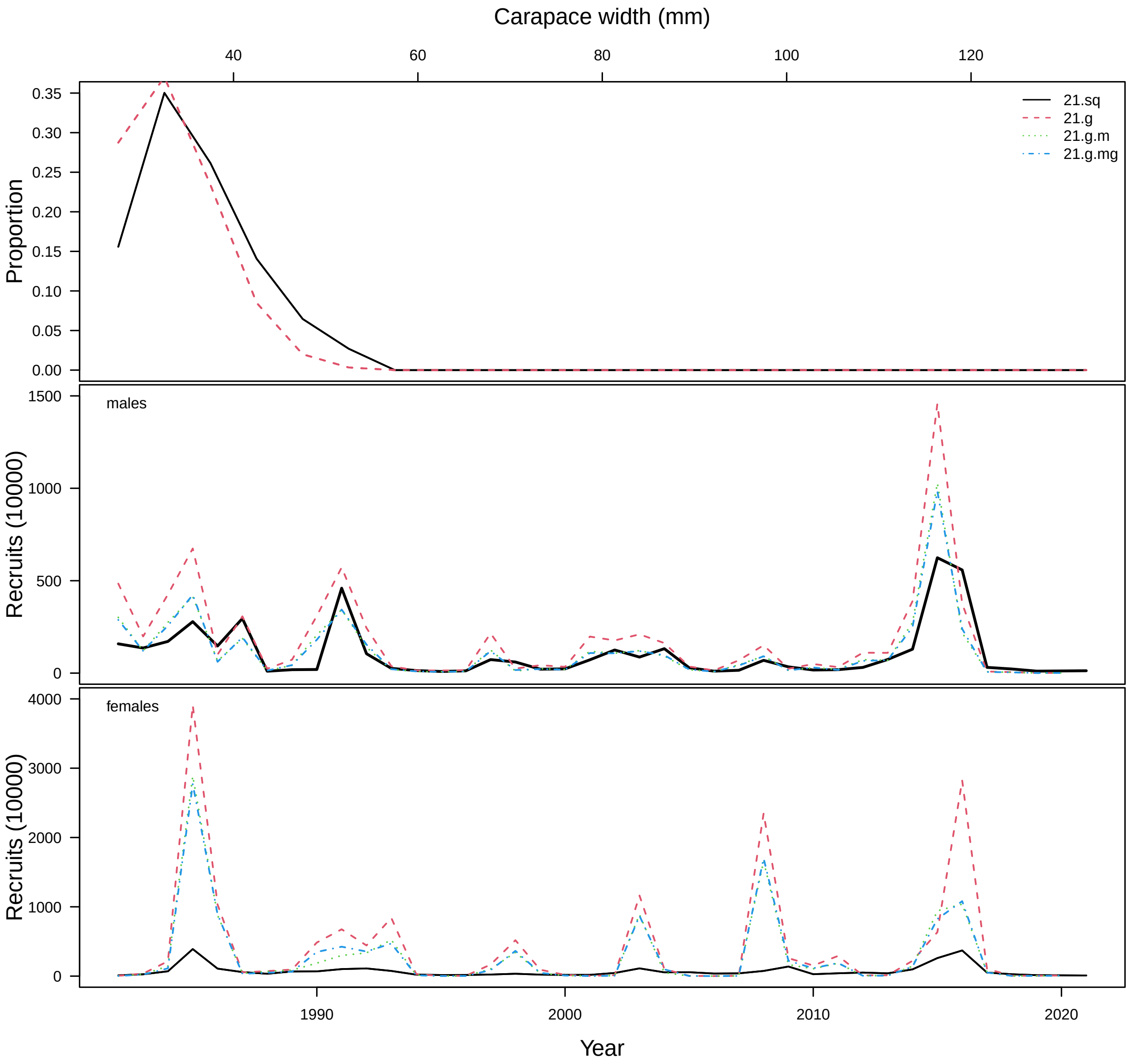


Figure 23: Estimated recruitment and proportions recruiting to length bin.

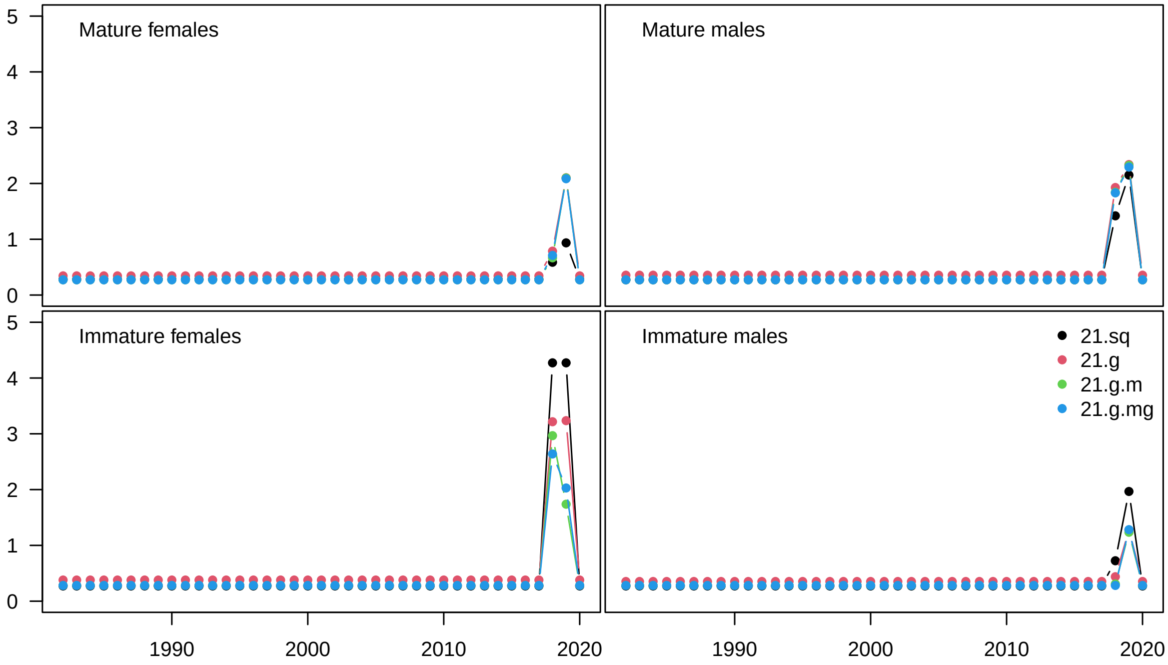


Figure 24: Estimated natural mortality by sex and maturity state.

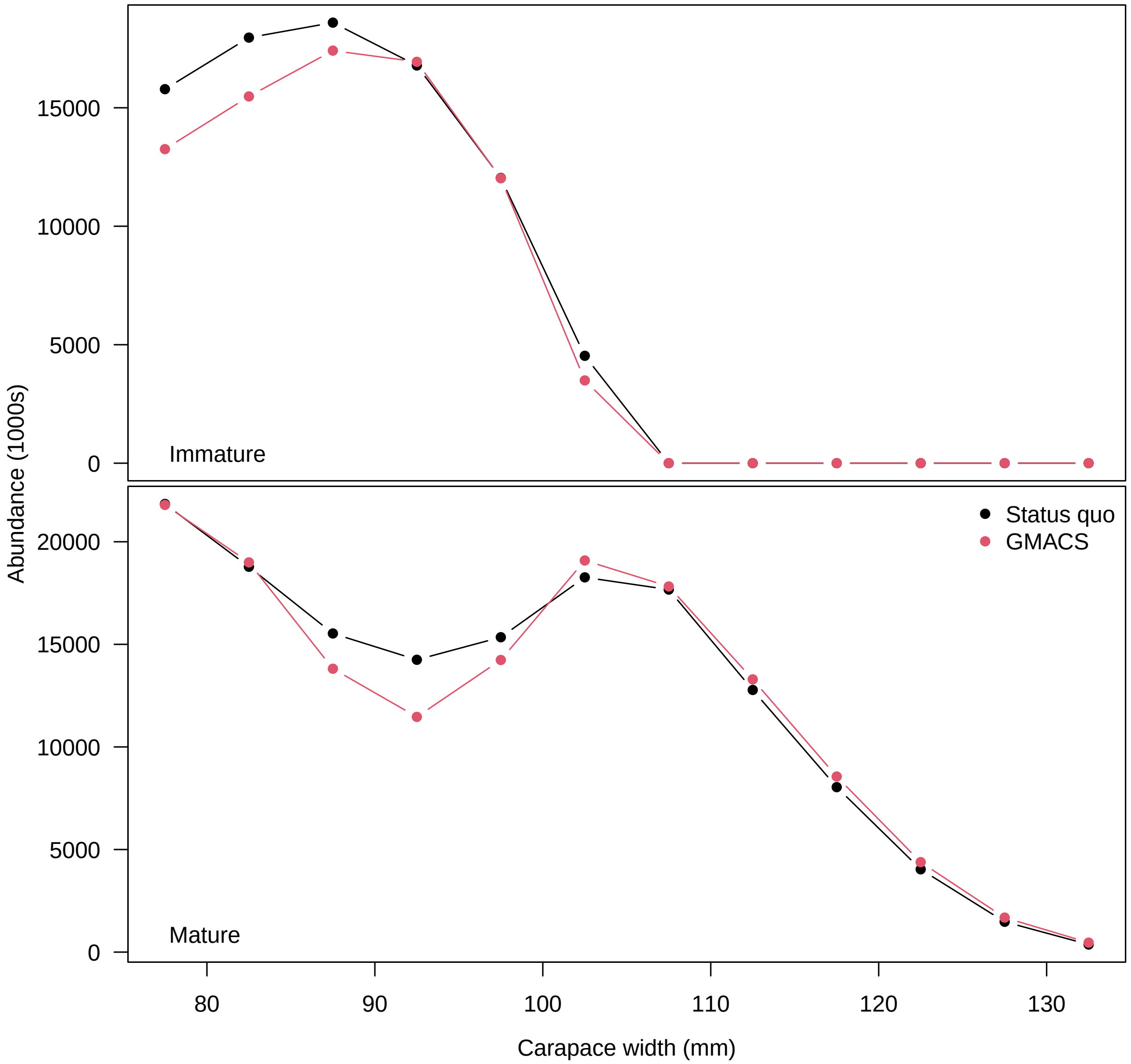


Figure 25: Abundances of immature and mature crab by model in 2021 estimated by the status quo model and GMACS.

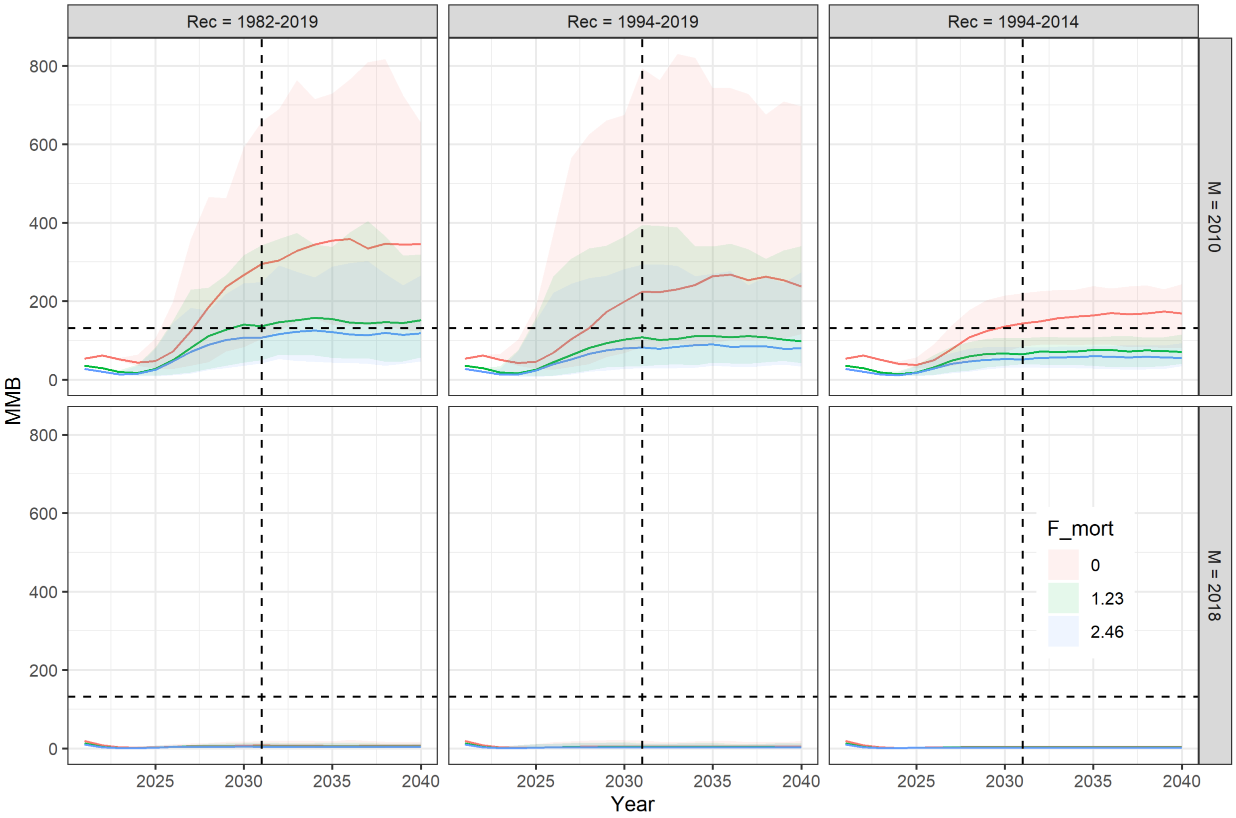


Figure 26: Projections of the GMACS model under different directed fishing, recruitment, and natural mortality scenarios.