May 2021 Tanner Crab Report:
Updates on Issues and Proposed Models for September

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Introduction

This report provides an in-progress update on work related to the Tanner crab assessment (which will be finalized in September) since September 2020 and proposed models to be evaluated for the September 2021 assessment.

Issues

The major issue addressed since the 2020 assessment with respect to the Tanner crab assessment model is the number of model parameters (11) that were estimated at either the upper or lower bound placed on them (Table 1). Most of these were related to selectivity or catchability, the exception being one which determined the scale parameter for the gamma distributions used to describe the probability of post-molt size given pre-molt size.

A second issue addressed is whether or not to use VAST model-based estimates of NMFS EBS Shelf Survey quantities in place of the standard design-based estimates in the assessment model. Models were run using VAST estimates of survey biomass for comparison with the 2020 assessment to determine the extent of changes using the VAST estimates in the assessment may entail.

A third issue addressed was the likelihood used to characterize fits to fishery catch biomass. Currently, uncertainty estimates are not available for the estimated fishery (by)catch biomass values used in any of the crab assessments. Consequently it is necessary to assign some level of uncertainty to those values. Most other Tier 3 crab assessments use a lognormal likelihood to characterize fits to fishery catch biomass, and assign a constant coefficient of variation (cv) to the data (the lognormal likelihood is also used in *all* Tier 3 assessments for survey biomass data, but these include accompanying estimates of uncertainty). Using a lognormal likelihood with a fixed cv is equivalent to assuming the *relative* error is constant. In previous Tanner crab assessments, the "norm2" function has been used to calculate the likelihood, with biomass expressed in 1000's t. This implicitly defined the uncertainty assigned to the fishery catch biomass data as a fixed standard deviation of 1,000 t, regardless of the actual level of the fishery catch. The implicit cv, then, decreased with increasing catch size. Thus, models that use lognormal likelihoods to assess fits to retained catch and bycatch biomass data were evaluated with those using the "norm2" likelihood.

The final issue addressed is the poor fits to male growth data in the assessment model. The model-estimated mean growth for males is increasingly biased high as pre-molt size increases, relative to available molt data and the relationship fit outside the model. A likelihood profiling analysis was undertaken to identify the tradeoffs the model makes with regard to male growth to arrive at its converged solution.

Modifications to the assessment model code

TCSAM02, the assessment model code, was modified to:

- allow specification of maximum possible sizes in the model separately by sex
    - previously, the maximum possible size in the model was the same for both sexes and was determined by the maximum male size incorporated in the model

  - these act as accumulator bins for size compositions, etc.
- allow specification of maximum size at recruitment (i.e., truncate the distribution)
- allow use of "tail compression" when calculating the likelihood associated with size compositions
- allow use of the Dirichlet-multinomial likelihood for size composition data
- incorporate alternative selectivity functions based on the normal function (various parameterizations of ascending ½-normal and double-normal functions)
- incorporate alternative nonparametric selectivity function parameterized on the arithmetic scale (as opposed to the. previous one parameterized on the logit-scale)

All model modifications were tested to make sure that they did not affect results from the 2020 assessment model. The current code is available at GitHub on the "202105CPTMeeting" branch.

Model explorations and analysis

In total, 16 different model configurations were evaluated for this report (Table 2). All models were initialized 600 times with values randomly jittered within the bounds set on each estimated parameter and evaluated to identify the parameter values associated with the global minimum for each model's objective function (i.e., the maximum likelihood estimate was determined). The model run with the smallest objective function was identified as the MLE. The value of the converged objective function for each model and its maximum gradient with respect to the parameters are listed in Table 2. In most cases, the objective function values are not directly comparable between different models. The number of estimated model parameters and the number that were estimated at an upper or lower bound are also listed. Summary results from OFL calculations are given in Table 3.

2020 assessment model

The data, processes and likelihood components included in the 2020 assessment model (20.07) are summarized in Tables 4-8 (see Stockhausen, 2020, for more details).

21.00 and 21.00a: VAST-based models

VAST-based estimates of annual survey biomass for males and immature and mature females were fairly similar to the design-based estimates currently used in the assessment (Tables 9-11, Figure 1), except that the associated cv's were substantially smaller. Mean relative differences for males, immature females, and mature females were -3, 2, and 3%, whereas the mean reduction in cv's was 50, 42, and 39%, respectively. Individual differences ranged from -27 to 23% for males, -27 to 53% for immature females, and -27 to 29% for mature females. The largest differences tended to occur in the 1975-1981 time frame; the area covered in the survey varied from year to year during this period.

Model 21.00 was run using the same configuration as the assessment model but substituting the VAST survey biomass estimates and cv's for their design-based counterparts. One concern with using the VAST estimates in the assessment is that the cv's may be overly-constraining in the model optimization process. Consequently, a second model configuration, 21.00a, was also tested. 21.00a was similar to 20.00, but estimated "additional survey variance" parameters that allowed the model greater flexibility in fitting the VAST data by inflating the variance used in the survey biomass likelihood.

Model 21.00a clearly used the additional flexibility to substantially downweight fitting the survey data (increasing the confidence intervals on the survey biomass data in Figure 2) in favor of better fitting the size composition data, in particular the NMFS survey size composition data (Table 12). Except for bycatch size compositions from the snow crab fishery, 21.00a fits all the size composition data better than both 20.07 and 21.00. However, the degree of downweighting is far in excess of what might be deemed acceptable.

The reduced cv's associated with the VAST survey biomass estimates force 21.00 to follow the survey biomass trajectories more closely than 20.07 does (Figure 3), with little consequence to fits to the various retained catch biomass and total catch biomass fishery data (Table 12, Figures 4-5). In fact, except in the case of bycatch in the BBRKC fishery, 21.00 fits the fishery catch biomass data better than 20.07. However, 21.00 fits all the size composition data much more poorly than 20.07 does, with the exception of bycatch size compositions in the BBRKC fishery (Table 12).

It was consequently surprising to find that 21.00 estimated NMFS survey catchability for female crab to be constant with crab size (Figure 6), despite fairly similar fits to survey size composition data (Figure 7). The time series of recruitment estimated in both models exhibited generally similar temporal patterns (Figure 8, lower figure), although the timing of peaks and valleys differ between the two models by up to two years and there is little agreement in the 1980s. Part of the difference in estimated recruitment in the 1980s is probably related to differences in estimated natural mortality in the early 1980s (Figure 8, upper figure).

Model 21.00 ended up with 12 parameters estimated at one of their bounds: one more than for 20.07 but the remaining 11 were not all the same as those for 20.07 (Table 13). Three were new parameters at-a-bound (pS1[19], size at 50% selected in the groundfish fisheries; and pS2[1] and pS2[2], the size differences between 50%- and 95%-selected for males in the NMFS survey, before 1982 and after 1981) while two parameters at-a-bound in 20.07 were estimated within bounds in 21.00 (pS1[27], size at 95% selected for female bycatch in the BBRKC fishery; pS1[4], size at 50% selected for females in the NMFS survey after 1981). Also, the estimated value for pS2[4], the size difference between 50%- and 95%-selected for females in the NMFS survey after 1981, changed from being estimated at its upper bound in 20.07 to its lower bound in 21.00 (the values for pS1[4] and pS2[4] explain why selectivity for females in the NMFS survey after 1981 was essentially a flat line for Model 21.00).

21.01: expanded bounds on survey catchability

Model 21.01 and all subsequent models revert to fitting the design-based survey biomass time series. In 20.07, two parameters (pQ[1], pQ[3]) reflecting fully-selected, sex-specific survey catchability during 1975-1981 were estimated at their lower bounds, while one parameter (pLgtRet[1]) reflecting the (logit-scale) maximum retention of legal Tanner crab in the directed fishery prior to the 1997 closure time period was estimated at its upper bound (implying essentially 100% retention; two similar parameters reflecting maximum retention in other time periods were almost at their upper bounds, as well). In Model 21.01, the lower bounds on all survey catchability parameters were decreased from 0.5 (1975-1981 time period) and 0.2 (1982-2019 time period) to 0.01 to essentially remove the lower bound constraint on these parameters. The values for all three logit-scale maximum retention parameters were also fixed, rather than estimated, at 14.9—i.e., maximum retention of legal-sized crab was essentially fixed at 100%.

Estimates for the pre-1982 survey catchability parameters (pQ[1] and pQ[3]) in Model 21.01 were indeed no longer at the bounds (0.2176 for males and 0.3244 for females), and the number of estimated parameters at one of their bounds was reduced from 11 to 7 (Table 14). The estimated NMFS survey selectivity curves (unscaled by fully-selected catchability) were almost identical with those from 20.07 (Figure 9). The additional parameter that moved off a bound (from an upper bound of 1.0 to 0.87) was pGrBeta[1], the scale parameter for the gamma distributions that determine the probability of post-molt size given pre-molt size. The remaining parameters hitting a bound were all related to selectivity. Fits to NMFS survey biomass were similar between the two models after 1981, but differed in the 1975-1981 period (Figure 10) due to the differences in the estimated parameters controlling fully-selected catchability. Annual variability in this early period of the survey was high (the area surveyed was inconsistent from year to year). 20.07 was able to fit several years with high survey biomass estimates but unable to fit years with relatively lower estimates, while the opposite was true for 20.01. Fits to fishery data (not shown) were essentially identical between the two models. Overall, the objective function value for Model 21.01 was about 40 likelihood units lower than that for 20.07, so 21.01 was considered an improvement over 20.07 (Table 15).

Estimates for mean growth, the probability of the molt to maturity, natural mortality during most of the model time period were almost identical for both models (Figure 12). However, Model 21.01 estimated substantially higher mortality on mature crab (0.69 for females, 0.80 for males) during the 1980-1984 elevated mortality period than was estimated using Model 20.07 (0.56 and 0.58, respectively). The temporal pattern of recruitment was similar in both models, but mean recruitment was higher in 21.01, leading to slightly higher mature biomass across the model time period (Figure 13).

21.03 and 21.04: lognormal likelihoods for fishery catch biomass data

In contrast to survey data, fishery catch biomass data for Tanner crab do not have uncertainty estimates (e.g., cv's) associated with them. Consequently, it is necessary to assume some level of uncertainty for each catch biomass estimate in order to calculate its contribution to the overall model likelihood. Fishery catch biomass likelihoods in Models 20.07-21.02 and previous assessments were based on the "norm2" function in ADMB, which resulted in an implicit standard deviation of 1,000 t being used as the uncertainty for all fishery catch biomass data. Thus, the fishery data was treated as though associated uncertainties were independent of the level of extrapolated catch. This is unlikely to be the case, and most other Tier 3 crab assessments assume the uncertainty scales with the extrapolated catch; these assessment use a lognormal distribution for fits to fishery catch biomass—similar to that used for survey biomass data. For Models 21.03 and 21.04, a lognormal distribution was used to quantify the model fits to fishery catch biomass for retained catch in the directed fishery and total catch in the directed fishery and the fisheries that take Tanner crab as bycatch. Retained catch biomass data is currently known with high precision, but with less precision in the past, so its uncertainty was characterized by a cv of 0.01 in 2005-the current, 0.025 for 1980-1996 (early domestic fisheries), and 0.10 for 1965-1980 (historical data from foreign fishing and joint ventures). Total catch biomass estimates for the directed fishery and bycatch fisheries rely on expansion of limited observer sampling by effort to the total associated fishery, and is thus much less precise than the retained catch data. Consequently, a cv of 0.20 was adopted for all estimates of total bycatch above 50 t. For catches under 50 t, the uncertainty was expressed as a fixed value of 10 t to keep the uncertainty from going to 0 in fisheries that take Tanner crab as bycatch.

Model 21.03 was identical in parameterization to 20.07, while Model 21.04 was identical in parameterization to 21.01. The tighter bounds on the estimates of the survey q's in Model 21.03, as derived from 20.07, led to these and other parameters (20 total) estimated at one of the parameter bounds in Model 21.03. Only 5 parameters (all related to selectivity) were estimated at a bound in Model 21.04. Thus, Model 21.04 was regarded as an improvement over 21.03, as 21.01 was over 20.07. Consequently, subsequent attention is focused on comparing 21.01 and 21.04.

Models 21.01 and 21.04 were essentially identical with respect to estimated population processes such as mean growth, terminal molt, and natural mortality (M), although female M was slightly higher in 21.04 compared to 21.01, while the reverse was true for males (Figure 14). Not surprisingly, then, the estimated cohort progressions (Figures 15 and 16) were nearly identical.

The estimated time series for recruitment were also very similar after 1990. Prior to 1990, differences were evident in the mid-1960s when recruitment in 21.01 was somewhat higher, while differences in the time series of MMB were negligible (Figure 17). Slight differences in time series of population abundance trends exhibited small differences between the models propagating from the differences in recruitment in the mid 1960s up to 1980 (Figure 18).

Both models estimate the same selectivity curves for the directed fishery, but retention curves rise slightly more sharply in 21.01 (Figure 19), although the differences between the curves are much less pronounced than for the selectivity curves in the bycatch fisheries, particularly for snow crab (Figure 20).

Estimated fishery capture rates were very similar in the directed fishery and groundfish fisheries between the two models (Figure 21), while those in the snow crab and BBRKC fisheries differed primarily in level.

Model-estimated time series of retained catch and total catch biomass in the directed fishery were very similar across the entire model time period (Figure 22), as were bycatch in the groundfish fisheries (Figure 23), but those for bycatch in the snow crab and BBRKC fisheries exhibited much larger differences. For bycatch in the BBRKC fishery, the differences primarily seemed to be with respect to level, but the differences in the timeseries estimates for bycatch in the snow crab fishery also include differences in the timing of peaks.

There were almost no differences in the estimated NMFS survey selectivity or catchability curves between the two models (Figures 24 and 25), and fits to survey biomass data from the NMFS and BSFRF surveys were almost the same (Figure 26). For the NMFS survey, this meant that neither model was able to track the survey well when it exhibited high values.

Differences in the fits to the fishery data were fairly small given the changes in assumed uncertainties and likelihoods (Figures 27 and 28). Values for the fishery components to the likelihood were not directly comparable between the two models due to the change in distributions and associated (assumed) uncertainties. The fits to retained and total catch biomass in the directed fishery (Figure 27) and to total catch biomass in the groundfish fishery (Figure 28) were very similar for the two models, with some small but detectable differences in the fits to total catch in the directed fishery principally prior to the 1997/98 closure. Fits to total bycatch in the snow crab and BBRKC fisheries were somewhat more variable.

Applying lognormal likelihoods to fishery catch biomass data did not change any quantities related to management substantially (Table 3). Model 21.04 was an improvement over 21.01 in that only five parameters (all related to selectivity) were estimated at a bound whereas 21.01 had seven (Tables 16 and 17). The five included four that were also at bounds in 21.01, and one new parameter (the descending slope for male bycatch selectivity in SCF, pS4[2]). As in 21.04, subsequent models employ lognormal likelihoods to fit fishery catch biomass data.

Assessing models fit to size composition data from comparison with mean size compositions, both models fit the survey and fishery size comps almost indistinguishably, the one exception being at the peak of the mean size composition for female bycatch in the snow crab fishery, where 21.01 exhibited a slightly sharper peak than that in 21.04 (Figures 29-31). Model estimates for annual male maturity ogives, as well as for individual growth, were also indistinguishable (Figures 32 and 33).

21.05-21.13: Attempts to deal with selectivity parameters estimated at a bound

All of the parameters estimated at a bound in Model 21.04 are related to characterizing selectivity in a survey or fishery. Potential causes for this type of behavior include biased likelihoods, unstable parameterization, and use of inappropriate selectivity functions. Models 21.05 through 21.13 were attempts to find solutions to these parameters by addressing the first two causes. These attempts were not terribly successful.

Two of the parameters at a bound in 21.04 (pS1[4] and pS2[4], Tables 16 and 17) are used to describe selectivity for females in the NMFS EBS Shelf Survey using an ascending logistic function. At the estimated values, females are only 50% selected in the NMFS survey at 69 mm CW and selectivity only increases to 95% by 169 mm CW. However, the latter is much larger than any female observed in the survey: the resulting pattern approximates a straight line. Because a straight line is determined by only two parameters, size specific catchability (i.e., selectivity *x* fully-selected catchability) for females is over-determined and these parameters are confounded with the estimate for fully-selected catchability for females in the survey. To break this confounding, Model 21.05 revised NMFS survey selectivity for females to be described by an ascending ½-normal curve—basically the left half of a normal curve until it reaches 1, above which it remains constant. The ½-normal describes a shape similar to the ascending logistic function (both are somewhat "S" shaped), but has the advantage that it actually reaches its maximum rather than simply approaching it asymptotically. The latter property means that there is no confounding between the parameters of a ½-normal selectivity function and the estimated fully-selected catchability. This curve was parameterized using the size at which female crabs were 10% selected and the difference in size at which they were 100% selected and 150 mm CW, with a lower limit of 0 (i.e., the maximum size at which females could be 100% selected was 150 mm CW).

Four of the five model parameters at a bound in 21.04 are related to determining the upper end of the selectivity curve describing the relationship between population size compositions and size compositions obtained in a survey or fishery. The bounds set on these parameters seem reasonable in terms of the observed size distributions, so it does not seem that expanding their bounds would allow these parameters to be better-estimated (attempts to do so have simply ended up with the parameter in question at the new bound). In an attempt to improve this situation, Model 21.06 incorporated so-called "tail compression" into the calculation of size composition likelihoods. Typically, size composition likelihoods are based on the multinomial distribution, which describes the probability of obtaining an observed set of observed proportions across a number of categories (size bins, for size composition data) based on an estimated set of proportions. Ideally, the proportions being fit in the multinomial are based on a large number of observations, with the rule of thumb being that the observed proportions should be based on at least 5 counts per bin. For survey and fishery size composition data, the number of observations contributing to the observed proportions in the smallest and largest bins of a size composition are frequently less than this, which can lead to spurious estimates of the true proportions. Tail compression simply aggregates observations and model estimates across bins in each tail of size composition data, essentially increasing the size of the smallest and largest bin, prior to calculating the associated likelihood. Tail compression has not been used previously in the Tanner crab model (it was implemented in the code following the previous assessment occurred). In model 21.06, tail compression was implemented by aggregating observed and model-estimated size compositions such that the observed proportion in the resulting smallest and largest bin were each at least 5%.

The sample sizes used to weight size composition data in multinomial likelihoods can be problematic in an integrated assessment because they affect the relative influence these data have on final parameter estimates (Thorson e t al., 2016). Reweighting techniques like the McAllister-Ianelli method (McAllister and Ianelli, 1997) estimate "effective sample sizes" for size composition data in an integrated assessment using an iterative approach based on estimating parameters and effective samples sizes using input sample sizes, adjusting the input sample sizes based on the effective sizes, then re-estimating parameters and effective sample sizes and continuing the iteration until the input sample sizes no longer change. In previous model explorations, reweighting size compositions in this manner was not found to be an effective approach for Tanner crab. A newer alternative is to use the Dirichlet-multinomial likelihood (Thorson et al., 2016) instead of the multinomial likelihood to determine the fits to size composition data. One advantage to the Dirichlet-multinomial likelihood is that it is self-scaling—i.e., part of its parameterization includes a parameter that determines the sample size weighting. The Dirichlet-multinomial was applied 1) to NMFS survey size composition data in 21.07, and to 2) to all size composition data (NMFS survey, BSFRF survey, retained catch, and total catch in the directed and bycatch fisheries) in 21.08. After running Model 21.08, it was found that effective sample sizes did not change from the input sample sizes for the NMFS survey size compositions, retained catch size compositions, total catch size compositions in the directed fishery and BBRKC fishery, and male bycatch size compositions in the snow crab and groundfish fisheries. Sample sizes were only being reweighted for size compositions from the BSFRF survey, female bycatch in the snow crab fishery, and female bycatch in the groundfish fisheries—the parameters affecting sample sizes for the other size composition data were estimated at their upper bounds (effectively infinity, implying no reweighting). In Model 21.09, the latter parameters were set to their upper limits and estimation was turned off, essentially returning these size compositions to multinomial likelihoods.

Several years of female bycatch size composition data from the BBRKC fishery have very small sample sizes (< 30 individuals) associated with them (1998/99, 1999/00, 2000/01, 2010/11, 2011/12, 2014/15, 2018/9, 2019/20). It was a concern that simply including these size compositions in the model fitting process, despite their very small sample sizes, introduced some instability into the estimation process. These were dropped from Model 21.10, but this had only a very small effect, at most, on the results (e.g., < 0.0001 % on OFL and current biomass).

Prior to Model 20.11, the accumulator size bin for females was the same as that for males, 180-185 mm. However, extremely few females larger than 140 mm CW have been reported in the bycatch size composition data, and none in the NMFS EBS Shelf Survey. It was hypothesized that creating an accumulator bin at a smaller size for females would possibly improve model stability. Consequently, the option to specify accumulator bins smaller than the maximum size bin in the model has been implemented. In Model 20.11 and subsequent models, the maximum size bin for females was set to 135-140 mm CW.

Model 20.12 replaced all ascending logistic selectivity functions for bycatch in the BBRKC fisheries with ascending ½-normal functions (2 sexes *x* three time periods) to try to address the issue of selectivity function parameters characterizing bycatch in the BBRKC fishery hitting bounds associated with asymptotic size. The reasoning was similar to that discussed above in regard to survey selectivity and Model 21.05.

Model 20.13 replaced the double-logistic functions used to describe dome-shaped male bycatch selectivity in the snow crab fishery with double-normal functions. A double-normal is basically, with increasing size, an ascending ½-normal, a plateau over some fully-selected size interval, and a descending ½-normal. As with the ascending ½-normal function, there is no confounding with a parameter reflecting fully-selected catchability.

Results from these models are compared in Figures 24-53. Only substantial differences are highlighted here. Models 21.12 and 21.13 exhibited substantially different time series trajectories in recruitment from the other models up to 1980, after which the temporal patterns were the same for all models and similar in mean level, except Models 21.12 and 21.13 in which mean levels were lower than for the other models (Figures 37 and 37a). Comparisons of time series for mature biomass (Figures 37 and 37a) and abundance of different population components (Figure 38) among the models were similar in nature to those for recruitment, except that the timing of pattern synchronization for 21.12 and 21.13 was delayed from ~1970 to ~1985 for mature males.

Capture selectivity curves in the directed fishery were almost identical among the models, but 21.08 exhibited retention functions that were slightly less steep than the other models up to 2013 (Figure 39). There was more diversity in estimated selectivity curves among the models for the bycatch fisheries (Figure 40). On the whole, Models 21.12 and 21.13 stood out as substantially different from the others, as well as different from one another, for certain sexes, fisheries, and time periods.

In general, fully-selected capture rates (Figure 41) followed similar trends in the directed fishery and the groundfish fisheries male bycatch for all of the models, with the exception of 21.12, which estimated an enormous spike in directed fishery capture rates in 1970 not seen in the other models. Bycatch rates for females in the groundfish fisheries were substantially different in level between Models 21.04-21.07 and Models 21.08-21.13. Models 21.12 and 21.13 exhibited substantially different levels of capture rates for male bycatch in the BBRKC fishery than the other models, but these were consistent with changes in estimated selectivity during the same period. Bycatch rates in the snow crab fishery differed in level among the models, and the relative differences changed depending on the selectivity time period. Most of the apparent complexity of these differences among models reflects changes in the associated selectivity functions and the accompanying change in what constitutes a "fully-selected" crab, which end up being offsetting in terms of estimating catch levels.

Estimates of male survey selectivity were similar among all the models (Figure 42). For female selectivity prior to 1982, the change to ½-normal in 21.05 shifted the curve by about 5 mm for sizes up to 100 mm CW while maintaining the selectivity value at 25 mm CW. The change in 21.06 left-shifted the ½-normal by 5 mm, while the change to 21.12 further shifted the curve toward even smaller sizes (both changes maintained the value at 25 mm CW). In the period after 1981, the change to ½-normal in 21.05 decreased the estimated selectivity at sizes less than 110 mm CW and increased it at larger sizes relative to 21.04. Subsequent model changes did not change the estimated selectivity until 21.12 when all remaining logistic selectivity functions were changed to ½-normals.

The estimated survey catchability functions differed both because of the changes to the associated selectivity function as well as the estimated fully-selected catchability (Figures 45). Changes in estimated fully-selected catchability for males during 1975-1981 were small among Models 21.04-21.11, but increased about 30% to ~0.32 in Models 20.12 and 20.13. The directionality of change was similar for fully-selected male catchability in 1982-2019, but the relative change was less (~0.42 to ~0.49). For female selectivity during 1975-1981, fully-selected catchability increased substantially with the change from logistic to ½-normal (because the effective size at full selection changed from 180 to 130 mm CW). Subsequent model changes reduced this difference to the point where the catchability curves for 21.04 and 21.13 are more similar to each other for females in 1975-1981 than to the intervening models. Female survey catchability during 1982-2019 exhibits a similar but somewhat larger set of changes, but with the result that catchability in 21.13 (and 21.12) is more similar to 21.04 than the other models.

Fits to NMFS survey biomass are fairly similar among all models—all fail to follow periods of elevated biomass very well (Table 15, Figure 44). Model 21.13 has the best fit to NMFS female survey biomass but 21.04 has the best fit to male survey biomass. Fits to BSFRF survey biomass are essentially identical given the observation uncertainties.

Fits to retained catch are quite similar for all models, differing by less than 1 likelihood unit among them (Figure 45). Fits to total catch in the directed fishery differ by up to 5 likelihood units, with 21.04 having the best fit and 21.11 the worst. All of the models underestimate the large male bycatch in 1990 and 1991 in the snow crab fishery and overestimate the smaller bycatch of females (Figure 46). This is a consequence of using a lognormal likelihood and assuming a fixed relative offset for female catchability relative to males: the models split the relative difference to fit males and females with relative equal errors. Similar patterns are evident in the fits to bycatch in the BBRKC fishery. The fits of models to bycatch in the groundfish fisheries differ by 5 likelihood units depending whether or not the Dirichlet-multinomial is used to fit the groundfish size compositions. Models that use this likelihood fit the catch biomass better.

Comparison with mean survey size compositions (Figure 47) appear to show models that incorporate tail compression fit poorly in the tails, but the figure is misleading because the observed mean size compositions are not plotted for the tail compressed data. The models that incorporate tail compression fit the tail-compressed size compositions as well as 21.04 and 21.05 fit the non-compressed data. Similar observations hold for retained catch and total catch size compositions in the directed and bycatch fisheries (Figures 48-50).

Finally, differences among the models with regard to fits to the maturity ogive and the growth data were quite small (Figures 51-52).

Incorporating NMFS catchability estimated outside the assessment model

Estimates of annual NMFS EBS Shelf Survey catchability for 1982-2019 were derived from a catch ratio analysis based on BSFRF side-by-side haul studies conducted from 2103-2017. The catch ratio analysis is described in detail in a separate report. It used generalized additive models to estimate smooth functions of crab size and bottom depth, bottom temperature, mean sediment grain size, and the sediment sorting coefficient as haul-specific environmental covariates that characterized haul-level catchability. Haul-specific mean grain size and sorting coefficient were interpolated to haul locations based on a kriging analysis of sediment data from the EBS The smoothed relationships were then applied retroactively on a haul-by-haul basis to estimate annual survey catchability from 1982 to 2019 outside the assessment model (Figure 53). The externally-estimated catchability curves essentially allow the NMFS survey data to be converted from relative to absolute estimates of size-specific population abundance, which should improve performance in the assessment model if the curves are unbiased and have reasonable precision (although what "reasonable" means in this context is undetermined).

Likelihood profiling on male growth

The mean growth curve (post-molt size as a function of pre-molt size) for males in the assessment model overestimates molt increment size for large crab, although the model includes 100 observations of molt increment for males (Figure 54) which are easily fit when analyzed outside the assessment model. This lack of fit to a robust dataset indicates that other data sources must be in conflict with the growth data. Mean growth in the model for males is parameterized by the post-molt sizes for small and large pre-molt crab (25 and 125 mm CW, respectively). In order to better characterize model performance, the model likelihood was profiled across a range of values (130 mm to 180 mm) for the parameter, pGrB[1], which determines mean post-molt size for large crab (125 mm pre-molt size). As pGrB[1] increases across this range, the male molt increment at all pre-molt sizes also increases, so increasing pGrB[1] is associated with increased male growth rates (all else remaining the same; Figure 55).

Figure 56 illustrates why Model 21.01 converged to the estimated mean post-molt size of 166.6 mm CW for pGrB[1], which is about 12 mm larger than the estimate made fitting the growth data outside the model, 154.5 mm CW. The best fit to the male growth data is indeed achieved at the latter value (Figure 57), but other components to the objective function conflict with this. The fit to the male maturity data is one component in conflict with the growth data (Figure 58): its contribution to the objective function declined by over 50 likelihood units across values for pGrB[1] from 154 mm to 167 mm. As pGrB[1] increased, the curves for the male probability of molt to maturity right-shifted toward larger sizes, resulting in a decreased chance of a male crab undergoing the molt to maturity at a given pre-molt size (Figure 58). If, in the model optimization, the probability of molt to maturity were independent of pGrB[1], male crab would reach maturity more quickly as the estimate for pGrB[1] increased. Instead, the molt-to-maturity probability curve changes to offset the effects of the increased growth rate, indicating that growth and the probability of molt to maturity are confounded for males in the model. The probability of molt to maturity cannot be estimated outside the model. It thus seems practical to estimate growth outside the model, fix it inside the model, and eliminate the confounding with estimating the probability of molt to maturity.

21.14 and 21.15

Models 21.14 and 21.15 use annual, externally-derived estimates of sex-specific catchability for NMFS EBS Shelf Survey in the 1982+ time period. Both models drop fitting the BSFRF SBS data inside the assessment model as redundant. To eliminate the indeterminacy between growth and terminal molt dynamics, Model 21.15 uses externally-estimated mean growth relationships (Figure 59) to fix male growth in the model while still estimating a size-specific curve for the probability of an immature male undergoing the terminal molt to maturity. Results from both models are compared together with 21.13 in Figures 60-79.

The number of parameters at bounds decreased from nine in 21.13 to seven in 21.14 and then increased by one to eight in 21.15 (Table 18). In 20.13, all parameters at bounds were directly related to selectivity. In 21.14 and 21.15, non-selectivity parameters related to the size distribution at recruitment (pRb[1]) and the ln-scale capture rate offset for female bycatch in the groundfish fisheries (pDC2[3]) were estimated at one of their bounds. The latter parameter was almost, but not quite, at its lower bound in 21.13.

Model-estimated mean growth, probability of molt to maturity, and rates of natural mortality are compared among the models in Figure 60. Of course, the mean growth curve in 21.15 was not estimated but, rather, fixed to values determined outside the assessment model. The three models exhibit little difference in the female growth curve, while the male growth curves diverge with increasing pre-molt size; growth is fastest in 21.14 and slowest in 21.15. The probability of the molt to maturity for females is shifted towards larger sizes by ~ 5 mm starting at 75 mm CW in 21.14 and 21.15 as compared to 21.13; thus, females mature more quickly in 21.13. The situation for males is quite different, with males in 21.14 maturing with slightly higher probabilities than in 21.13, but with much reduced probability in 21.15 (consistent with results from the likelihood profiling). Rates of natural mortality (M) are also somewhat different among the models, with 21.14 estimated the highest M's during the "normal period" of the three models for immature crab and mature males while 21.13 estimated the highest M for mature females.

The consequences of the differences in these processes on cohort growth for females and males is illustrated in Figures 61 and 62, respectively. The smaller immature M in 21.13 translates into a larger relative number of crab surviving to age 8 for both males and females. The differences in mean growth and probability of maturing give rise to different progressions among the three models, but the final (age 8) distributions are only slightly different (once scale is taken into account).

The scale of recruitment is quite a bit larger for models 21.14 and 21.15 compared with 21.13 but the temporal patterns are similar (but not identical; Figure 63). Despite this difference in the scale of recruitment, the trajectories of mature male biomass converge in about 1985 (and earlier in 1980 for mature male abundance) and remain very similar (Figures 63, 63a, and 64)—in fact, the mature male biomass trajectories for 21.13 and 21.14 are almost identical after 2000, which is not the case for mature female biomass (Figure 63a).

Selectivity and retention functions in the directed fishery are almost the same for the three models (Figure 65). Relatively small differences are evident in a few of the bycatch selectivity functions (e.g., for female bycatch in the snow crab in 2005-2019) but the largest differences among the models were for male bycatch in the groundfish fisheries during 1987-1996 (Figure 66). The size at 50% selected in 21.15 was almost 50 mm larger in than that in 21.13.

Capture rates for fully-selected crab in the directed and bycatch fisheries exhibit the same temporal patterns in all three models, but the scale varies with the size corresponding to full selectivity (Figure 67). The major difference that stands out among the three models is the 3-year spike in directed fishery capture rates for males during 1969-71 in Model 21.14. This spike is also reflected in the model-estimated total catch biomass values for 1969-71 (Figure 68); it soars to 300000 t in 1970 in Model 21.14. Although this spike is certainly inconsistent with the other models, it is also inconsistent with the estimated retained catch—where no sign of it can be seen and the three models are in good agreement from 1965 on. Model-estimated bycatch biomass is generally very similar among the three models during the time periods when catch data constrains the model but differs quite a bit before 1990 when catch is assumed to be proportional to effort.

Estimated survey selectivity functions prior to 1982 are identical across the models for males and only slightly higher for Model 21.13 compared with the others for females (Figure 70). The corresponding catchability functions indicate that fixing growth (21.15) had a fairly large effect on male catchability during this time period, but a smaller effect on female catchability (Figure 71). The annual estimates of catchability determined outside the assessment model indicate that dome-shaped selectivity functions may be more appropriate to describe NMFS survey selectivity parametrically than asymptotic ones like the logistic or ½-normal.

Fits to NMF EBS Shelf Survey biomass time series are compared in Figure 72. Models 21.14 and 21.15 fit the data for males better than 21.13 during the period of decline and increase from1988 to 2008, but worse during the early 1980's period of decline and initial recovery, as well as the low values in 2009-2012. In terms of likelihoods, 21.13 and 21.14 fit the time series equally well, but 70 units better than 21.15. All three models generally predict similar biomass trajectories, by maturity state, for females. None of the three models fit the trajectories for immature and mature female biomass well when survey biomass was relatively high (1987-91, 2005-06, 2011-12 for immature females; 1980-82 and 1990-92 for mature females). In terms of likelihoods, 21.13 fits the data 30 units better than 21.14 and 50 units better than 21.15. Note that 21.14 and 21.15 do not include the BSFRF survey data in their optimizations so the poor "fits" in Figure 72 are not surprising.

All three models fit the retained catch biomass very well; 21.13 had the best fit by 6 likelihood units over the worst (21.15; Table 15, Figure 73). The three models fit total catch biomass for males rather equally well, with 21.15 providing a slightly better fit by 5 likelihood units. However, 21.15 fit the directed fishery female catch biomass more poorly than the other two models by 13 likelihood units over the best (21.13). The three models fit the bycatch biomass data in the snow crab, BBRKC and groundfish fisheries rather equally well, with differences in likelihood among the model's for each fishery less than 4 likelihood units.

Comparison with mean size compositions from the NMFS EBS Shelf Survey suggest that Model 21.13 fit the male and immature female size compositions better at small crab sizes than the other models (Figure 75), which is born out by the associated likelihood values (21.13 has lower likelihood for these components by over 100 likelihood units; Table 15). Comparison with mean size compositions from retained catch data indicate the three models fit these data equally well (there is less than 3 likelihood units difference among the models), while Model 21.15 fits the total catch size compositions from the directed fishery only slightly better than the other models (by 4 likelihood units). The three models also fit the mean bycatch size compositions similarly for the snow crab and BBRKC fisheries, with differences in likelihood less than 6 likelihood units. However, 21.13 fits the bycatch size compositions from the groundfish fisheries much better than the other two models (differences are over 100 likelihood units); Table 15).

Fixing growth in Model 21.15 resulted in a very poor fit to the maturity ogive data (Figure 78), which suggests that either the assessment model has little flexibility to fit the maturity ogive data or the maturity data is in conflict with one of the other datasets in the model. Since the model describes the probability of terminal molt using a nonparametric approach which should allow substantial flexibility, a lack of flexibility seems unlikely.

Discussion

Adopting the VAST NMFS survey biomass time series to fit in the model is premature at this point. The potential disconnect between the VAST model-based survey biomass time series and the design-based survey size compositions remains a point of concern for a model that has enough warts as it is. It makes sense to combine VAST biomass estimates with VAST size composition estimates. In addition, it is unclear how in the assessment model to combine the VAST estimates with BSFRF survey biomass estimates that are absolute estimates of Tanner crab population size, but within a geographic area that varied annually and sampled differentially sampled different elements of the stock each year as a consequence (e.g., immature females vs. mature males). Certainly combining the survey catchability curves estimated outside the assessment model from the catch ratio analysis with the VAST suvey biomass estimates within the assessment model seems problematic.

With regard to the likelihood assumed for fishery catch biomass data, it makes practical sense to adopt the lognormal likelihood, as was done in all models subsequent to 21.01 here. If nothing else, it aligns the assessment model with those for other crab stocks. It also, though, makes sense from a statistical point-of-view in that the estimates of total catch and bycatch from observer data are scaled from observed to unobserved catch using a multiplicative framework, so that even constant levels of uncertainty at the observer level are scaled by multiplying by the ratio of total to observed effort.

Although none of the attempted solutions to eliminate parameters estimated at bounds were successful, the methods applied seem useful to continue to use: 1) tail compression, 2) fixing an accumulator bin for females less than that for males, 3) dropping size compositions with very small sample sizes (i.e., < 30), and 4) replacing logistic-based selectivity functions with normal-based ones. The first three make sense from a statistical point-of-view and should improve model stability. The final one makes sense from a practical sense of dealing with continued selectivity parameters-at-bounds issues: the final solution may be to fix parameters at a bound because it makes no sense to try to increase the bound. For example, if selectivity in a fishery or survey is thought to be asymptotic with size, it makes sense to set the upper bound on what should be considered a "fully selected" size to less than the largest size observed. Allowing it flexibility to be larger increases the confounding with the associated "fully-selected" quantity (i.e., catchability or capture rate). In particular, it seems prudent to fix parameters that are hitting bounds larger than expected Tanner crab sizes in the selectivity functions defined for bycatch in the BBRKC fishery. It also makes sense to re-visit the assumptions of asymptotic-ness in the fisheries and surveys.

The Dirichlet-multinomial likelihood should be implemented as a substitute for all multinomial size composition likelihoods. It has the advantage that it estimates the sample size scaling intrinsically within the optimization process when fitting size composition data, but it essentially reverts to the multinomial if the scaling parameter is fixed to a large value.

The growth data available to use in the assessment model provides a direct and unambiguous characterization of growth when analyzed outside the model. Prior to 2015, molt increment data was not available for Tanner crab from the Bering Sea, so growth needed to be estimated within the assessment model with information coming indirectly from fitting size composition data. This need no longer be the case, and the parameters reflecting growth can reasonably be fixed to the values determined by the external analysis, not withstanding the poor fit this currently engenders with respect to the maturity ogive data. The source of inflexibility or conflict with fitting the maturity ogive data must be addressed. It may be that this component is simply underweighted in the likelihood, but previous experiments with adjusting its weight indicated that the model's ability to converge was sensitive to increasing the weight.

Using annual survey catchability curves for 1982-2019 estimated from the catch ratio analysis of the BSFRF/NMFS side-by-side haul data seems a bit premature at this point. The large variability in the curves at large crab size in some years seems unrealistic and more an issue with extrapolating beyond the analysis, so there needs to be a way to de-weight the effects of potentially spurious estimates. A possible way forward may be to use these annual curves (and possibly the associated uncertainty from the catch ratio analysis) to define a prior (or set of priors) to constrain non-parametric estimates for survey catchability within the assessment model.

Proposed models for the September 2021 Assessment

Models with a combination of at least some of the following properties should be included for the September assessment:

- lognormal likelihoods for fishery catch biomass estimates
- Dirichlet multinomial likelihoods for size composition data
- tail compression
- max size bin for females (an accumulator bin)
- normal-based selectivity functions

The following models are proposed to be evaluated for the September 2021 assessment:

- 20.07, with updated data for 2020/21.
- 21.20: 21.13 + fixed growth
- 21.21: 21.20 + estimated nonparametric catchability functions for NMFS survey data with the catch ratio analysis used to define an appropriate prior.

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Tables

Table 1. Parameters in the 2020 assessment model (20.07) which were estimated at either its upper or lower bound.

process	name	lower bound	upper bound	estimate	which bound?	description
growth	pGrBeta[1]	0.5	1	1.0000	at upper bound	scale parameter for growth gamma distributions
selectivity	pS1[4]	-50	69	69.0000	at upper bound	size at 50% selectivity for females in the NMFS survey
selectivity	pS1[23]	95	180	180.0000	at upper bound	size at 95% selected for males (1997-2004) by the RKF
selectivity	pS1[24]	95	180	180.0000	at upper bound	size at 95% selected for males (2005+) by the RKF
selectivity	pS1[27]	100	140	140.0000	at upper bound	size at 95% selected for females (2005+) by the RKF
selectivity	pS2[4]	0	100	100.0000	at upper bound	size difference between 50% and 95% selected females in the NMFS survey (1982+)
selectivity	pS2[10]	0.1	0.5	0.1000	at lower bound	ascending slope for SCF selectivity (males, pre-1997)
selectivity	pS4[1]	0.1	0.5	0.1000	at lower bound	descending slope for SCF selectivity (males, pre-1997)
fisheries	pLgtRet[1]	0	15	14.9989	at upper bound	TCF: logit-scale max retention (pre-1997)
surveys	pQ[1]	0.5	1.001	0.5000	at lower bound	ln-scale fully-serlected catchability, NMFS trawl survey: males, 1975-1981
surveys	pQ[3]	0.5	1.001	0.5000	at lower bound	ln-scale fully-serlected catchability, NMFS trawl survey: females, 1975-1981

Table 2. Model configurations evaluated for this report. Note: there is no Model 21.02.

model configuration	parent	additions	subtractions	label	number of parameters	number at bounds	objective function value	max gradient
20.07	--	--	--	2020 assessment model	349	11	3429.39	2.31E-04
21.00	20.07	NMFS VAST survey biomass estimates	NMFS design-based survey biomass estimates	VAST	349	12	4439.15	9.07E-05
21.00a	21.00	additional variance estimated for NMFS surveys		VAST+ExtraCVs	353	13	2964.76	4.98E-04
21.01	20.07	expanded limits on q's, fixed logit-scale retention parameters at upper limits		ExpandedQ's	346	7	3389.46	3.66E-04
21.03	20.07	lognormal fishery catch biomass likelihoods	"norm2" fishery catch biomass likelihoods	Lognormal	349	20	-1992.57	2.45E-03
21.04	21.02 + 21.03	lognormal fishery catch biomass likelihoods + SCF, RKF devs start in 1990	"norm2" fishery catch biomass likelihoods	Lognormal+ExpandedQ's	350	5	3165.74	1.08E-03
21.05	21.04	1/2-normal (ascnormal3) for NMFS female selectivity			350	5	3187.26	5.02E-04
21.06	21.05	tail compression in all size comp likelihoods		TailCompression	350	7	3049.36	3.86E-03
21.07	21.06	Switched to Dirichlet Multinomial likelihood for NMFS survey size comps	Dropped multinomial likelihoods for NMFS survey size comps	SurveyDMs	352	9	5600.78	2.10E-03
21.08	21.07	Switched to Dirichlet Multinomial likelihood for ALL size comps	Dropped multinomial likelihoods for size comp data	AllDMs	363	19	10204.84	1.89E-03
21.09	21.08	returned to multinomial likelihoods for NMFS survey and TCF, RKF, and GF fisheries		SomeDMs	355	8	6639.69	2.46E-02
21.10	21.09	Removed size comps with small sample sizes from likelihoods		NoSmallSSs	355	8	6639.44	2.53E-02
21.11	21.10	Imposed size limits on female growth		SizeLimits	355	8	6633.71	2.26E-02
21.12	21.11	1/2- normal (ascnormal) selectivity functions estimated for all RKF time periods	Ascending logistic selectivity functions for all RKF time periods	AscNrmRKF	355	9	6086.02	2.81E-02
21.13	21.12	Double normal selectivity functions estimated for male bycatch in SCF	double logistic selectivity functions	DblNrmSCF	355	9	6089.24	1.18E-02
21.14	21.13	Annual 1982+ NMFS survey catchability determined outside model, no fits to BSFSF data	2 catchability, 4 selectivity parameters	FixedSurveySels	343 (??)	7	6078.26	7.97E-02
21.15	21.14	mean growth parameters determined outside model	4 growth parameters	FixedSurveySels+FixedGrowth	339	7	6349.95	1.71E-02

Table 3. Model convergence information and sample results from OFL calculations for each model.

case	average recruitment (millions)	B100 (1000's t)	Bmsy (1000's t)	current year MMB (1000's t)	Fmsy	MSY (1000's t)	Fofl	OFL (1000's t)	projected MMB (1000's t)
20.07	374.43	105.05	36.77	66.87	0.98	16.94	0.94	21.13	35.33
21.00	311.56	76.77	26.87	56.00	1.30	14.47	1.27	19.59	26.36
21.00a	477.66	134.75	47.16	63.02	1.37	19.21	1.00	18.80	35.67
21.01	436.93	116.66	40.83	74.58	1.13	18.77	1.07	24.35	38.61
21.03	344.78	73.37	25.68	47.94	2.88	14.26	2.57	15.72	23.19
21.04	424.93	115.23	40.33	73.90	1.12	18.39	1.06	24.11	38.40
21.05	497.90	120.06	42.02	76.45	1.12	19.05	1.05	24.94	39.76
21.06	477.22	114.82	40.19	74.30	1.08	18.27	1.03	24.29	38.59
21.07	475.67	114.96	40.24	74.73	1.07	18.27	1.02	24.47	38.78
21.08	470.22	121.35	42.47	81.65	0.98	18.80	0.98	26.66	42.75
21.09	455.33	117.07	40.97	78.69	0.98	18.18	0.98	25.65	41.26
21.10	455.33	117.07	40.97	78.69	0.98	18.18	0.98	25.65	41.26
21.11	462.11	116.35	40.72	78.28	1.00	18.11	1.00	25.57	41.00
21.12	355.36	107.92	37.77	74.14	0.94	16.76	0.94	23.72	39.30
21.13	359.13	107.91	37.77	74.12	0.95	16.85	0.95	23.80	39.15
21.14	1439.75	126.13	44.14	74.86	1.15	23.22	0.96	23.58	37.62
21.15	1409.54	124.67	43.63	72.21	1.20	20.70	0.99	23.87	36.80

Table 4. Data coverage in the assessment model (color shading highlights different model time periods and data components, x's denote new data in 2020).

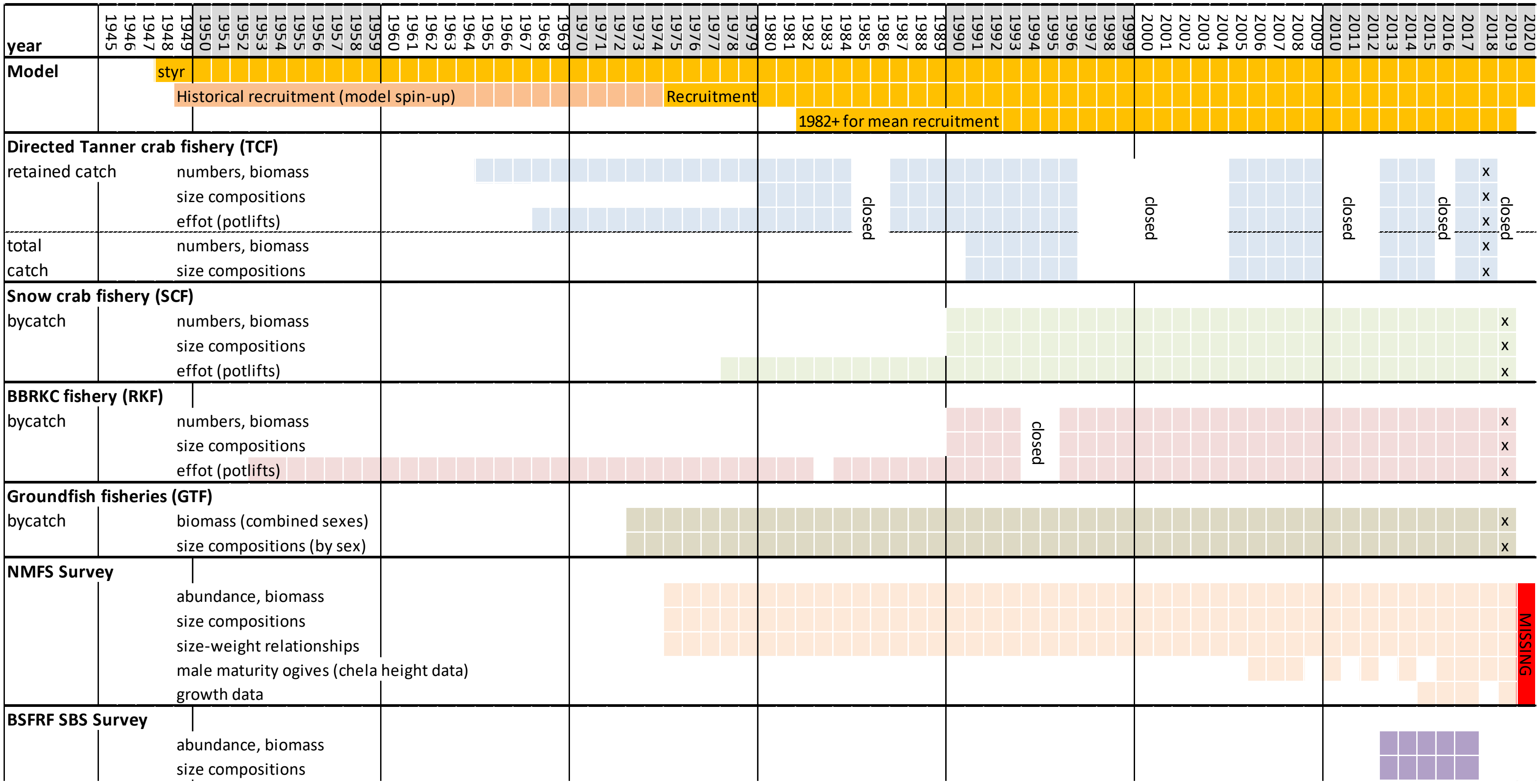


Table 5. Population-related processes included in the 2020 assessment model (20.07).

process	time blocks	description
Population rates and quantities		
Population built from annual recruitment		
Recruitment	1949-1974	ln-scale mean + annual devs constrained as AR1 process
	1975+	ln-scale mean + annual devs
Growth	1949+	sex-specific
		mean post-molt size: power function of pre-molt size
		post-molt size: gamma distribution conditioned on pre-molt size
Maturity	1949+	sex-specific
		size-specific probability of terminal molt
		logit-scale parameterization
Natural mortalty	1949-1979,	estimated sex/maturity state-specific multipliers on base rate
	1985+	priors on multipliers based on uncertainty in max age
	1980-1984	estimated "enhanced mortality" period multipliers

Table 6. Surveys and survey-related processes included in the 2020 assessment model (20.07).

process	time blocks	description
Surveys		
NMFS EBS trawl survey		
male survey q	1975-1981	ln-scale
	1982+	ln-scale w/ prior based on Somerton's underbag experiment
female survey q	1975-1981	ln-scale
	1982+	ln-scale w/ prior based on Somerton's underbag experiment
male selectivity	1975-1981	ascending logistic
	1982+	ascending logistic
female selectivity	1975-1981	ascending logistic
	1982+	ascending logistic
BSFRF SBS trawl surveys		
male catchability	2016-2017	fixed at 1 for all sizes
male availability	2016-2017	empirically-determined outside the model
female catchability	2016-2017	fixed at 1 for all sizes
female availability	2016-2017	empirically-determined outside the model

Table 7. Fisheries and fishery-related processes included in the 2020 assessment model (20.07).

Fishery/process	time blocks	description
TCF	directed Tanner crab fishery	
capture rates	pre-1965	male nominal rate
	1965+	male ln-scale mean + annual devs
	1949+	ln-scale female offset
male selectivity	1949-1990	ascending logistic
	1991-1996	annually-varying ascending logistic
	2005+	annually-varying ascending logistic
female selectivity	1949+	ascending logistic
male retention	1949-1990, 1991-1996, 2005-2009, 2013-2015, 2017	ascending logistic
SCF	bycatch in snow crab fishery	
capture rates	pre-1978	nominal rate on males
	1979-1991	extrapolated from effort
	1992+	male ln-scale mean + annual devs
	1949+	ln-scale female offset
male selectivity	1949-1996	dome-shaped
	1997-2004	dome-shaped
	2005+	dome-shaped
female selectivity	1949-1996	ascending logistic
	1997-2004	ascending logistic
	2005+	ascending logistic
RKF	bycatch in BBRKC fishery	
capture rates	pre-1952	nominal rate on males
	1953-1991	extrapolated from effort
	1992+	male ln-scale mean + annual devs
	1949+	ln-scale female offset
male selectivity	1949-1996	ascending logistic
	1997-2004	ascending logistic
	2005+	ascending logistic
female selectivity	1949-1996	ascending logistic
	1997-2004	ascending logistic
	2005+	ascending logistic
GTF	bycatch in groundfish fisheries	
capture rates	pre-1973	male ln-scale mean from 1973+
	1973+	male ln-scale mean + annual devs
	1973+	ln-scale female offset
male selectivity	1949-1986	ascending logistic
	1987-1996	ascending logistic
	1997+	ascending logistic
female selectivity	1949-1986	ascending logistic
	1987-1996	ascending logistic
	1997+	ascending logistic

Table 8. Likelihood components in the 2020 assessment model (20.07).

Model	Component	Type	included in optimization	Distribution	Likelihood
20.07	TCF: retained catch	biomass	yes	norm2	males only
		size comp.s	yes	multinomial	males only
	TCF: total catch	biomass	yes	norm2	by sex
		size comp.s	yes	multinomial	by sex
	SCF: total catch	biomass	yes	norm2	by sex
		size comp.s	yes	multinomial	by sex
	RKF: total catch	biomass	yes	norm2	by sex
		size comp.s	yes	multinomial	by sex
	GF All: total catch	abundance	yes	norm2	by sex
		biomass	yes	norm2	by sex
		size comp.s	yes	multinomial	by sex
	NMFS "M" survey (males only, no maturity)	biomass	yes	lognormal	all males
		size comp.s	yes	multinomial	all males
	NMFS "F" survey (females only, w/ maturity)	biomass	yes	lognormal	by maturity classification
		size comp.s	yes	multinomial	by maturity classification
	BSFRF "M" survey (males only, no maturity)	biomass	yes	lognormal	all males
		size comp.s	yes	multinomial	all males
	BSFRF "F" survey (females only, w/ maturity)	biomass	yes	lognormal	by maturity classification
		size comp.s	yes	multinomial	by maturity classification
	growth data	EBS only	yes	gamma	by sex
	male maturity ogive data	EBS only	yes	binomial	males only

Table 9. Comparison of design-based vs. VAST-based Tanner crab biomass estimates from the NMFS EBS Shelf Survey.

survey year	Design-Based		VAST		%	% cv
	biomass	cv	biomass	cv	difference	reduction
1975	31.42	0.20	41.22	0.12	-27	60
1976	157.02	0.138	196.11	0.089	-22	64
1977	138.50	0.121	178.35	0.084	-25	69
1978	98.30	0.118	117.46	0.078	-18	66
1979	50.04	0.138	54.65	0.076	-9	55
1980	152.48	0.155	155.26	0.076	-2	49
1981	79.92	0.128	84.86	0.074	-6	57
1982	65.85	0.143	71.51	0.068	-8	48
1983	37.98	0.148	37.11	0.066	2	44
1984	30.50	0.128	30.47	0.066	0	52
1985	14.90	0.135	15.09	0.078	-1	58
1986	21.59	0.221	17.16	0.064	23	29
1987	45.50	0.137	45.86	0.070	-1	51
1988	99.21	0.208	88.37	0.079	12	38
1989	132.80	0.121	129.02	0.068	3	56
1990	132.42	0.126	142.55	0.068	-7	54
1991	145.79	0.172	145.86	0.065	0	38
1992	127.58	0.230	111.11	0.074	14	32
1993	73.27	0.142	76.17	0.068	-4	48
1994	48.33	0.119	52.82	0.066	-9	55
1995	34.98	0.165	33.49	0.071	4	43
1996	30.76	0.211	28.25	0.078	9	37
1997	14.63	0.110	16.17	0.069	-10	63
1998	15.00	0.099	16.68	0.064	-11	65
1999	21.53	0.255	20.66	0.082	4	32
2000	23.33	0.197	24.41	0.089	-5	45
2001	29.25	0.130	31.52	0.070	-7	54
2002	27.41	0.130	30.83	0.075	-12	58
2003	37.80	0.127	41.93	0.073	-10	57
2004	38.87	0.138	41.05	0.068	-5	49
2005	63.74	0.116	66.42	0.062	-4	53
2006	101.53	0.152	104.35	0.071	-3	47
2007	104.18	0.181	99.74	0.068	4	37
2008	84.90	0.249	77.50	0.067	9	27
2009	47.41	0.137	50.49	0.069	-6	50
2010	49.00	0.166	51.06	0.072	-4	43
2011	62.66	0.170	61.82	0.068	1	40
2012	80.11	0.170	72.79	0.067	10	39
2013	103.37	0.211	88.43	0.073	16	35
2014	108.91	0.099	115.49	0.062	-6	63
2015	74.23	0.090	78.67	0.056	-6	61
2016	69.62	0.094	75.88	0.059	-9	63
2017	54.20	0.109	59.16	0.062	-9	57
2018	47.08	0.095	52.05	0.061	-10	64
2019	28.67	0.116	30.70	0.058	-7	50

Table 10. Comparison of design-based vs. VAST-based immature female Tanner crab biomass estimates from the NMFS EBS Shelf Survey.

survey year	Design-Based biomass	cv	VAST biomass	cv	% difference	% cv reduction
1975	31.42	0.20	41.22	0.12	-27	60
1976	6.37	0.253	6.00	0.094	6	37
1977	14.47	0.596	8.43	0.128	53	22
1978	6.81	0.243	7.85	0.111	-14	46
1979	3.83	0.223	4.18	0.104	-9	47
1980	13.51	0.229	15.76	0.118	-15	52
1981	1.52	0.210	1.46	0.102	4	49
1982	1.71	0.270	1.55	0.120	10	44
1983	2.27	0.237	2.26	0.089	0	37
1984	2.23	0.212	2.05	0.081	9	38
1985	0.99	0.178	0.97	0.075	3	42
1986	2.69	0.170	2.64	0.076	2	44
1987	14.99	0.291	12.63	0.101	17	35
1988	10.17	0.173	9.57	0.077	6	44
1989	11.81	0.190	10.37	0.078	13	41
1990	9.86	0.187	9.11	0.075	8	40
1991	7.01	0.171	6.69	0.072	5	42
1992	1.98	0.169	2.10	0.081	-6	48
1993	1.06	0.186	1.11	0.091	-4	49
1994	1.20	0.325	1.03	0.107	15	33
1995	1.05	0.155	1.13	0.083	-7	54
1996	1.43	0.208	1.44	0.086	-1	41
1997	1.39	0.266	1.32	0.089	5	34
1998	1.96	0.191	1.95	0.076	0	40
1999	2.85	0.195	3.08	0.077	-8	39
2000	2.47	0.153	2.57	0.073	-4	48
2001	6.27	0.206	6.21	0.077	1	37
2002	5.49	0.164	5.97	0.079	-8	48
2003	4.66	0.240	4.34	0.078	7	33
2004	4.08	0.147	4.14	0.065	-2	45
2005	10.37	0.196	10.06	0.089	3	45
2006	13.24	0.225	12.15	0.081	9	36
2007	5.58	0.229	5.23	0.081	7	36
2008	2.84	0.208	2.66	0.082	6	40
2009	2.54	0.272	2.54	0.090	0	33
2010	3.77	0.163	3.57	0.066	6	40
2011	10.34	0.190	8.99	0.070	14	37
2012	11.65	0.240	10.08	0.088	14	37
2013	6.37	0.181	5.97	0.068	7	38
2014	2.45	0.207	2.36	0.068	4	33
2015	1.65	0.172	1.78	0.086	-8	50
2016	1.12	0.215	1.12	0.099	0	46
2017	1.38	0.185	1.65	0.101	-18	55
2018	5.02	0.171	5.00	0.074	0	43
2019	4.92	0.164	4.90	0.067	0	41

Table 11. Comparison of design-based vs. VAST-based mature female Tanner crab biomass estimates from the NMFS EBS Shelf Survey.

survey year	Design-Based		VAST		%	% cv
	biomass	cv	biomass	cv	difference	reduction
1975	31.42	0.20	41.22	0.12	-27	60
1976	31.16	0.193	32.00	0.076	-3	39
1977	38.57	0.309	37.09	0.095	4	31
1978	25.75	0.227	25.74	0.102	0	45
1979	19.32	0.298	16.26	0.111	17	37
1980	63.78	0.276	47.68	0.090	29	33
1981	42.58	0.252	37.24	0.109	13	43
1982	64.14	0.258	55.95	0.112	14	43
1983	20.43	0.183	20.22	0.081	1	44
1984	14.91	0.224	13.23	0.088	12	39
1985	5.55	0.263	5.07	0.093	9	35
1986	3.37	0.197	3.48	0.075	-3	38
1987	5.14	0.164	5.65	0.076	-9	47
1988	25.37	0.233	22.89	0.076	10	33
1989	19.40	0.151	20.53	0.063	-6	42
1990	37.69	0.267	32.09	0.070	16	26
1991	44.76	0.219	37.54	0.073	18	33
1992	26.23	0.164	25.76	0.065	2	40
1993	11.64	0.144	12.76	0.067	-9	46
1994	9.85	0.206	10.02	0.073	-2	36
1995	12.40	0.219	10.96	0.078	12	36
1996	9.58	0.280	8.14	0.082	16	29
1997	3.40	0.185	3.68	0.077	-8	42
1998	2.28	0.158	2.61	0.082	-14	52
1999	3.83	0.216	4.12	0.078	-7	36
2000	4.13	0.282	3.95	0.089	5	32
2001	4.56	0.225	4.76	0.087	-4	39
2002	4.47	0.202	4.84	0.090	-8	45
2003	8.40	0.191	9.08	0.080	-8	42
2004	4.73	0.173	5.07	0.074	-7	43
2005	11.58	0.188	10.26	0.077	12	41
2006	14.94	0.172	14.71	0.070	2	41
2007	13.44	0.188	14.10	0.075	-5	40
2008	11.66	0.182	11.99	0.082	-3	45
2009	8.48	0.206	8.08	0.079	5	38
2010	5.47	0.219	5.49	0.087	0	40
2011	5.41	0.144	5.80	0.065	-7	45
2012	12.36	0.224	10.63	0.066	15	29
2013	17.85	0.215	15.70	0.074	13	34
2014	14.86	0.286	12.08	0.071	21	25
2015	11.21	0.250	9.67	0.081	15	32
2016	7.63	0.256	6.94	0.082	9	32
2017	7.11	0.230	6.83	0.095	4	41
2018	4.97	0.203	5.11	0.085	-3	42
2019	4.85	0.218	4.84	0.082	0	38

Table 12. Objective function values (negative log-likelihoods) for various data components by model case. The likelihoods for the biomass components are not comparable among the three models.

Data source	'20.07	'21.00	21.00a
fisheries data			
GF All			
total catch			
biomass	32.03	14.75	40.06
n.at.z	538.82	648.19	531.85
RKF			
total catch			
biomass	25.86	40.80	11.79
n.at.z	73.55	71.45	51.56
SCF			
total catch			
biomass	18.36	4.27	29.64
n.at.z	134.22	159.45	137.88
TCF			
retained catch			
biomass	8.13	8.51	7.31
n.at.z	55.13	55.77	36.43
total catch			
biomass	12.97	11.58	13.04
n.at.z	103.07	107.80	75.78
growth data			
(blank)			
(blank)			
EBS_molt_increment_data	549.26	592.72	485.02
maturity ogive data			
NMFS_M			
(blank)			
EBS_male_maturity_ogives	107.27	97.85	104.91
surveys data			
NMFS F			
index catch			
biomass	139.92	467.05	42.73
n.at.z	330.88	432.46	308.88
NMFS M			
index catch			
biomass	65.33	115.14	38.39
n.at.z	411.35	568.86	366.97
SBS BSFRF females			
index catch			
biomass	-6.64	-4.25	-5.19
n.at.z	146.29	198.33	145.13
SBS BSFRF males			
index catch			
biomass	-1.02	0.94	-3.20
n.at.z	153.24	205.17	137.44

Table 13. Parameters estimated at an upper or lower bound for Models 20.07 and 21.00. "-1" indicates parameter at the lower bound, "1" indicates parameter at upper bound, "—" indicates parameter not at bound, "zXX" indicates crab size at which XX% are selected.

process	name	20.07	21.00	description
fisheries	pLgtRet[1]	1	1	TCF: logit-scale max retention (pre-1997)
growth	pGrBeta[1]	1	1	gamma distribution scale parameter for both sexes
selectivity	pS1[19]	--	-1	z50 for GF.AllGear selectivity (males, pre-1987)
	pS1[23]	1	1	z95 for RKF selectivity (males, 1997-2004)
	pS1[24]	1	1	z95 for RKF selectivity (males, 2005+)
	pS1[27]	1	--	z95 for RKF selectivity (females, 2005+)
	pS1[4]	1	--	z50 for NMFS survey selectivity (females, 1982+)
	pS2[1]	--	1	z95-z50 for NMFS survey selectivity (males, pre-1982)
	pS2[10]	-1	-1	ascending slope for SCF selectivity (males, pre-1997)
	pS2[2]	--	1	z95-z50 for NMFS survey selectivity (males, 1982+)
	pS2[4]	1	-1	z95-z50 for NMFS survey selectivity (females, 1982+)
	pS4[1]	-1	-1	descending slope for SCF selectivity (males, pre-1997)
surveys	pQ[1]	-1	-1	NMFS trawl survey: males, 1975-1981
	pQ[3]	-1	-1	NMFS trawl survey: females, 1975-1981

Table 14. Values for parameters estimated at an upper or lower bound in Model 20.07 or 21.01. "zXX" indicates crab size at which XX% are selected. See previous table for information on bounds.

process	name	20.07	21.01	description
fisheries	pLgtRet[1]	15	14.9	TCF: logit-scale max retention (pre-1997)
growth	pGrBeta[1]	1	0.8674	both sexes
selectivity	pS1[23]	180	180	z95 for RKF selectivity (males, 1997-2004)
	pS1[24]	180	180	z95 for RKF selectivity (males, 2005+)
	pS1[27]	140	140	z95 for RKF selectivity (females, 2005+)
	pS1[4]	69	69	z50 for NMFS survey selectivity (females, 1982+)
	pS2[10]	0.1	0.1	ascending slope for SCF selectivity (males, pre-1997)
	pS2[4]	100	100	z95-z50 for NMFS survey selectivity (females, 1982+)
	pS4[1]	0.1	0.1	descending slope for SCF selectivity (males, pre-1997)
surveys	pQ[1]	0.5	0.2176	NMFS trawl survey: males, 1975-1981
	pQ[3]	0.5	0.3244	NMFS trawl survey: females, 1975-1981

Table 15. Objective function values for data components. GF All: bycatch in groundfish fisheries; RKF: bycatch in the BBRKC fishery; SCF: bycatch in the snow crab fishery; TCF: the directed Tanner crab fishery; NMFS F: NMFS EBS Shelf Survey, females only; NMFS M: NMFS EBS Shelf Survey, males only; SBS BSFRF females: BSFRF side-by-side studies surveys, females only; SBS BSFRF males: BSFRF side-by-side studies surveys, males only.

category	fleet	catch type	data type	sex	20.07	21.01	21.04	21.05	21.06	21.07	21.08	21.09	21.1	21.11	21.12	21.13	21.14	21.15
fisheries data	**GF All**	total catch	**biomass**	all sexes	32.03	33.23	-65.79	-65.47	-65.55	-65.52	-69.97	-70.01	-70.01	-70.04	-70.75	-70.77	-70.95	-70.16
			n.at.z	female	262.14	260.71	246.51	252.16	234.93	234.43	1446.39	1448.42	1448.42	1444.84	1423.56	1423.82	1446.95	1458.53
				male	276.68	283.07	290.75	296.21	289.64	289.10	1886.83	1885.44	1885.44	1883.33	1863.36	1864.83	1958.25	1999.47
	RKF	total catch	**biomass**	female	0.06	0.07	17.91	17.90	17.80	17.81	17.93	17.80	17.80	17.79	16.06	16.11	16.44	16.69
				male	25.79	25.31	-17.81	-17.80	-16.97	-16.94	-16.55	-16.66	-16.66	-16.62	-40.43	-40.40	-39.86	-39.41
			n.at.z	female	2.91	2.92	2.96	2.97	2.13	2.13	32.81	2.04	1.79	1.78	2.17	2.16	2.39	2.36
				male	70.64	71.20	76.30	76.27	68.45	68.35	291.16	68.52	68.53	68.71	33.72	33.59	31.87	35.16
	SCF	total catch	**biomass**	female	1.91	1.93	10.57	10.64	10.43	10.41	10.21	10.08	10.08	10.11	9.74	9.85	12.71	11.05
				male	16.44	16.31	-18.11	-18.13	-18.21	-18.21	-18.31	-18.43	-18.43	-18.38	-20.01	-19.87	-18.63	-17.99
			n.at.z	female	14.57	14.48	18.46	18.03	14.77	14.79	101.43	101.33	101.33	101.32	100.50	103.40	105.57	104.97
				male	119.65	118.54	99.51	99.14	89.12	88.92	484.03	485.05	485.05	485.35	484.32	483.36	485.56	488.67
	TCF	retained catch	**biomass**	female	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				male	8.13	8.05	-132.22	-132.31	-132.32	-132.29	-131.99	-132.30	-132.30	-132.18	-132.77	-132.76	-133.88	-126.66
			n.at.z	male	55.13	46.67	49.51	49.42	49.37	49.26	447.99	49.54	49.54	49.56	54.22	53.84	52.08	50.90
		total catch	**biomass**	female	9.28	9.67	58.16	57.31	66.69	66.89	61.31	68.34	68.34	68.60	64.53	65.21	72.45	78.38
				male	3.69	3.33	11.89	11.94	7.62	7.52	13.30	7.05	7.05	6.94	9.80	9.41	4.65	4.38
			n.at.z	female	13.74	13.65	13.50	13.63	11.55	11.54	98.32	11.81	11.81	11.83	11.92	11.88	13.03	12.47
				male	89.33	79.70	73.90	73.70	62.88	63.11	348.73	65.11	65.11	65.17	69.81	69.68	75.33	65.16
growth data	**'--**	'--	**EBS_molt_increment_data**	female	252.78	246.79	247.04	243.72	246.87	247.12	251.66	253.94	253.93	251.10	260.70	259.95	269.86	233.17
				male	296.49	285.08	285.15	284.90	287.79	288.04	291.67	292.98	292.98	290.56	294.68	293.99	310.92	235.71
maturity ogive data	**NMFS_M**	'--	**EBS_male_maturity_ogives**	male	107.27	100.30	101.21	104.07	99.13	99.71	103.89	103.23	103.23	103.36	103.17	102.61	97.80	249.72
surveys data	**NMFS F**	index catch	**biomass**	female	139.92	148.37	157.94	169.15	174.47	175.57	183.24	179.79	179.79	179.18	156.49	156.08	189.69	207.37
				male	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			n.at.z	female	330.88	329.79	325.78	337.58	306.63	1328.47	1320.63	312.69	312.69	315.10	293.99	293.82	422.92	435.90
	NMFS M	index catch	**biomass**	female	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				male	65.33	58.92	63.58	64.63	65.25	67.11	82.62	78.29	78.29	78.74	69.74	70.15	70.05	141.53
			n.at.z	male	411.35	406.38	404.94	404.38	374.75	1900.51	1902.17	380.19	380.19	377.49	382.07	383.57	544.41	658.84
	SBS BSFRF females	index catch	**biomass**	female	-6.64	-4.00	-4.83	-4.41	-4.21	-4.14	-4.20	-5.07	-5.07	-4.76	-4.70	-4.55	0.00	0.00
				male	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			n.at.z	female	146.29	146.75	147.05	144.50	132.66	132.65	223.26	222.98	222.98	225.72	229.87	229.98	0.00	0.00
	SBS BSFRF males	index catch	**biomass**	female	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				male	-1.02	0.21	-0.24	0.40	-0.37	-0.36	1.60	0.74	0.74	0.64	-0.16	-0.10	0.00	0.00
			n.at.z	male	153.24	147.84	146.63	141.97	131.84	132.08	285.73	285.53	285.53	287.27	293.77	293.84	0.00	0.00
Grand Total					**2898.02**	**2855.27**	**2610.28**	**2636.48**	**2507.17**	**5058.08**	**9645.88**	**6088.42**	**6088.19**	**6082.51**	**5959.40**	**5962.66**	**5919.59**	**6236.20**

Table 16. Parameters estimated at an upper or lower bound in Model 21.01 or in 21.04. "-1" indicates parameter at the lower bound, "1" indicates parameter at upper bound, "—" indicates parameter not at bound, "zXX" indicates crab size at which XX% are selected.

name	21.01	21.04	description
pS1[23]	1	1	z95 for RKF selectivity (males, 1997-2004)
pS1[24]	1	1	z95 for RKF selectivity (males, 2005+)
pS1[27]	1	--	z95 for RKF selectivity (females, 2005+)
pS1[4]	1	1	z50 for NMFS survey selectivity (females, 1982+)
pS2[10]	-1	--	ascending slope for SCF selectivity (males, pre-1997)
pS2[4]	1	1	z95-z50 for NMFS survey selectivity (females, 1982+)
pS4[1]	-1	--	descending slope for SCF selectivity (males, pre-1997)
pS4[2]	--	-1	descending slope for SCF selectivity (males, 1997-2004)

Table 17. Values for parameters estimated at an upper or lower bound in Model 20.01 or 21.04. "zXX" indicates crab size at which XX% are selected. See previous table for information on bounds.

name	21.01	21.04	description
pS1[23]	180	180	z95 for RKF selectivity (males, 1997-2004)
pS1[24]	180	180	z95 for RKF selectivity (males, 2005+)
pS1[27]	140	137.0766	z95 for RKF selectivity (females, 2005+)
pS1[4]	69	69	z50 for NMFS survey selectivity (females, 1982+)
pS2[10]	0.1	0.1309	ascending slope for SCF selectivity (males, pre-1997)
pS2[4]	100	100	z95-z50 for NMFS survey selectivity (females, 1982+)
pS4[1]	0.1	0.3887	descending slope for SCF selectivity (males, pre-1997)
pS4[2]	--	0.1	descending slope for SCF selectivity (males, 1997-2004)

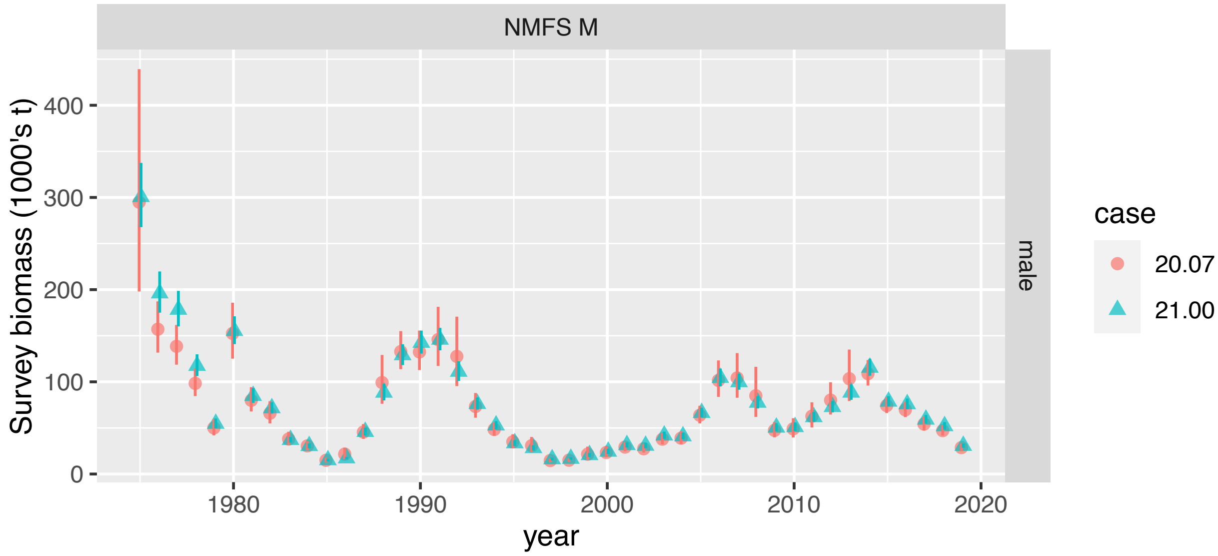
Table 18. Values for parameters estimated at an upper or lower bound in Model 21.04 and subsequent models. “-1” indicates parameter at the lower bound, “1” indicates parameter at upper bound, “—" indicates parameter not at bound, “zXX” indicates crab size at which XX% are selected.

process	name	21.04	21.05	21.06	21.07	21.08	21.09	21.1	21.11	21.12	21.13	21.14	21.15	parameter description
recruitment	pRb[1]	--	--	--	--	--	--	--	--	--	--	-1	-1	fixed value
growth	pGrBeta[1]	--	--	--	--	1	--	--	--	--	--	--	--	both sexes
fisheries	pDC2[3]	--	--	--	--	-1	-1	-1	-1	--	--	-1	-1	GTF: female offset
Dirichlet-Multinomial	pLnDirMul[1]	--	--	--	1	1	--	--	--	--	--	--	--	ln(theta) parameter for NMFS M
	pLnDirMul[2]	--	--	--	1	1	--	--	--	--	--	--	--	ln(theta) parameter for NMFS F
	pLnDirMul[5]	--	--	--	--	1	--	--	--	--	--	--	--	ln(theta) parameter for TCF retained catch
	pLnDirMul[6]	--	--	--	--	1	--	--	--	--	--	--	--	ln(theta) parameter for TCF total male catch
	pLnDirMul[7]	--	--	--	--	1	--	--	--	--	--	--	--	ln(theta) parameter for TCF total female catch
	pLnDirMul[8]	--	--	--	--	1	--	--	--	--	--	--	--	ln(theta) parameter for SCF total male catch
	pLnDirMul[10]	--	--	--	--	1	--	--	--	--	--	--	--	ln(theta) parameter for RKF total male catch
	pLnDirMul[11]	--	--	--	--	1	--	--	--	--	--	--	--	ln(theta) parameter for RKF total female catch
	pLnDirMul[12]	--	--	--	--	1	--	--	--	--	--	--	--	ln(theta) parameter for GF All total male catch
selectivity	pS1[4]a	1	--	--	--	--	--	--	--	--	--	--	--	z50 for NMFS survey selectivity (females, 1982+)
	pS1[4]b	--	-1	-1	-1	-1	-1	-1	-1	--	--	--	--	size delta from max possible size at for NMFS survey selectivity (females, 1982+)
	pS1[4]c	--	--	--	--	--	--	--	--	1	1	--	--	size at 1 for NMFS survey selectivity (females, 1982+)
	pS1[10]	--	--	--	--	--	--	--	--	--	1	1	1	ascending z-at-1 for SCF selectivity (males, pre-1997)
	pS1[20]	--	--	--	--	--	--	--	--	-1	-1	--	--	z50 for GF.AllGear selectivity (females, 1987-1996)
	pS1[22]	--	--	--	--	--	--	--	--	1	1	1	1	size at 1 for RKF selectivity (males, pre-1997)
	pS1[23]a	1	1	1	1	1	1	1	1	--	--	--	--	z95 for RKF selectivity (males, 1997-2004)
	pS1[23]b	--	--	--	--	--	--	--	--	1	1	--	--	size at 1 for RKF selectivity (males, 1997-2004)
	pS1[24]a	1	1	1	1	1	1	1	1	--	--	--	--	z95 for RKF selectivity (males, 2005+)
	pS1[24]b	--	--	--	--	--	--	--	--	1	1	1	--	size at 1 for RKF selectivity (males, 2005+)
	pS1[25]	--	--	--	--	--	--	--	--	1	1	--	1	size at 1 for RKF selectivity (females, pre-1997)
	pS1[27]	--	--	--	--	1	--	--	--	--	--	--	--	z95 for RKF selectivity (females, 2005+)
	pS2[4]	1	--	--	--	--	--	--	--	--	--	--	--	z95-z50 for NMFS survey selectivity (females, 1982+)
	pS2[10]	--	--	-1	-1	-1	-1	-1	-1	--	--	--	--	ascending slope for SCF selectivity (males, pre-1997)
	pS3[1]	--	--	--	--	--	--	--	--	-1	--	--	--	ln(dz50-az50) for SCF selectivity (males, pre-1997)
	pS3[2]a	--	--	--	--	--	--	--	--	-1	--	--	--	ln(dz50-az50) for SCF selectivity (males, 1997-2004)
	pS3[2]b	--	--	--	--	--	--	--	--	--	-1	-1	-1	scaled increment for descending z-at-1 for SCF selectivity (males, 1997-2004)
	pS3[3]	--	--	--	--	--	--	--	--	--	-1	-1	-1	scaled increment for descending z-at-1 for SCF selectivity (males, 2005+)
	pS3[5]	--	-1	-1	-1	-1	-1	-1	-1	--	--	--	--	size at selectivity pS2 NMFS survey selectivity (females, 1982+)
	pS4[1]	--	--	1	1	1	1	1	1	-1	--	--	--	descending slope for SCF selectivity (males, pre-1997)
	pS4[2]	-1	-1	-1	-1	-1	-1	-1	-1	--	--	--	--	descending slope for SCF selectivity (males, 1997-2004)

Table 19. Values for parameters estimated at an upper or lower bound in Model 21.04 and subsequent models. “zXX” indicates crab size at which XX% are selected.

process	name	21.04	21.05	21.06	21.07	21.08	21.09	21.10	21.11	21.12	21.13	21.14	21.15	label
fisheries	pDC2[3]	--	--	--	--	-5.00	-5.00	-5.00	-5.00	--	--	-10.00	-10.00	GTF: female offset
Dirichlet-Multinomial	pLnDirMul[1]	--	--	--	5.00	8.00	--	--	--	--	--	--	--	ln(theta) parameter for NMFS M
	pLnDirMul[10]	--	--	--	--	8.00	--	--	--	--	--	--	--	ln(theta) parameter for RKF total male catch
	pLnDirMul[11]	--	--	--	--	8.00	--	--	--	--	--	--	--	ln(theta) parameter for RKF total female catch
	pLnDirMul[12]	--	--	--	--	8.00	--	--	--	--	--	--	--	ln(theta) parameter for GF All total male catch
	pLnDirMul[2]	--	--	--	5.00	8.00	--	--	--	--	--	--	--	ln(theta) parameter for NMFS F
	pLnDirMul[5]	--	--	--	--	8.00	--	--	--	--	--	--	--	ln(theta) parameter for TCF retained catch
	pLnDirMul[6]	--	--	--	--	8.00	--	--	--	--	--	--	--	ln(theta) parameter for TCF total male catch
	pLnDirMul[7]	--	--	--	--	8.00	--	--	--	--	--	--	--	ln(theta) parameter for TCF total female catch
	pLnDirMul[8]	--	--	--	--	8.00	--	--	--	--	--	--	--	ln(theta) parameter for SCF total male catch
growth	pGrBeta[1]	--	--	--	--	1.00	--	--	--	--	--	--	--	gamma distribution scale factor for growth
recruitment	pRb[1]	--	--	--	--	--	--	--	--	--	--	1.00	1.00	gamma distribution scale factor for size at recruitment
selectivity	pS1[10]	--	--	--	--	--	--	--	--	--	140.00	140.00	140.00	ascending z-at-1 for SCF selectivity (males, pre-1997)
	pS1[20]	--	--	--	--	--	--	--	--	40.00	40.00	--	--	z50 for GF.AllGear selectivity (females, 1987-1996)
	pS1[22]	--	--	--	--	--	--	--	--	180.00	180.00	180.00	180.00	size at 1 for RKF selectivity (males, pre-1997)
	pS1[23]	--	--	--	--	--	--	--	--	180.00	180.00	--	--	size at 1 for RKF selectivity (males, 1997-2004)
		180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	--	--	--	--	z95 for RKF selectivity (males, 1997-2004)
	pS1[24]	--	--	--	--	--	--	--	--	180.00	180.00	180.00	--	size at 1 for RKF selectivity (males, 2005+)
		180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	--	--	--	--	z95 for RKF selectivity (males, 2005+)
	pS1[25]	--	--	--	--	--	--	--	--	140.00	140.00	--	140.00	size at 1 for RKF selectivity (females, pre-1997)
	pS1[27]	--	--	--	--	140.00	--	--	--	--	--	--	--	z95 for RKF selectivity (females, 2005+)
	pS1[4]	--	--	--	--	--	--	--	--	130.00	130.00	--	--	size at 1 for NMFS survey selectivity (females, 1982+)
		--	0.00	0.00	0.00	0.00	0.00	0.00	0.00	--	--	--	--	size delta from max possible size at for NMFS survey selectivity (females, 1982+)
		69.00	--	--	--	--	--	--	--	--	--	--	--	z50 for NMFS survey selectivity (females, 1982+)
	pS2[10]	--	--	0.10	0.10	0.10	0.10	0.10	0.10	--	--	--	--	ascending slope for SCF selectivity (males, pre-1997)
	pS2[4]	100.00	--	--	--	--	--	--	--	--	--	--	--	z95-z50 for NMFS survey selectivity (females, 1982+)
	pS3[1]	--	--	--	--	--	--	--	--	2.00	--	--	--	ln(dz50-az50) for SCF selectivity (males, pre-1997)
	pS3[2]	--	--	--	--	--	--	--	--	2.00	--	--	--	ln(dz50-az50) for SCF selectivity (males, 1997-2004)
		--	--	--	--	--	--	--	--	--	0.00	0.00	0.00	scaled increment for descending z-at-1 for SCF selectivity (males, 1997-2004)
	pS3[3]	--	--	--	--	--	--	--	--	--	0.00	0.00	0.00	scaled increment for descending z-at-1 for SCF selectivity (males, 2005+)
	pS3[5]	--	25.00	25.00	25.00	25.00	25.00	25.00	25.00	--	--	--	--	size at selectivity pS2 NMFS survey selectivity (females, 1982+)
	pS4[1]	--	--	0.50	0.50	0.50	0.50	0.50	0.50	0.01	--	--	--	descending slope for SCF selectivity (males, pre-1997)
	pS4[2]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	--	--	--	--	descending slope for SCF selectivity (males, 1997-2004)

Figures



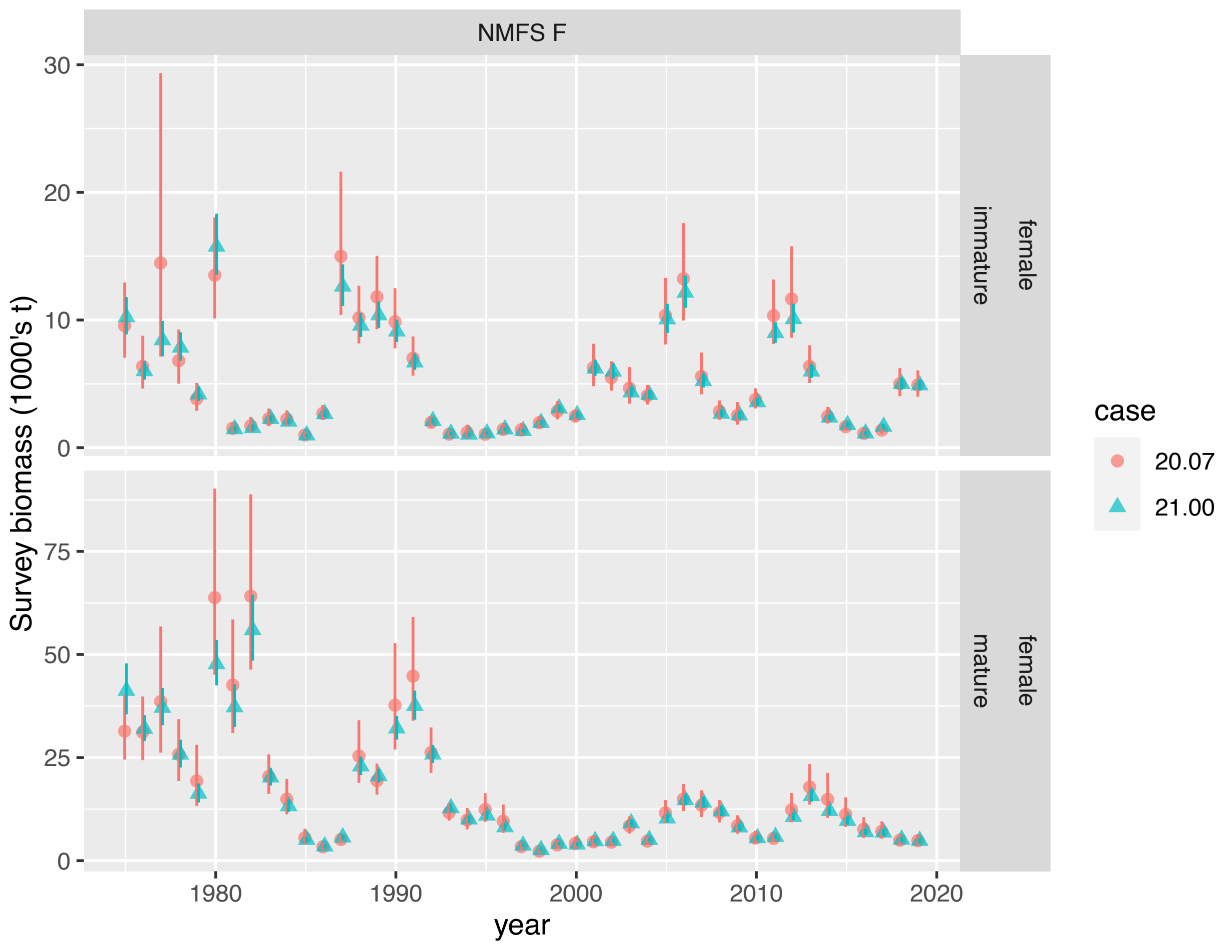


Figure 1. Comparison of NMFS EBS Shelf Survey biomass time series for male and female Tanner crab using design-based (20.07) and VAST approaches (21.00).

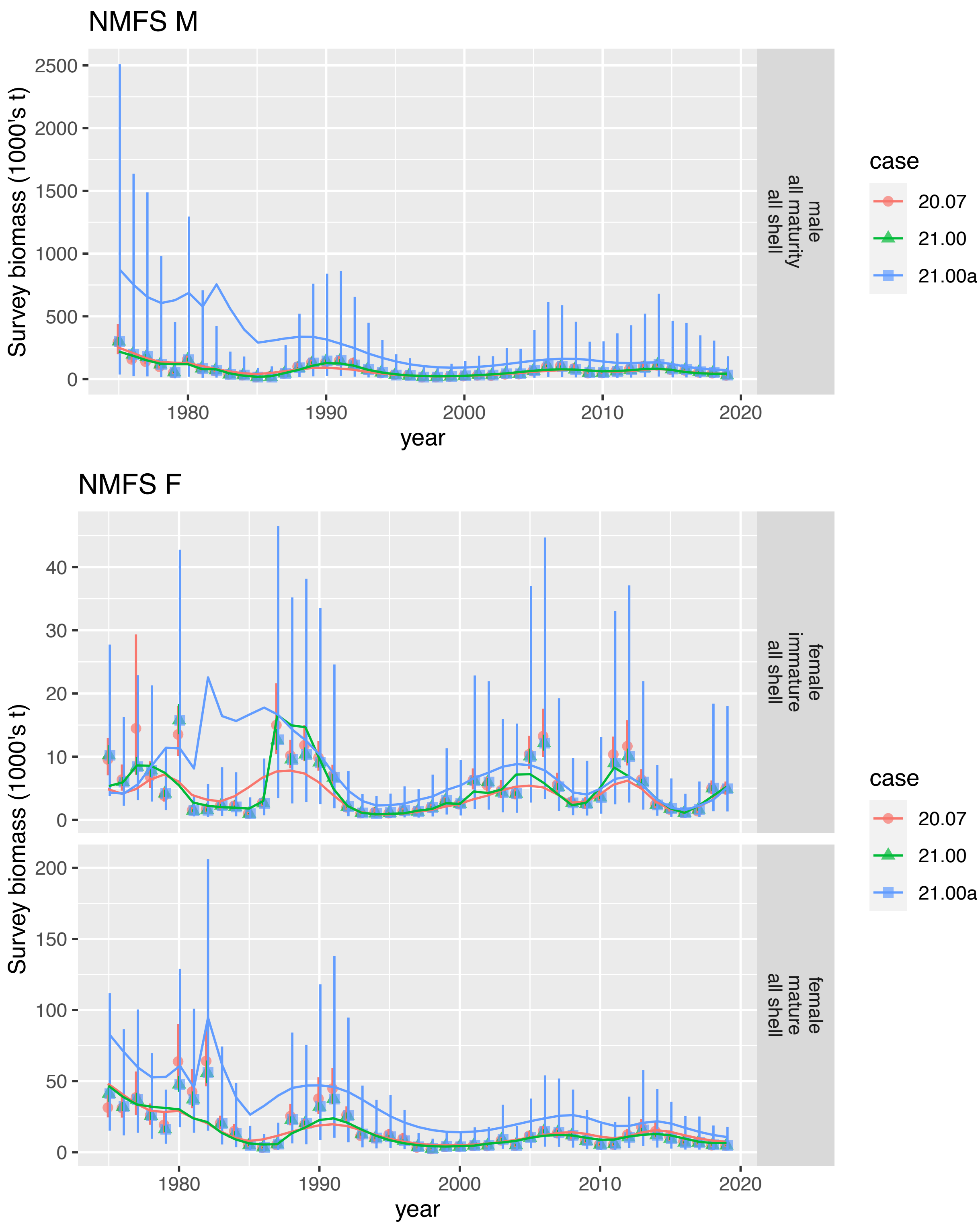


Figure 2. Comparison of assessment model fits to NMFS EBS Shelf Survey biomass time series for male (uppermost plot) and female (lower two plots) Tanner crab based on the design-based (20.07) and VAST approaches (21.00 and 21.00a). Models 20.07 and 21.00 are identical except for the difference in biomass time series. 21.00a estimates 4 “additional variance” parameters, which result in increased confidence intervals on the VAST time series.

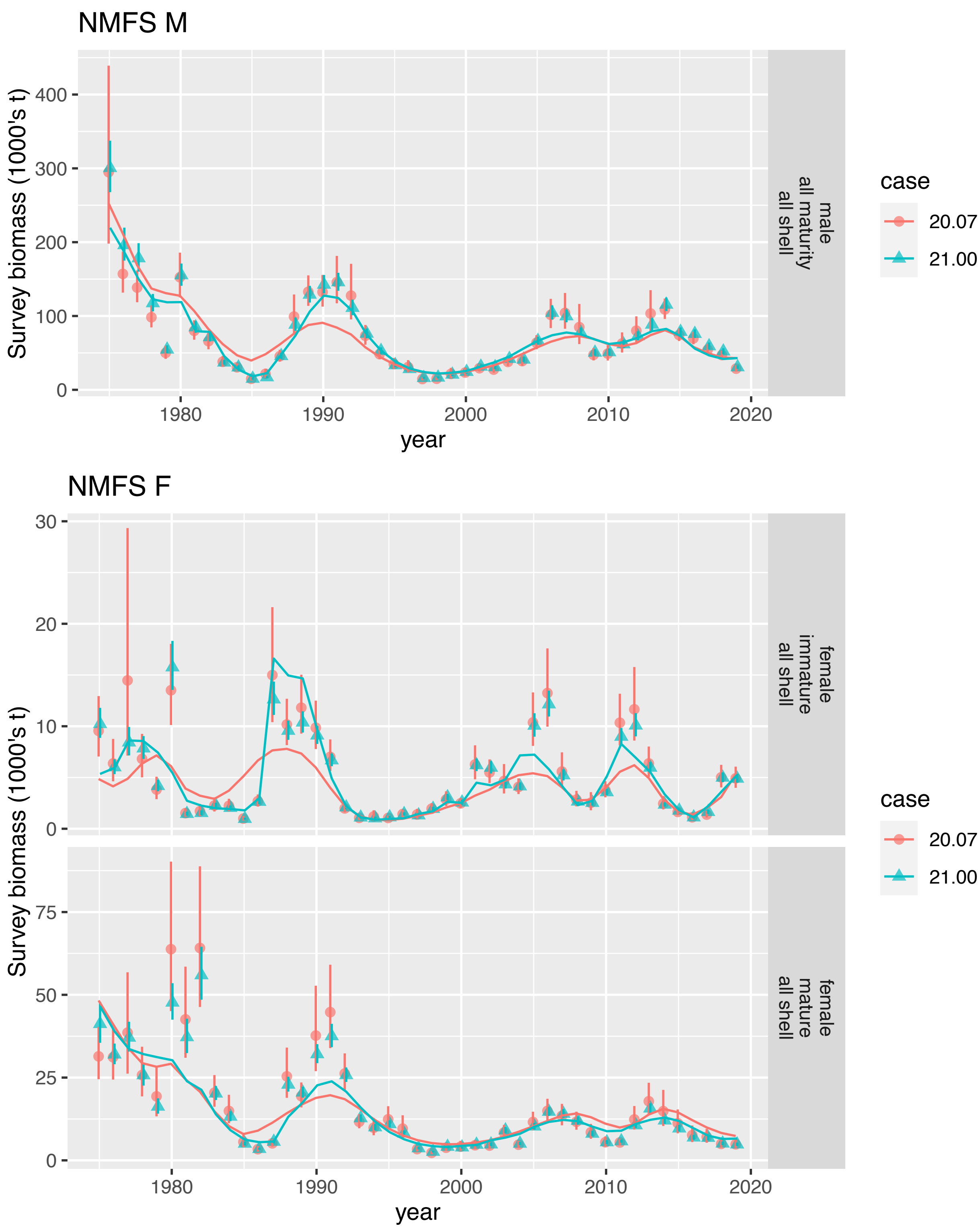


Figure 3. Comparison of fits to the NMFS EBS Shelf Survey biomass time series for male (uppermost plot) and female (lower two plots) Tanner crab based on the design-based (20.07) and VAST approaches (21.00).

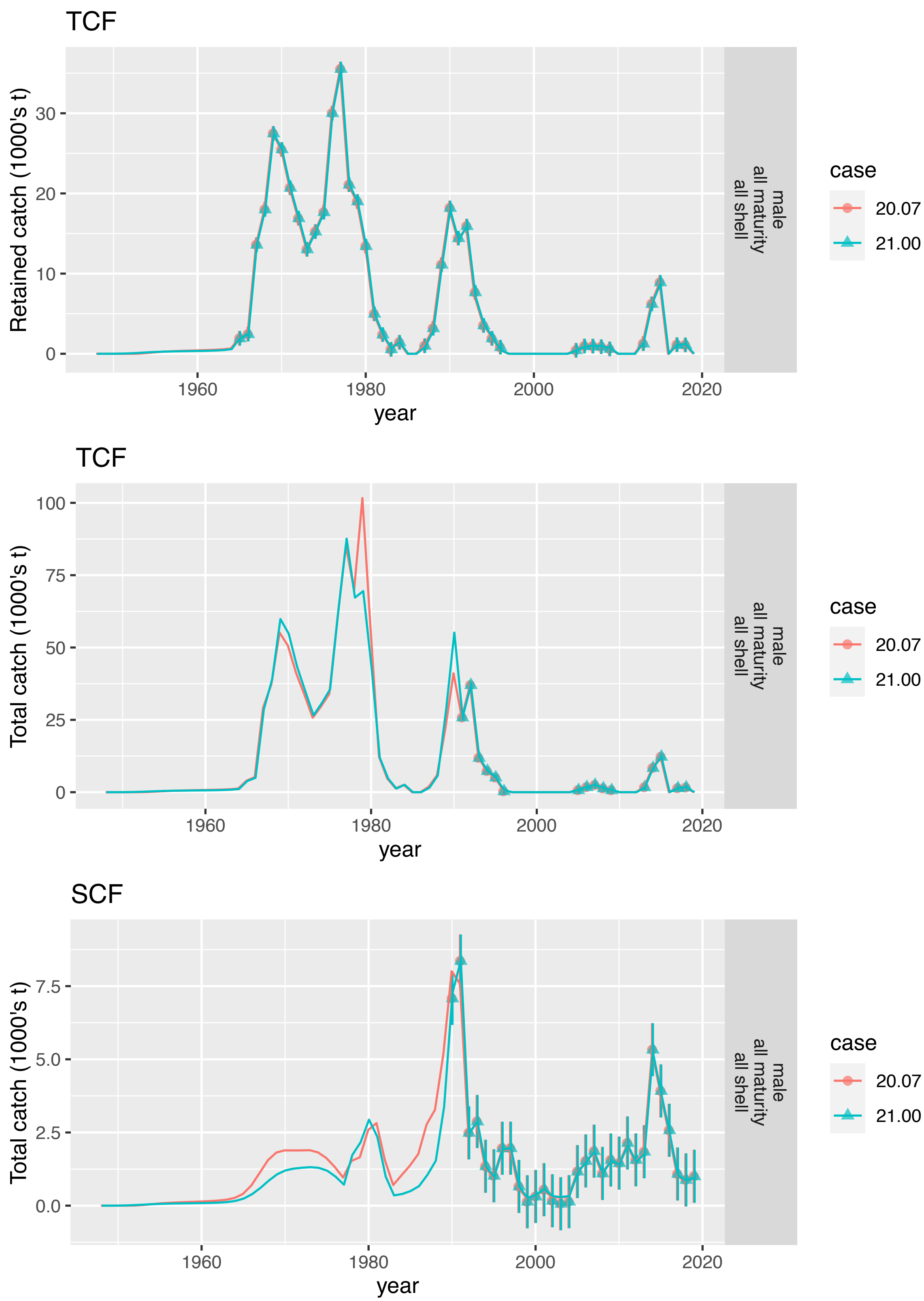


Figure 4. Comparison of NMFS EBS Shelf Survey biomass time series for male and female Tanner crab using design-based (20.07) and VAST approaches (21.00).

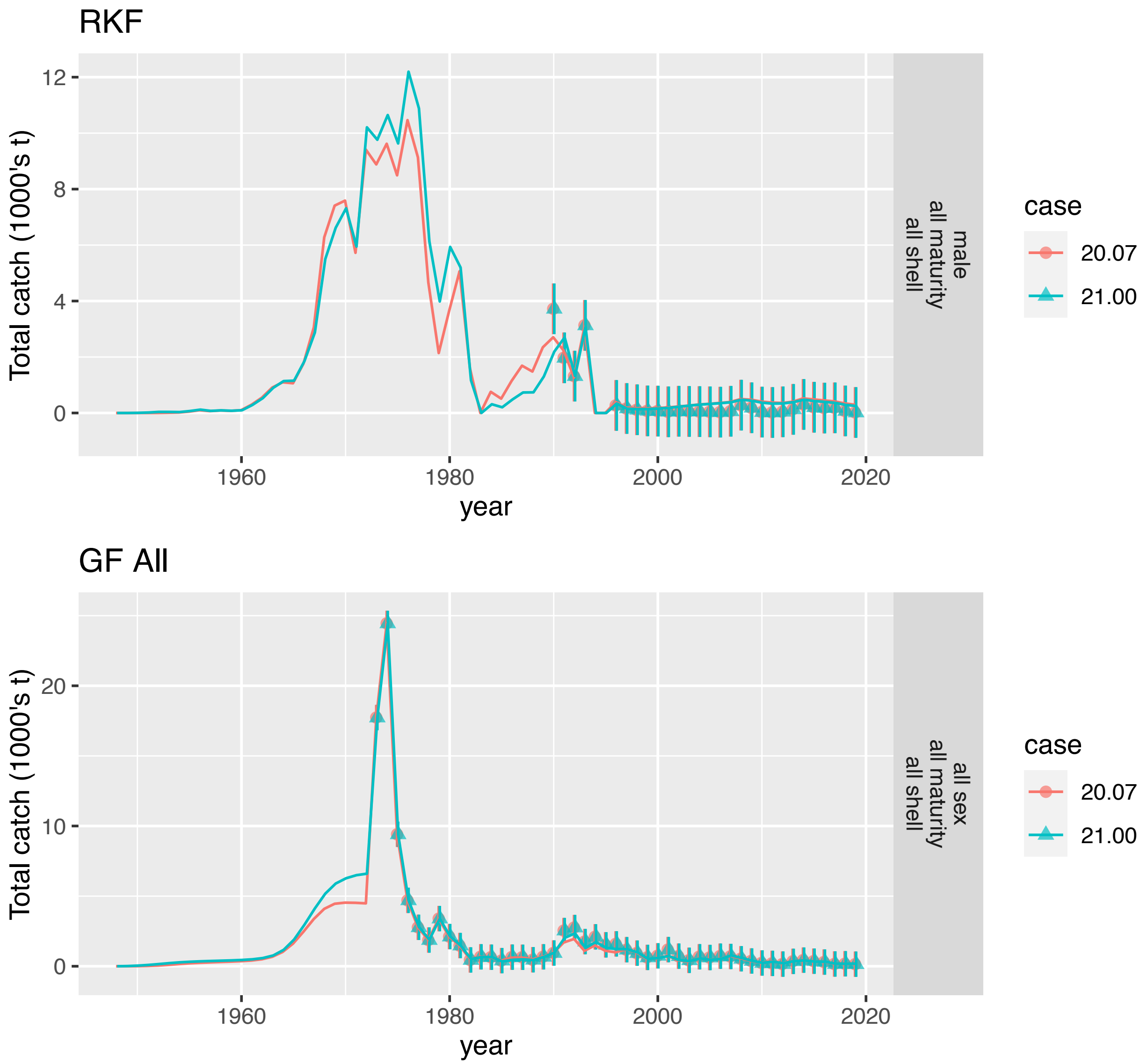


Figure 5. Comparison of NMFS EBS Shelf Survey biomass time series for male and female Tanner crab using design-based (20.07) and VAST approaches (21.00).

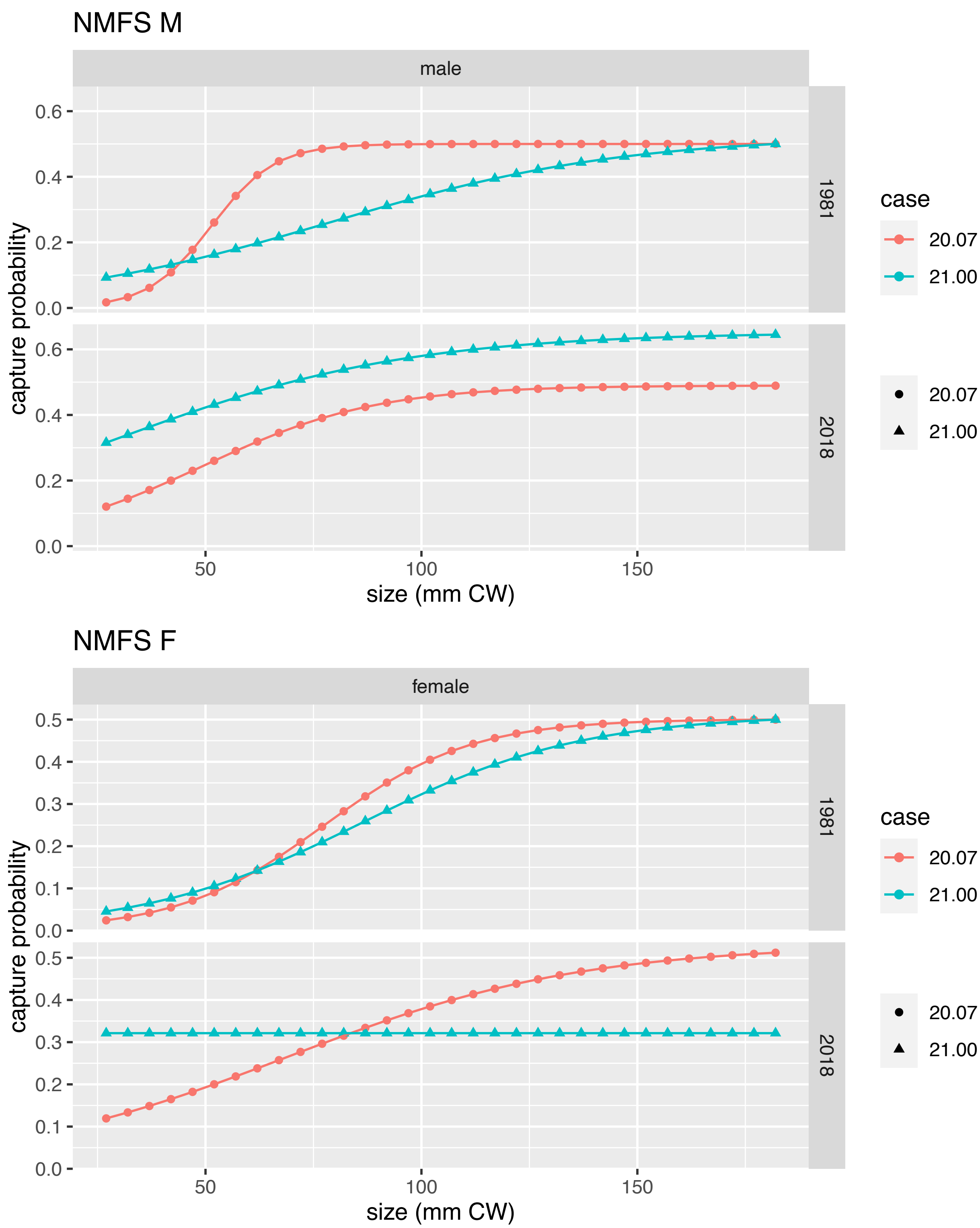


Figure 6. Comparison of NMFS survey catchability curves as estimated by models 20.07 and 21.00 in two time periods (1975-1981 and 1982-2019).

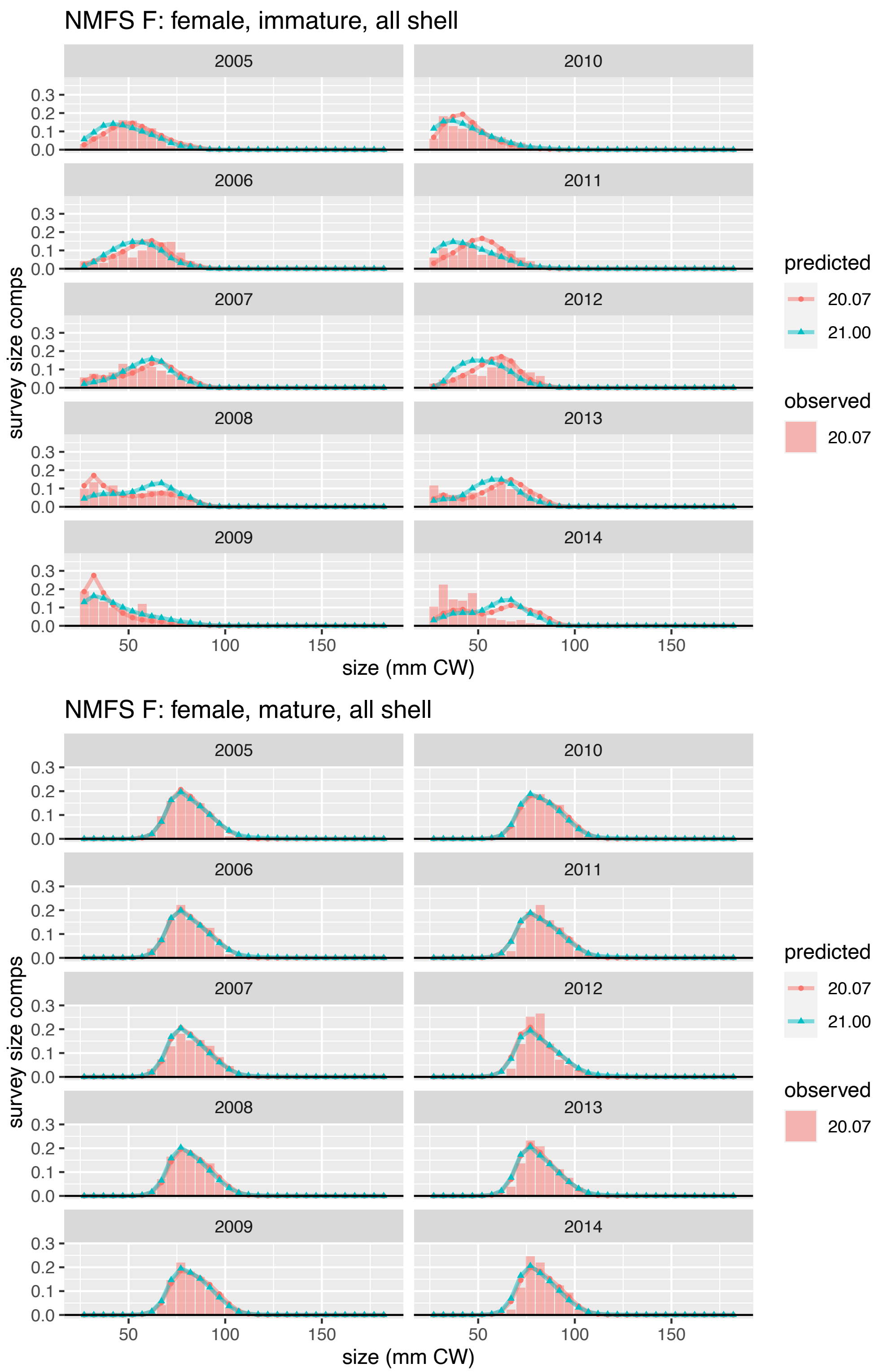


Figure 7. Example fits to NMFS survey size compositions by models 20.07 and 21.00 .

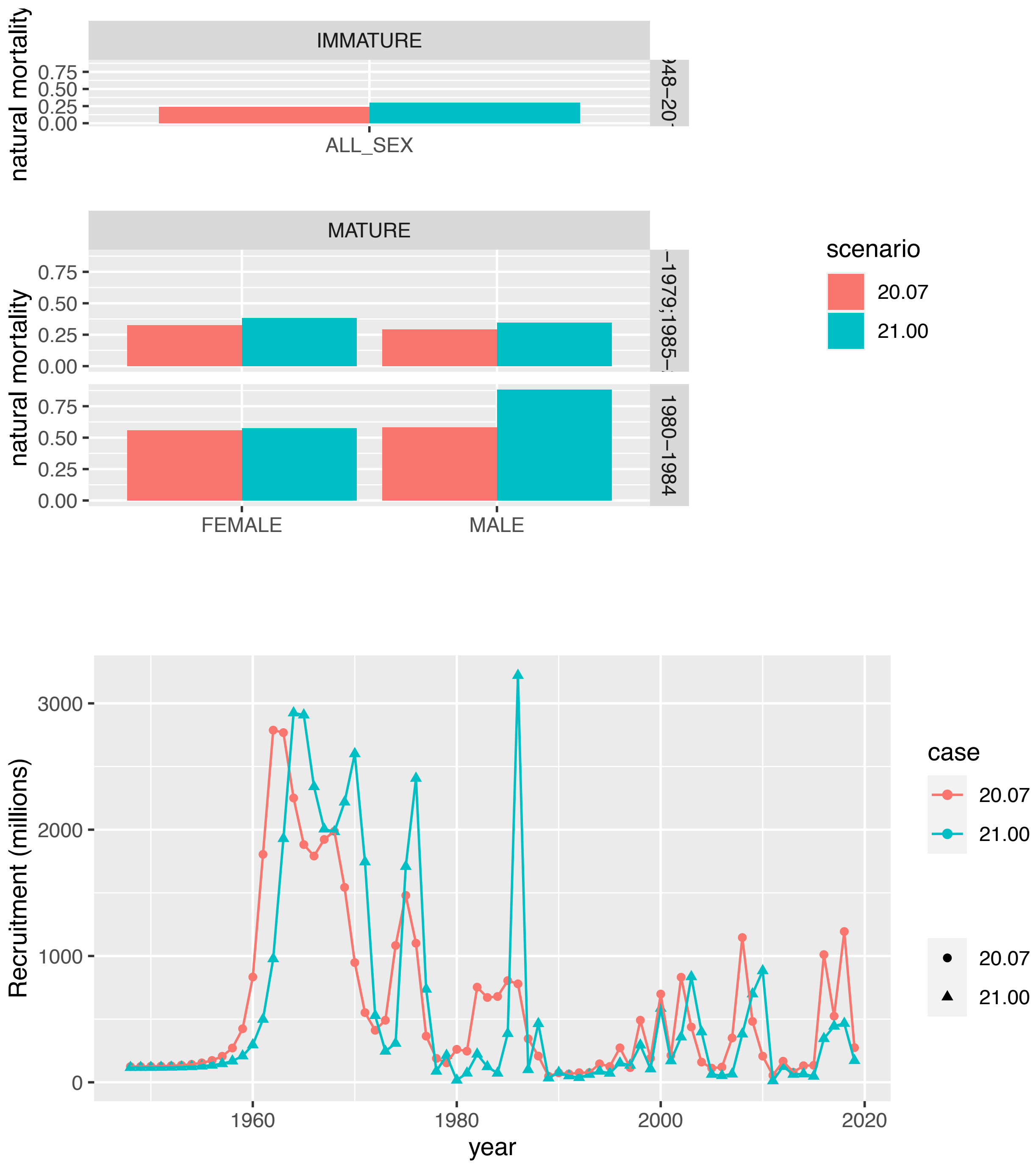


Figure 8. Estimates of natural mortality and recruitment time series by models 20.07 and 21.00 .

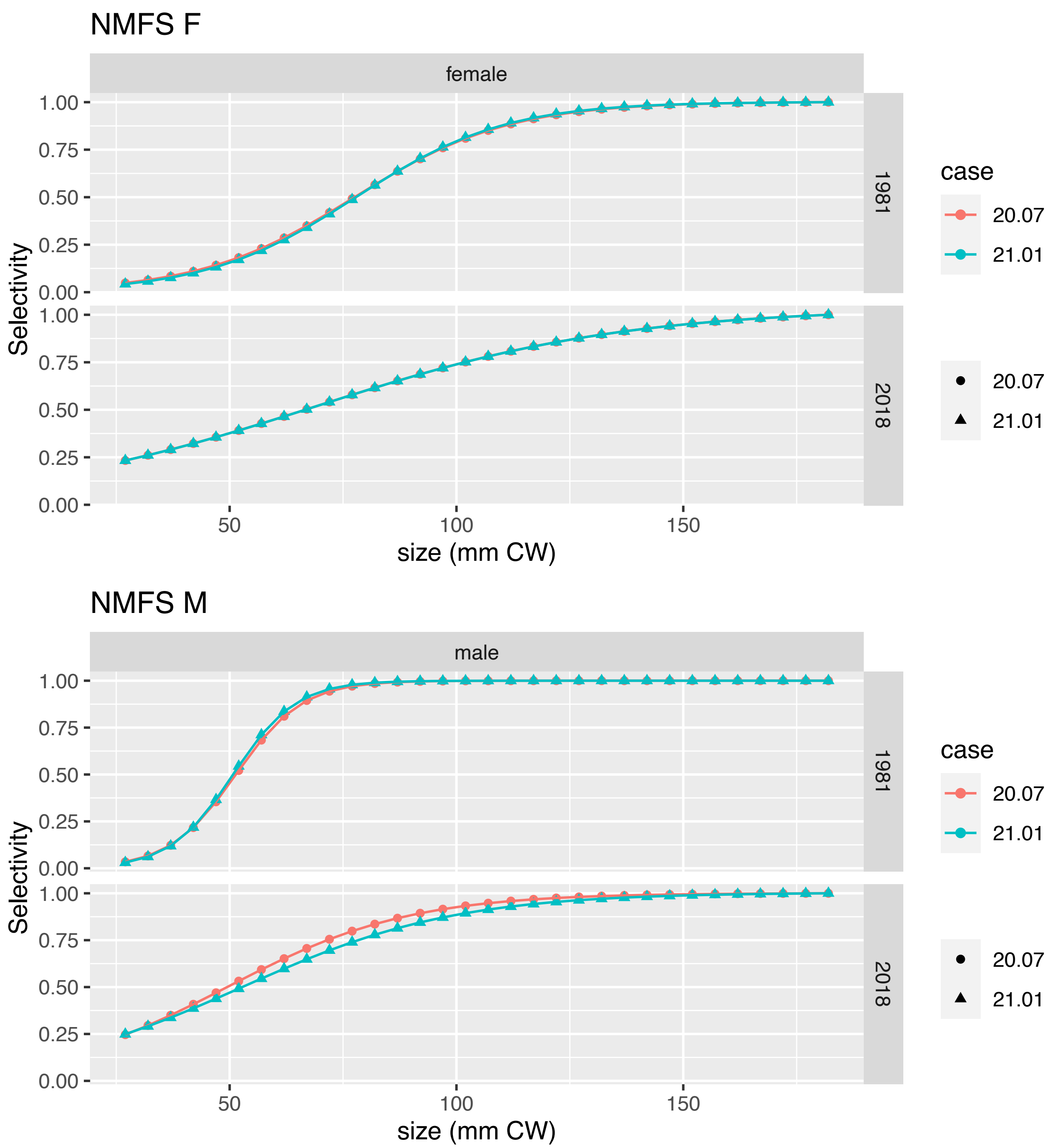


Figure 9. Estimated NMFS survey selectivity curves from models 20.07 and 21.01..

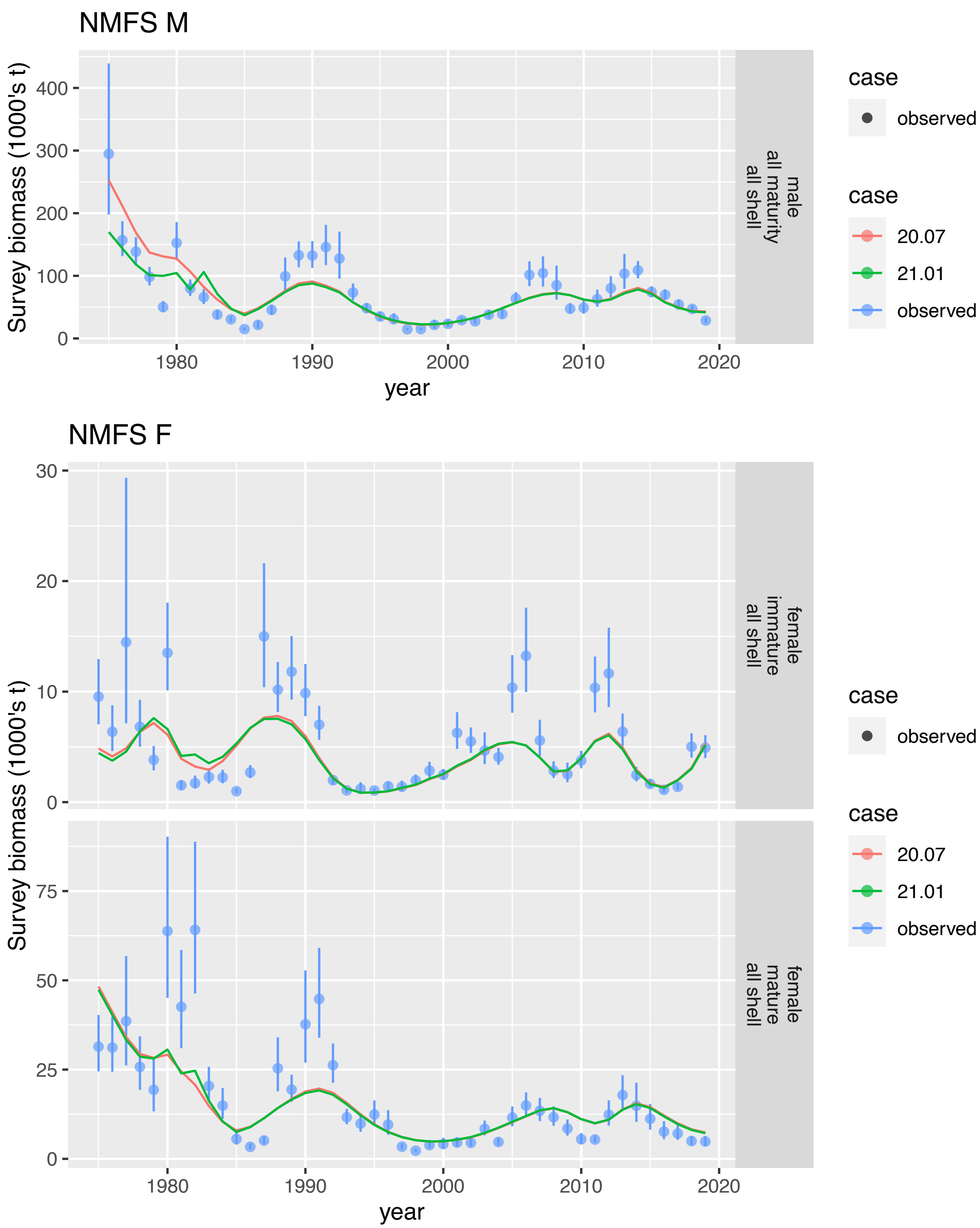


Figure 10. Fits to design-based NMFS survey biomass time series for models 20.07 and 21.01 .

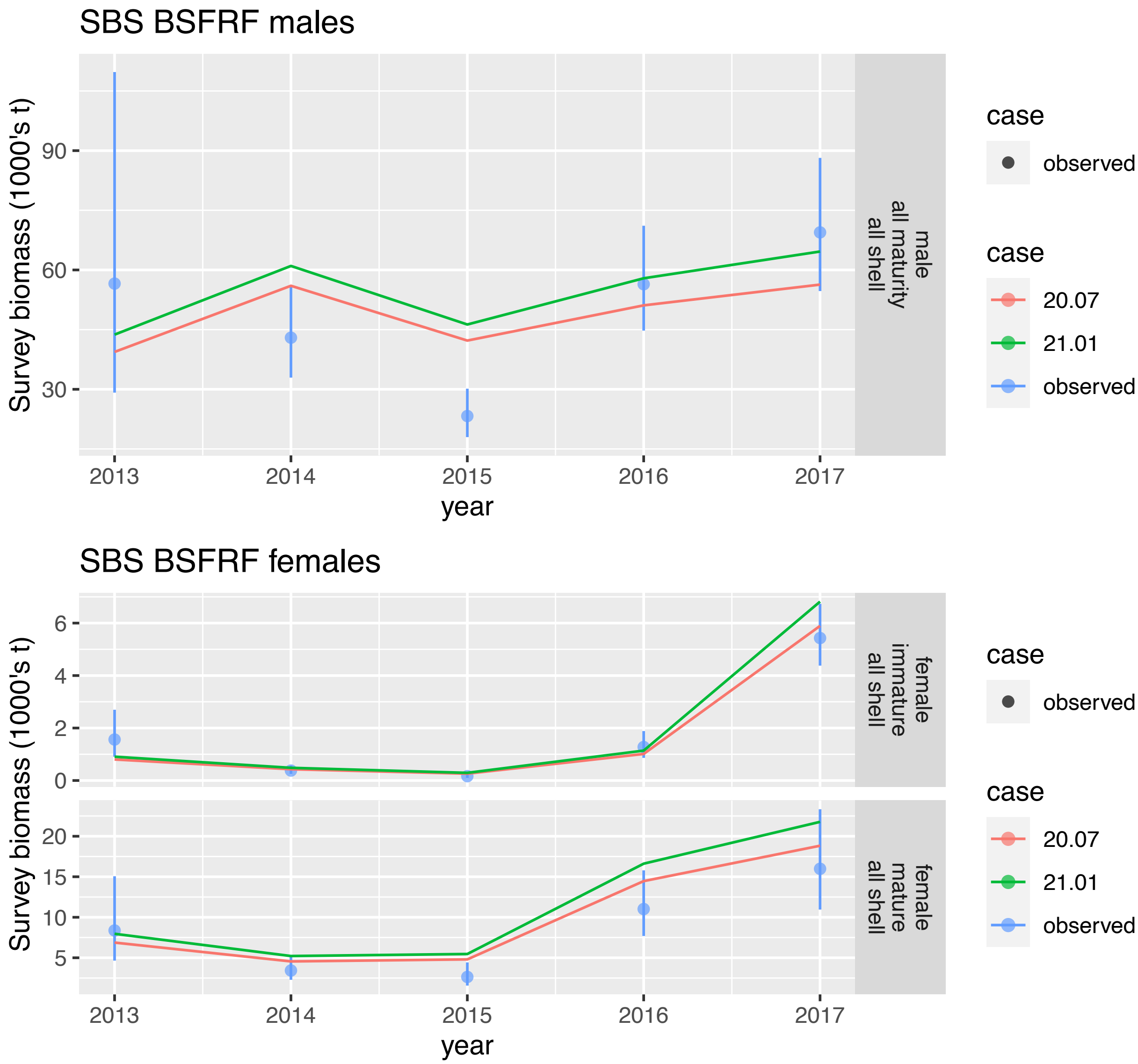


Figure 11. Fits to BSFRF survey biomass time series for models 20.07 and 21.01 .

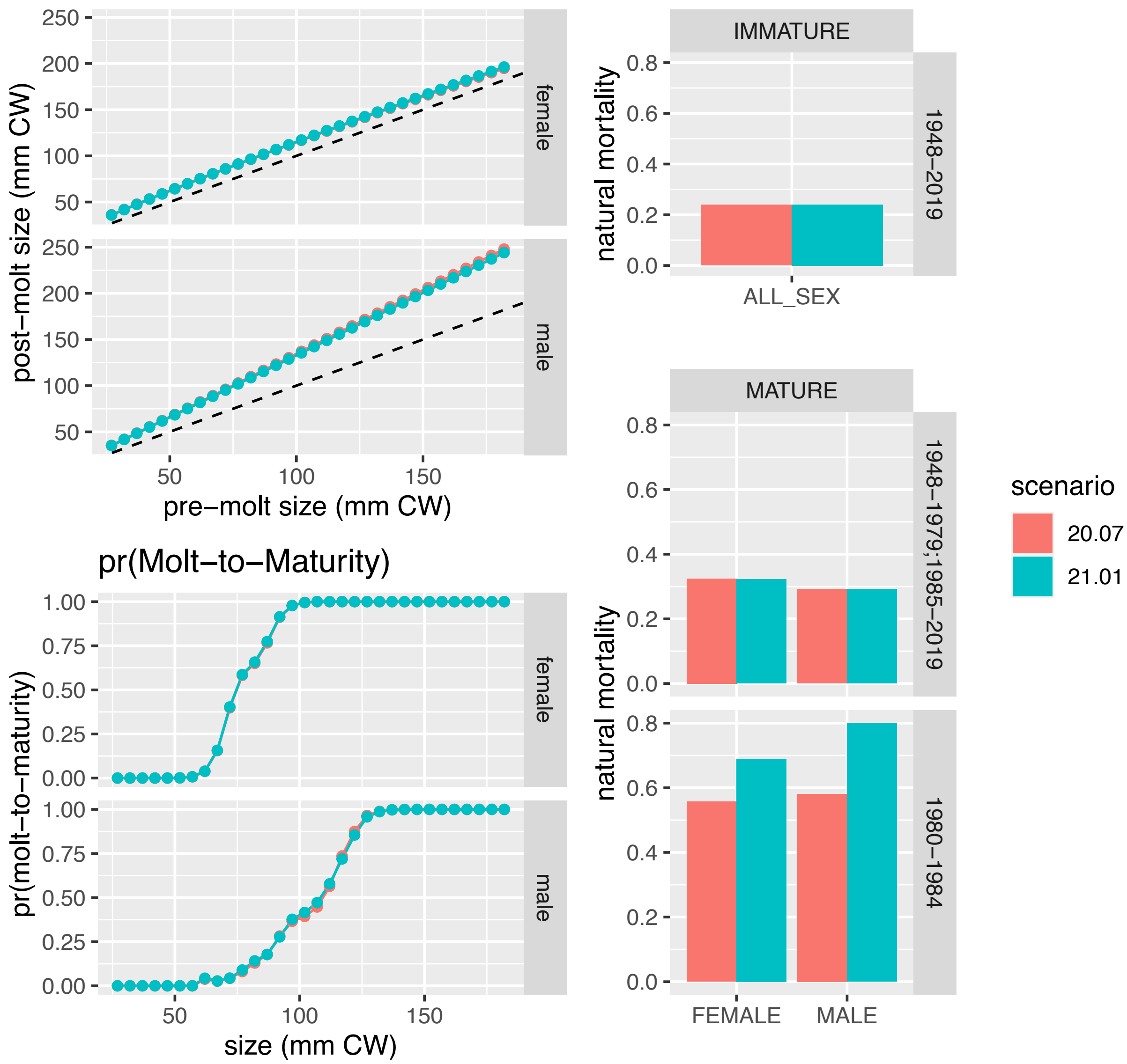


Figure 12. Estimates of population processes from models 20.07 and 21.01. upper left: mean growth; lower left: probability of molt-to-maturity; right: natural mortality.

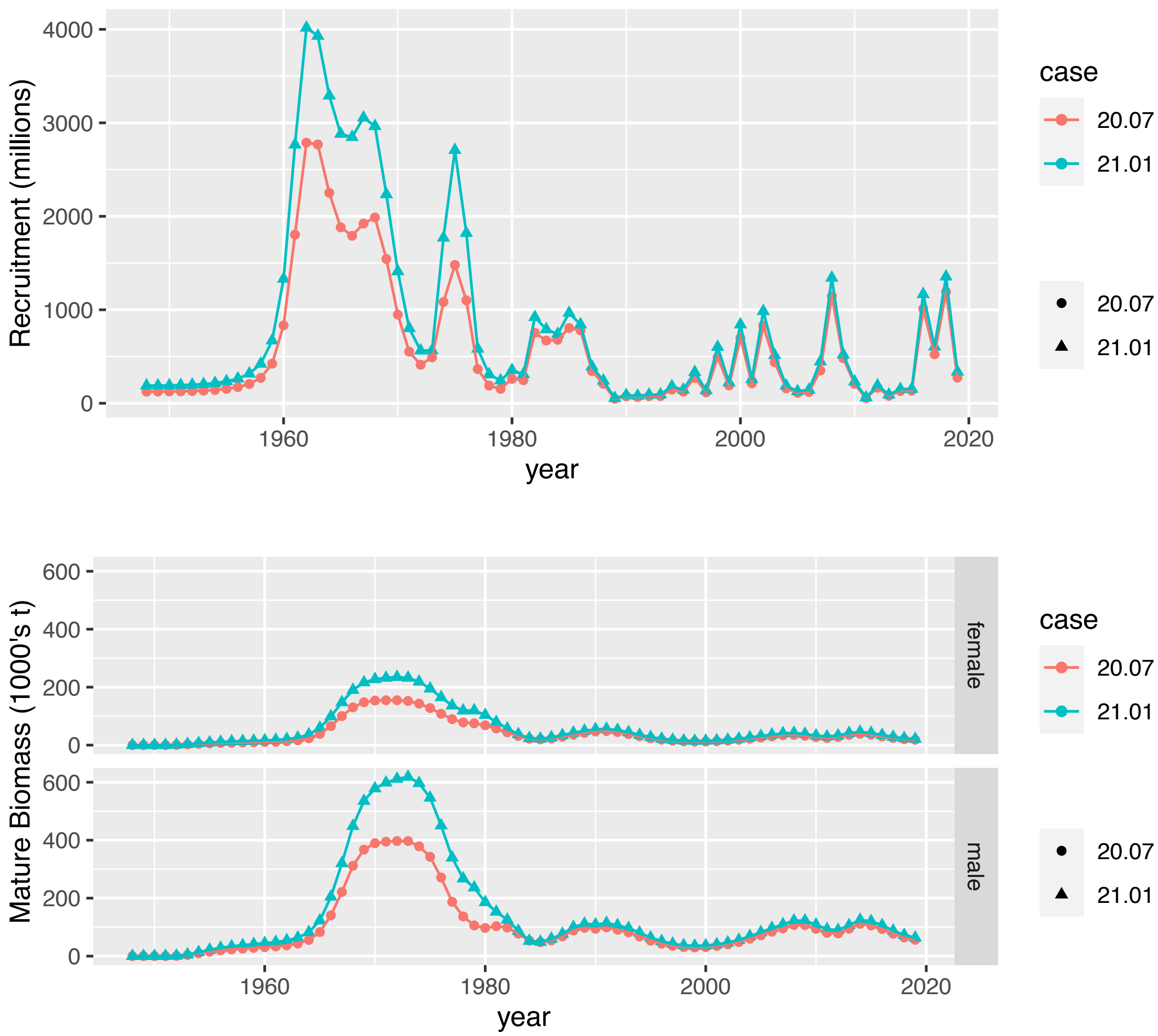


Figure 13. Estimates of recruitment and mature biomass time series from models 20.07 and 21.01 .

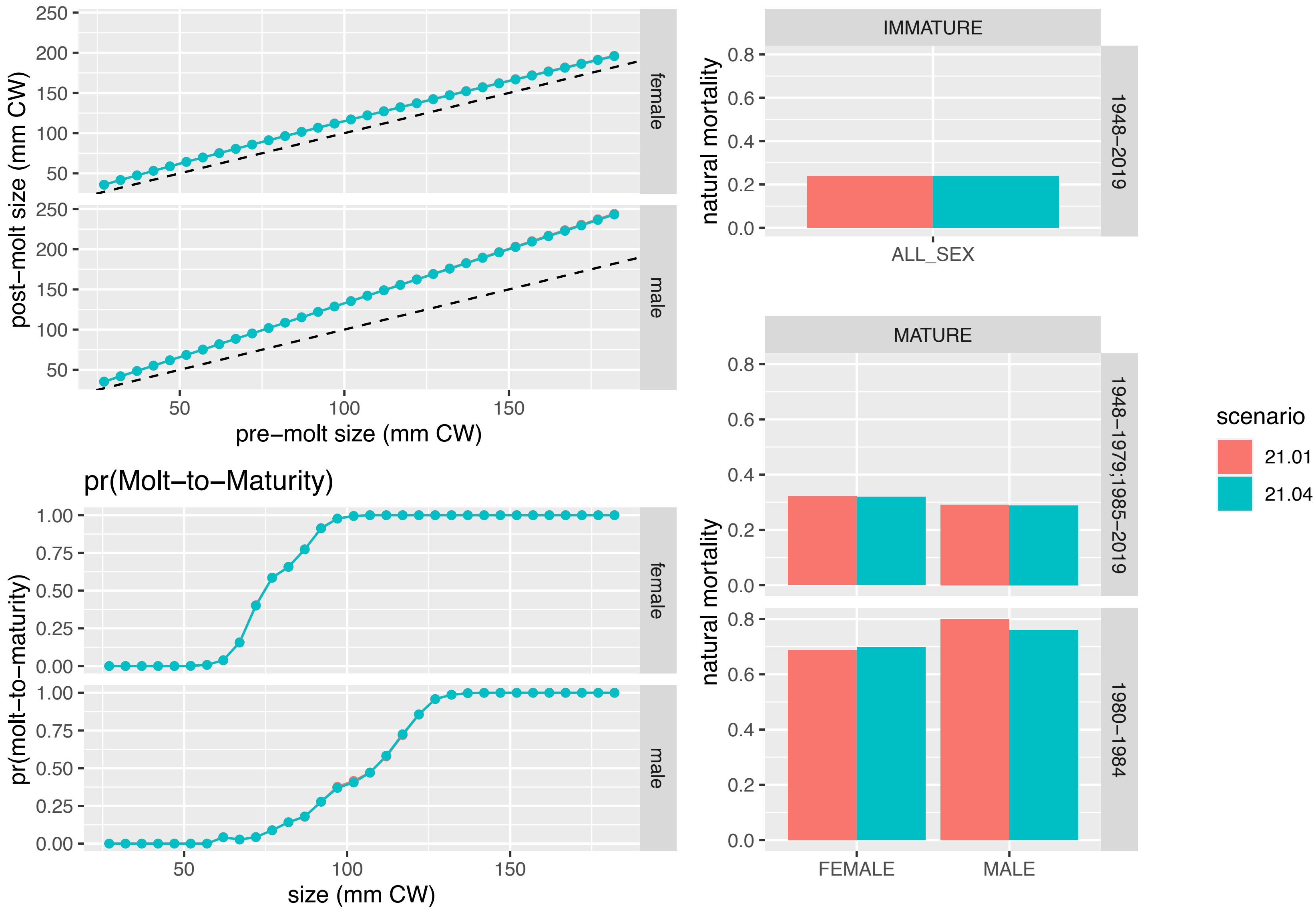


Figure 14. Estimated population processes.

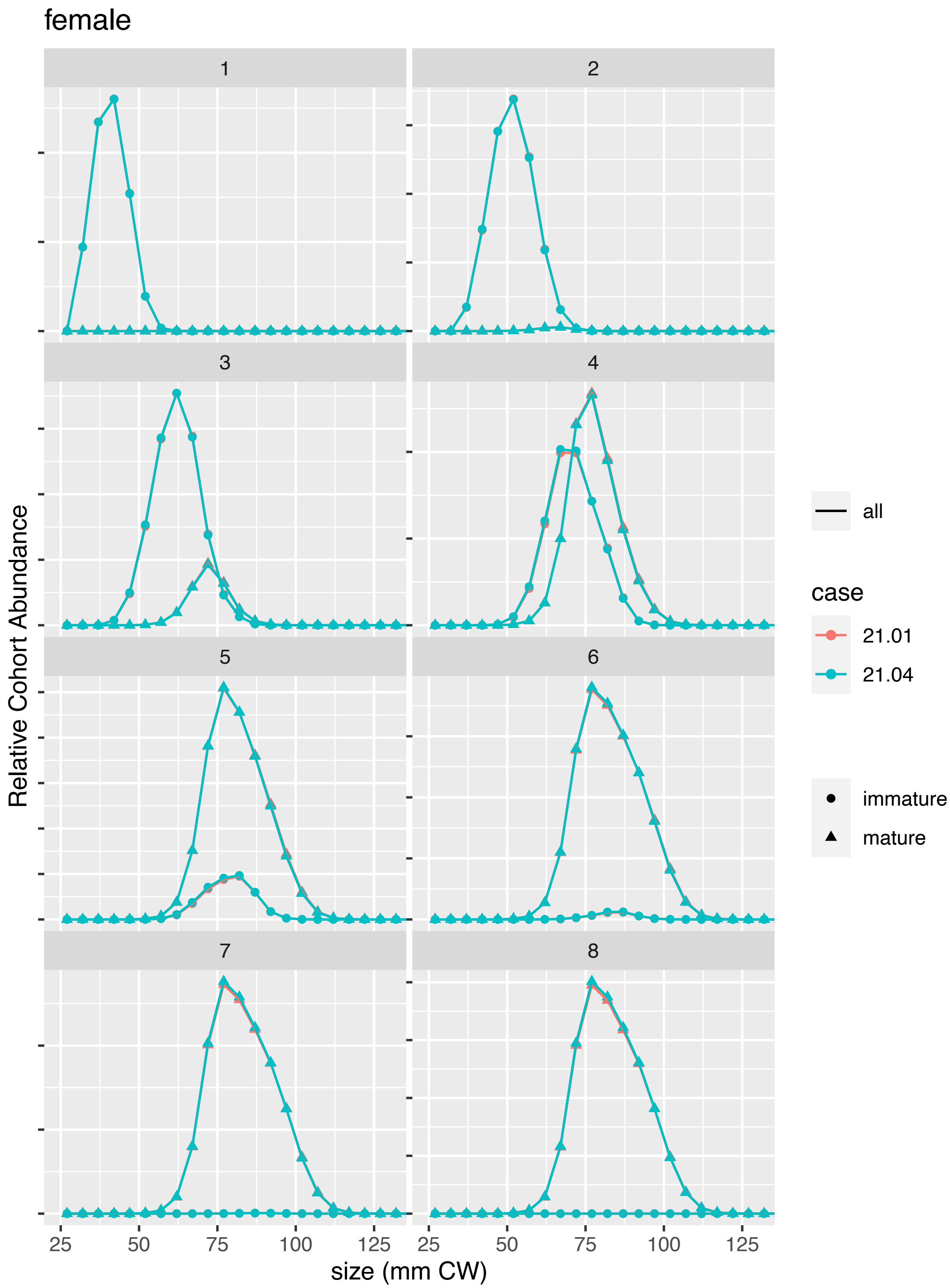


Figure 15. Estimated size progression of a cohort of female crab through time (years).

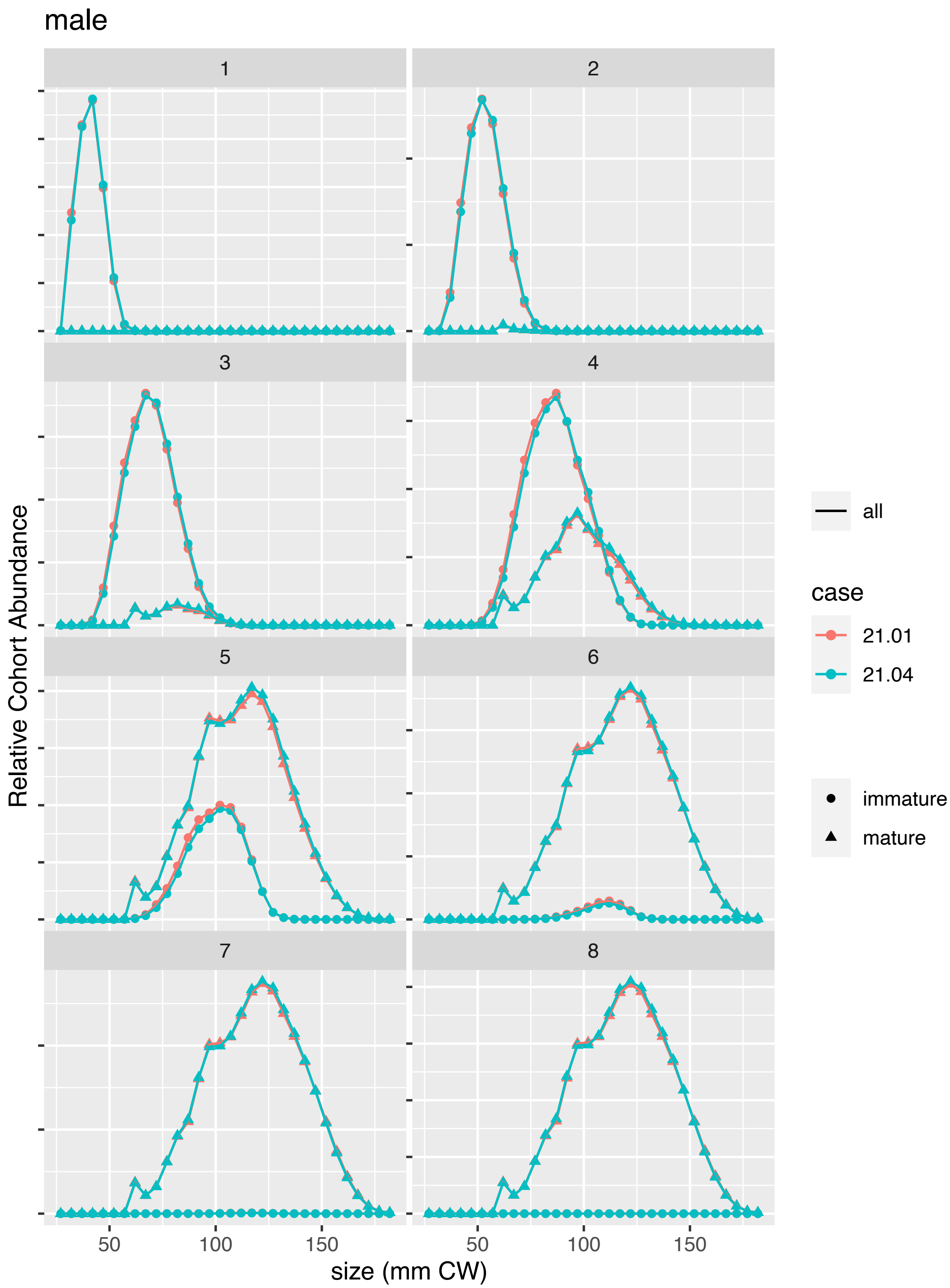


Figure 16. Estimated size progression of a cohort of male crab through time (years).

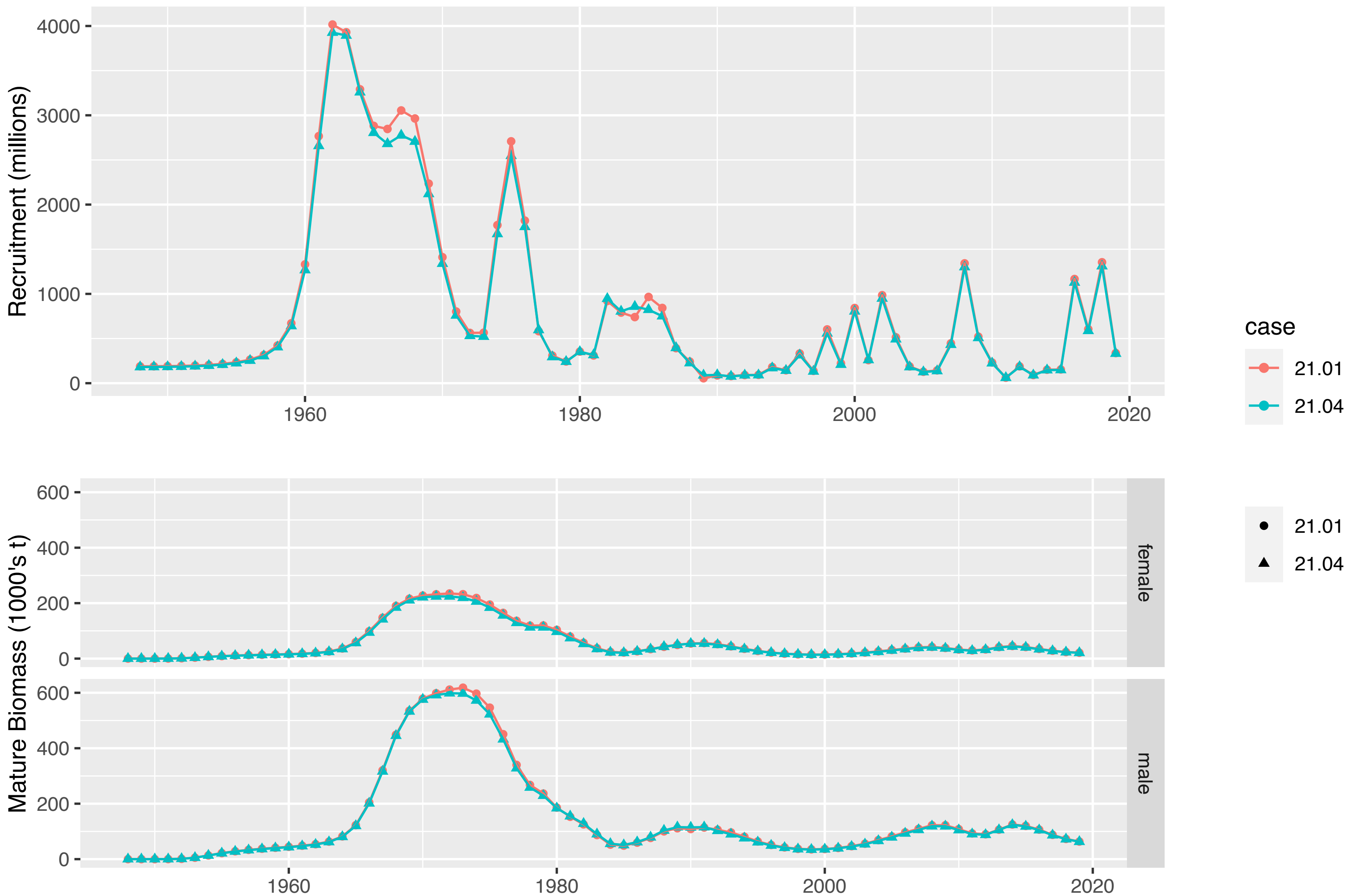


Figure 17. Estimated time series of recruitment and mature biomass.

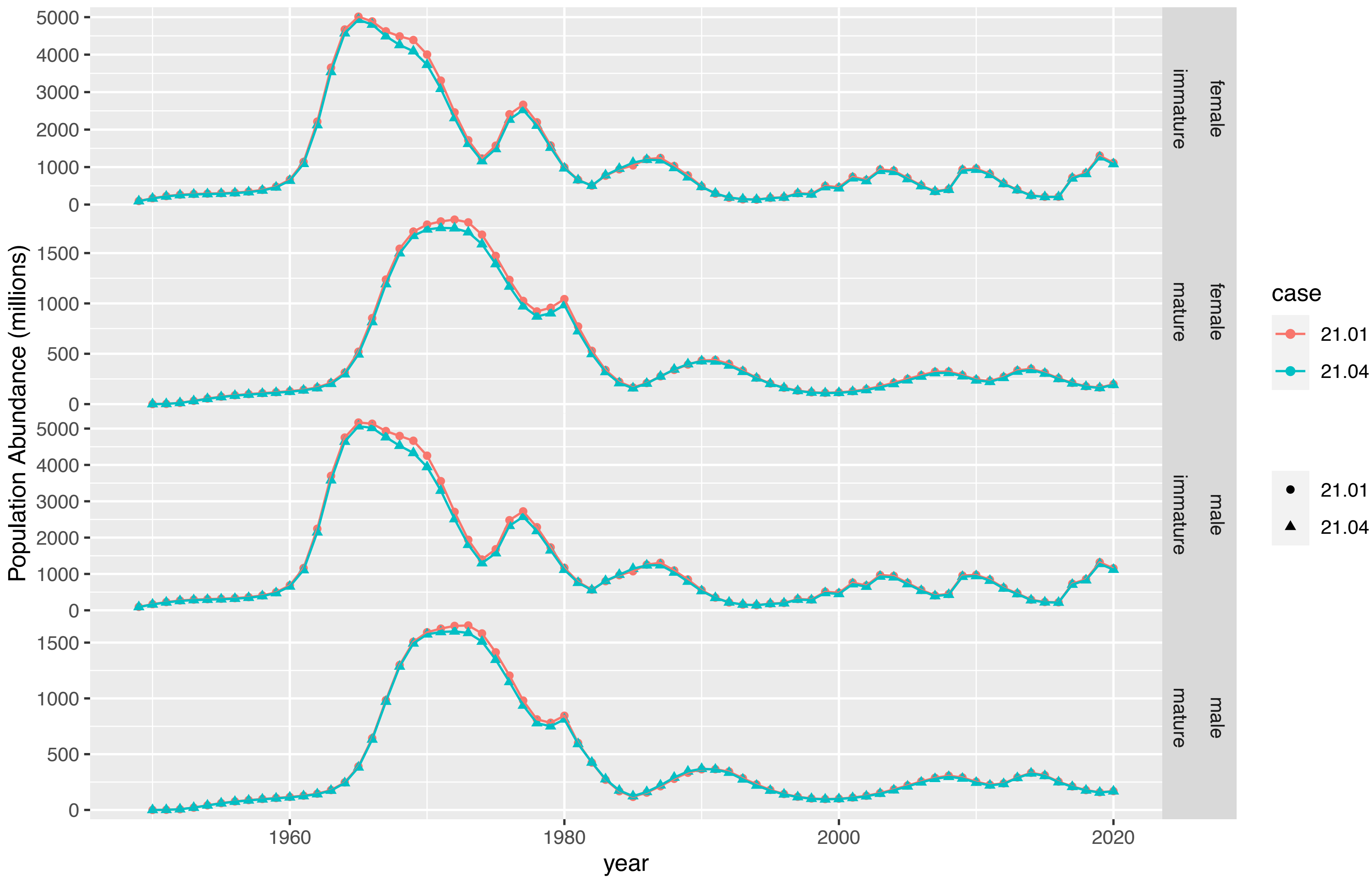


Figure 18. Estimated time series of population abundance.

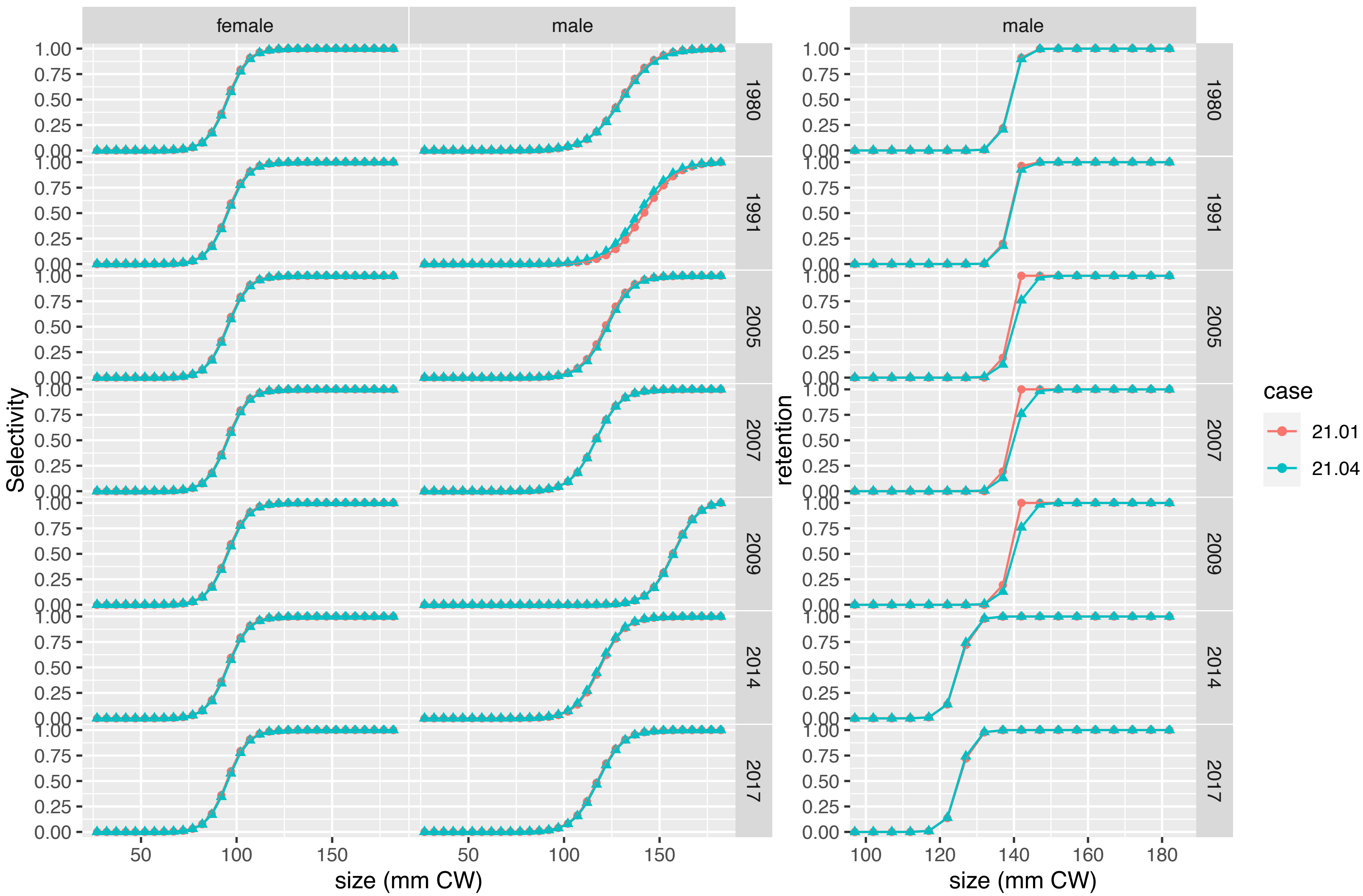


Figure 19. Estimated retention and total catch selectivity in the directed fishery ("TCF").

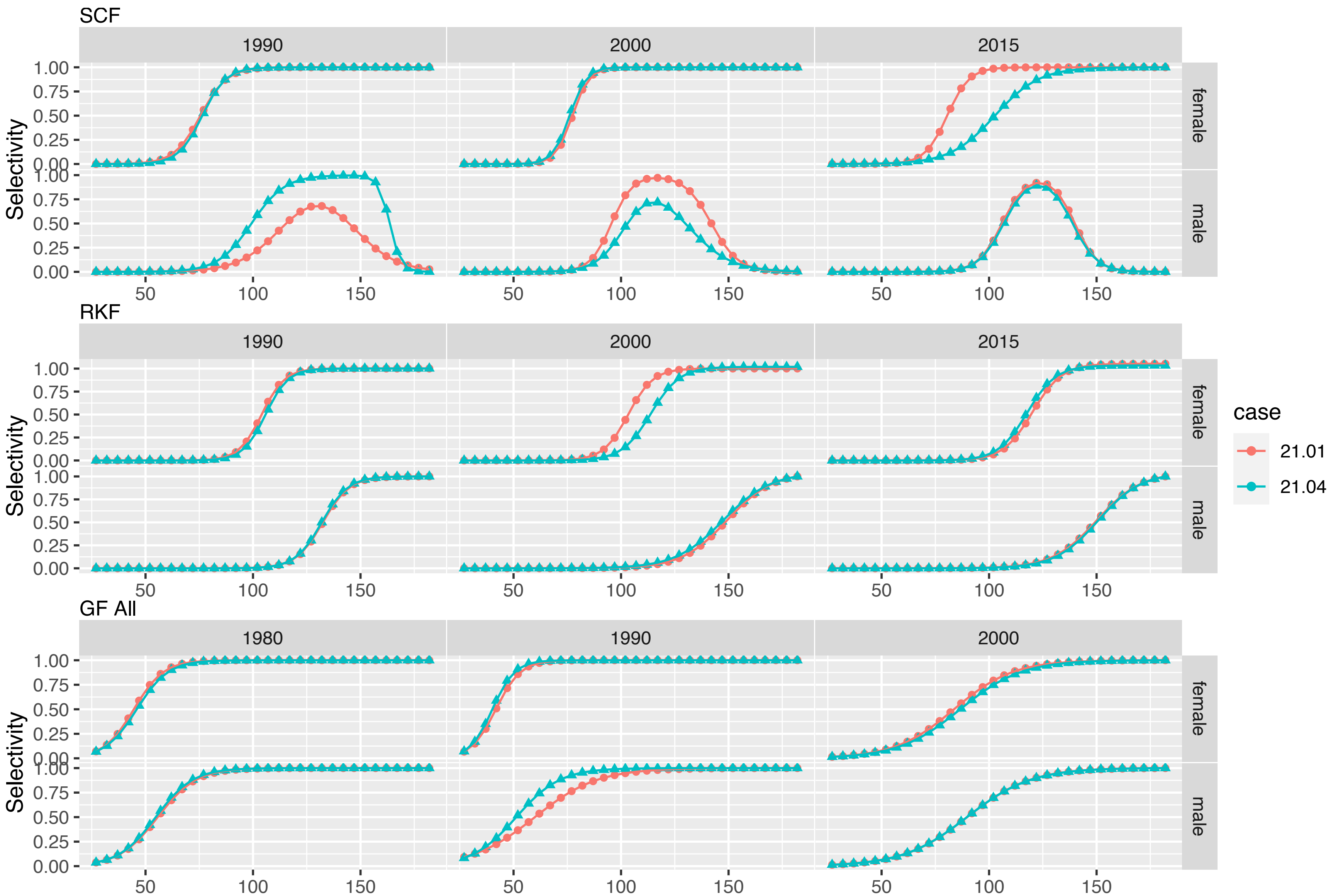


Figure 20. Estimated fishery selectivity in fisheries that take Tanner crab as bycatch: snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

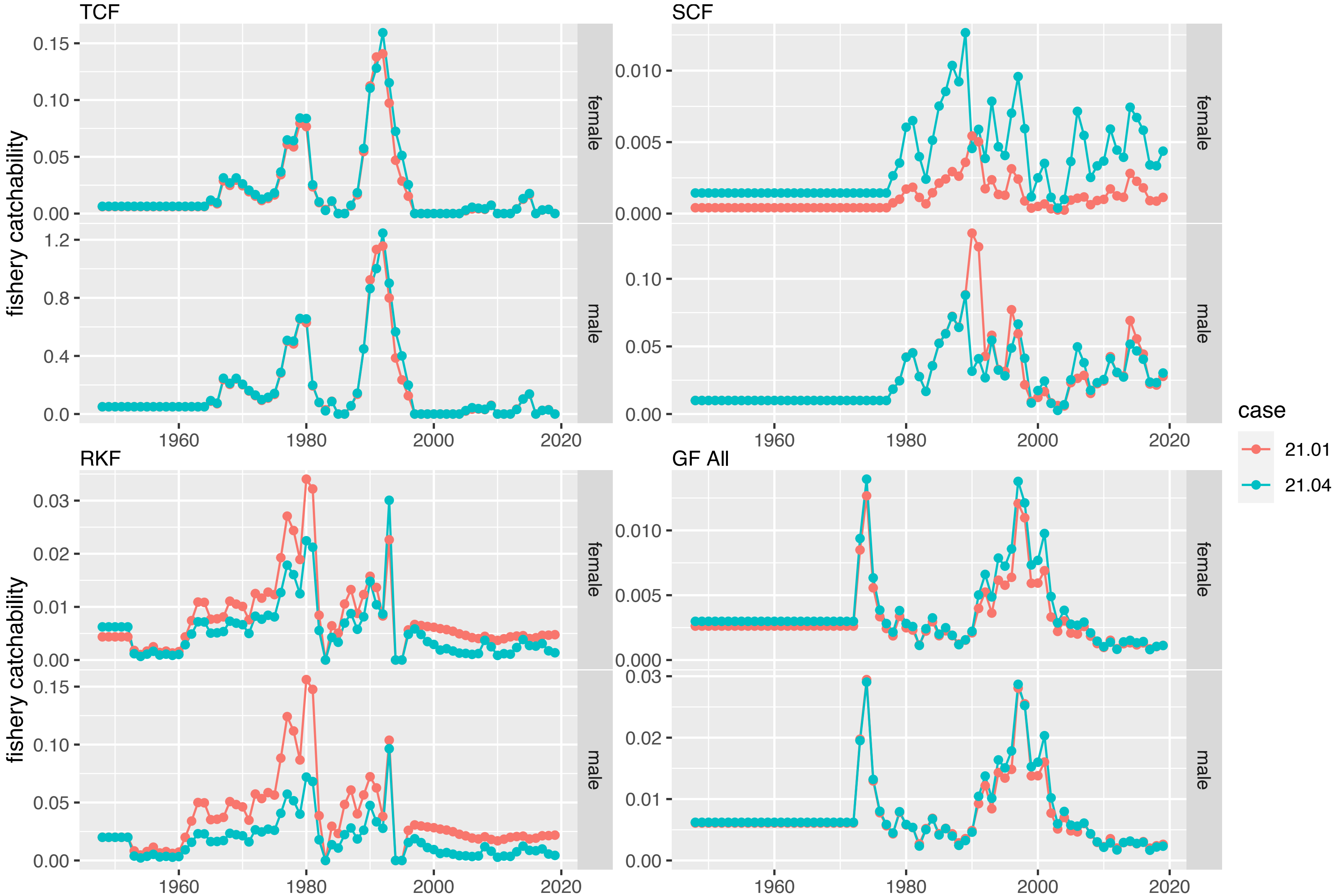


Figure 21. Estimated fishery capture rates in the directed fishery ("TCF") and other fisheries that take Tanner crab as bycatch: snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

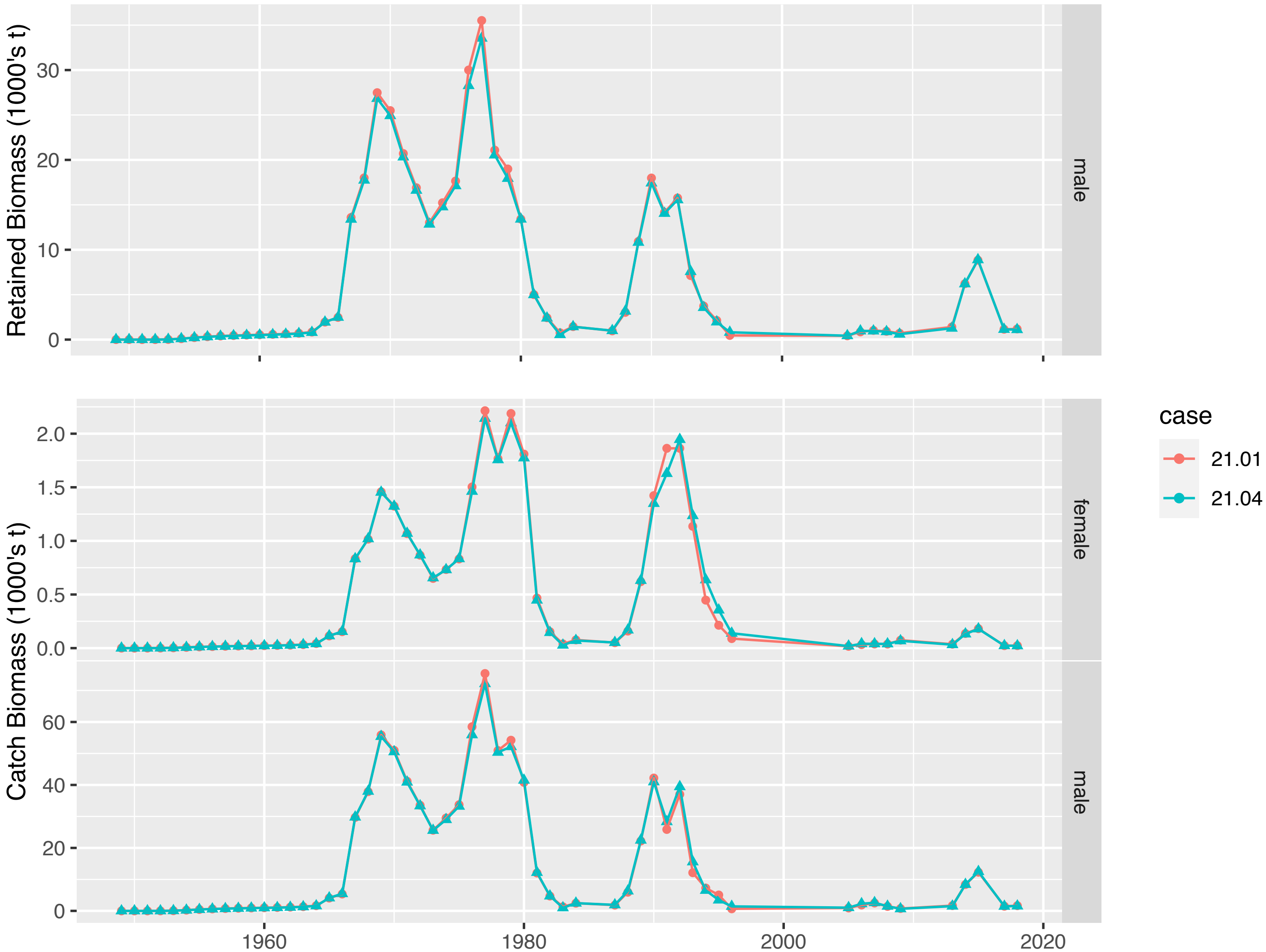


Figure 22. Model-estimated retained catch and total catch biomass in the directed fishery ("TCF").

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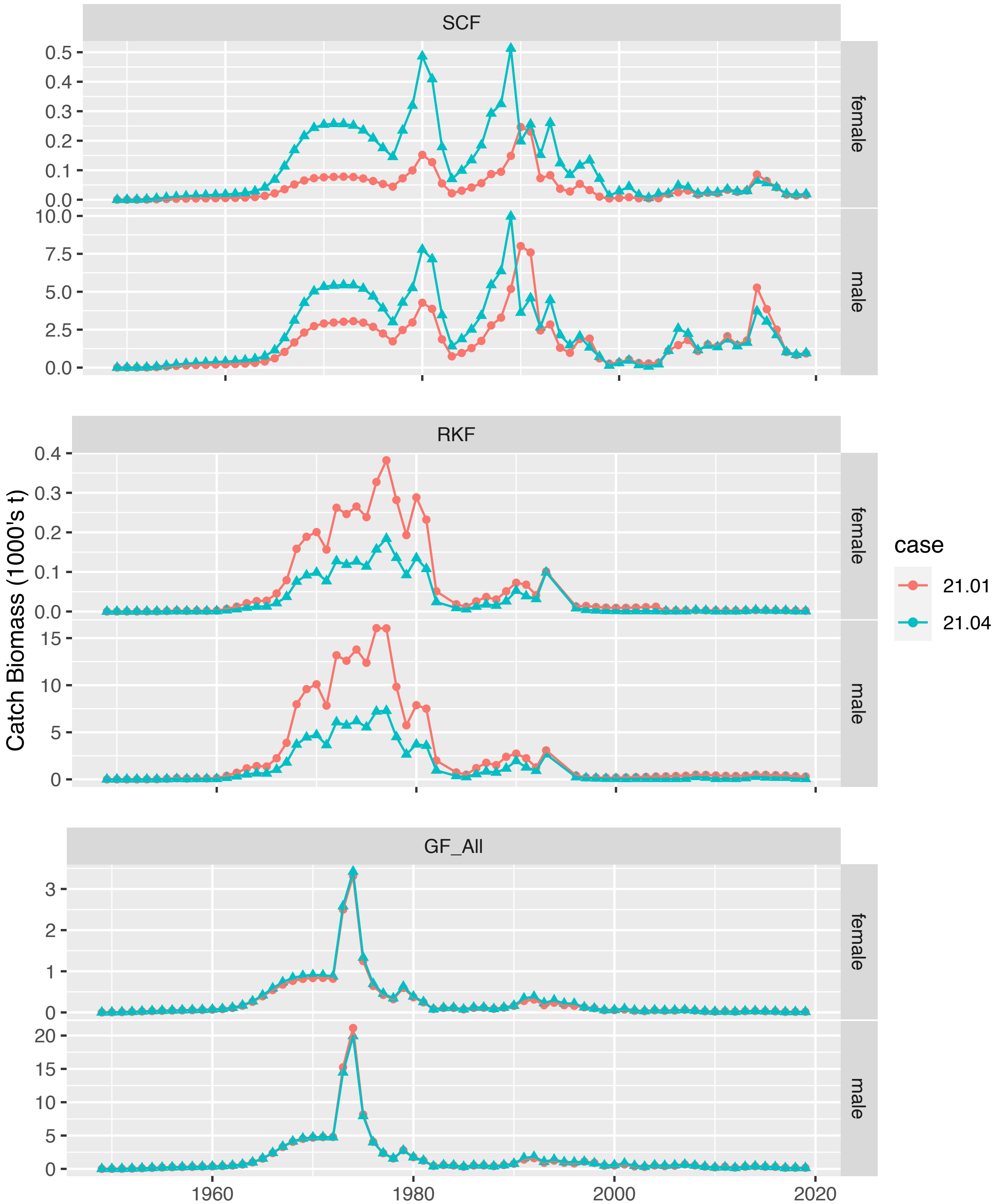


Figure 23. Model-estimated bycatch biomass in fisheries that take Tanner crab as bycatch: snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

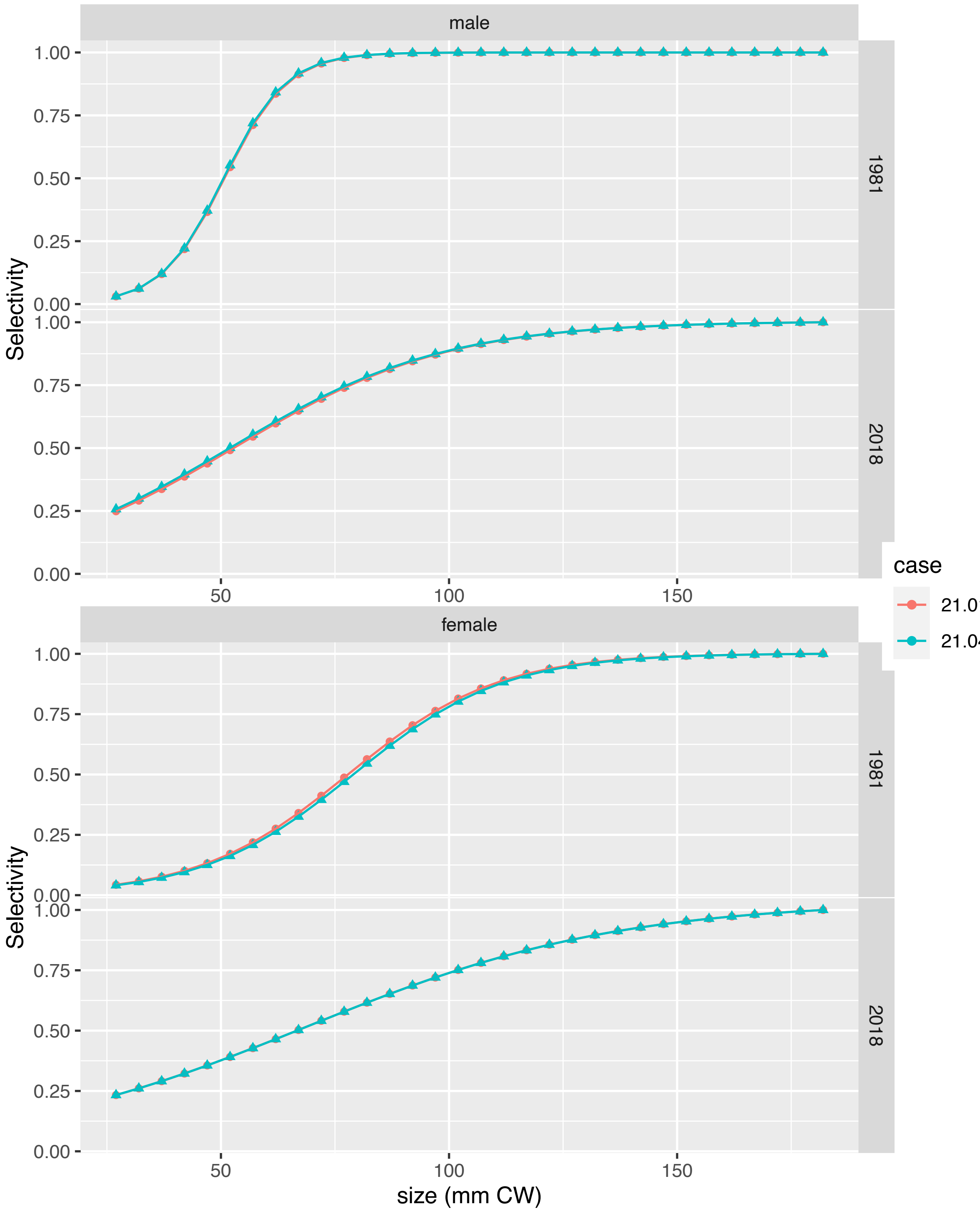


Figure 24. Estimated survey selectivity for the NMFS EBS Shelf Survey.

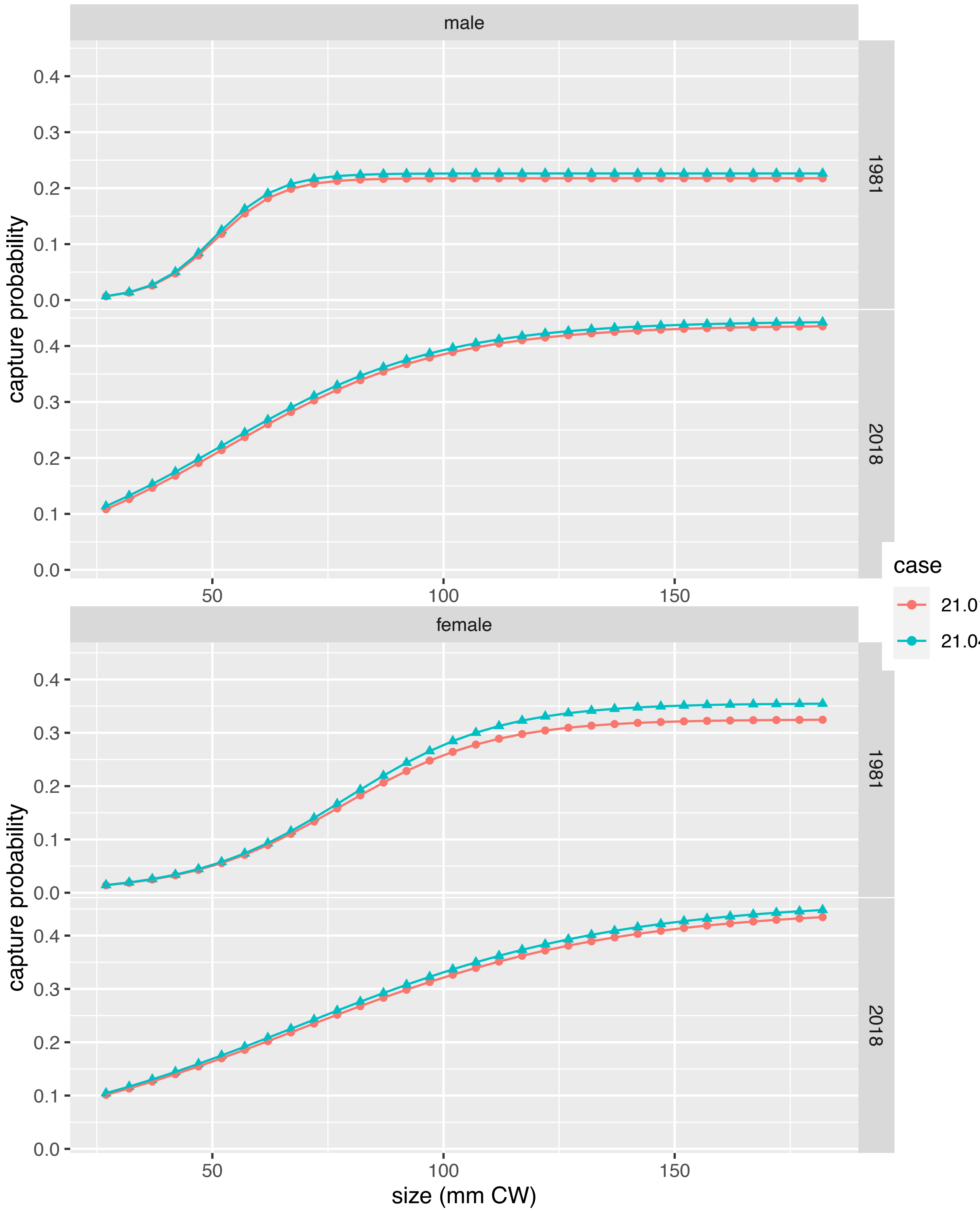


Figure 25. Estimated survey catchability for the NMFS EBS Shelf Survey.

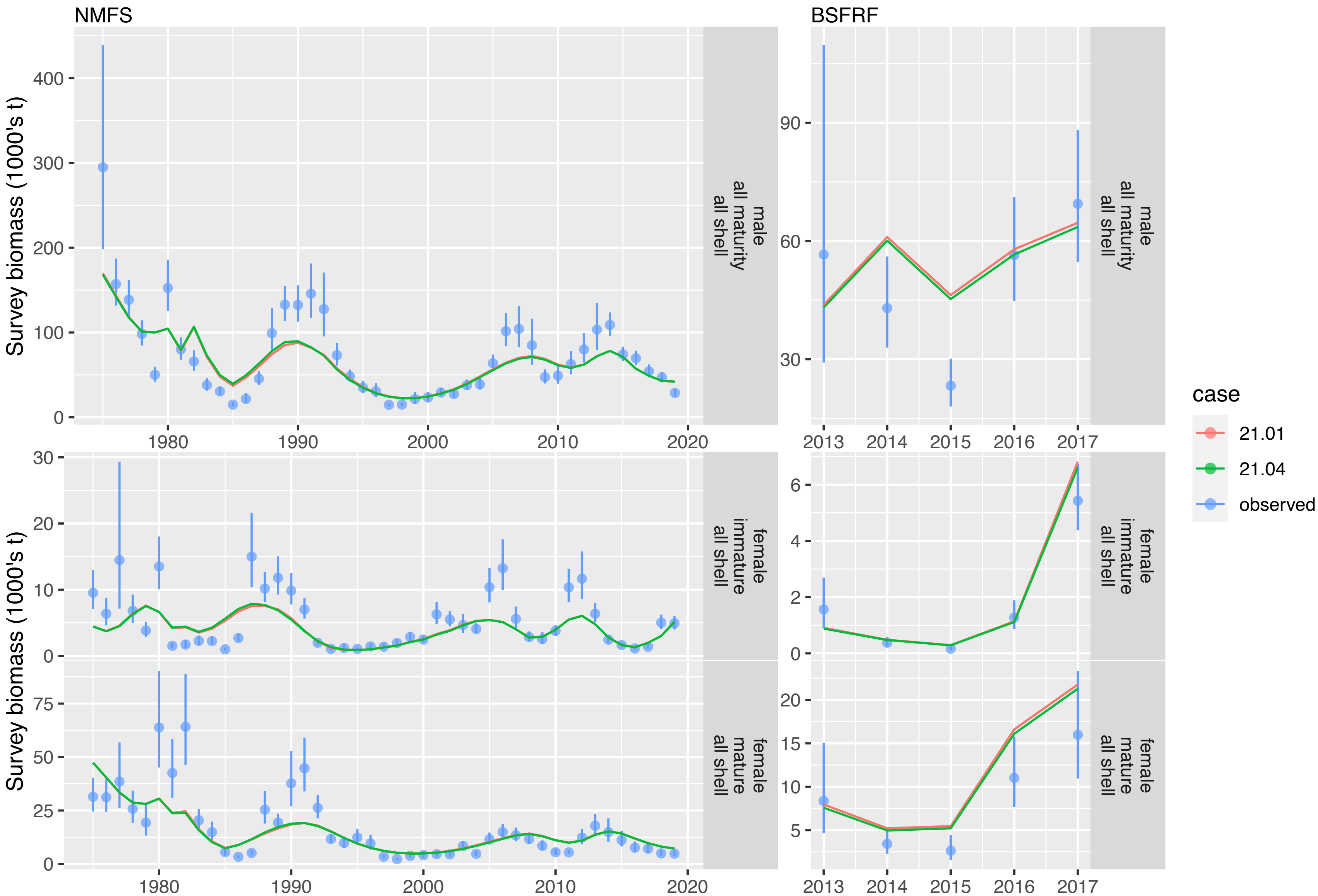


Figure 26. Fits to survey biomass time series from the NMFS EBS Shelf Survey and BSFRF side-by-side surveys.

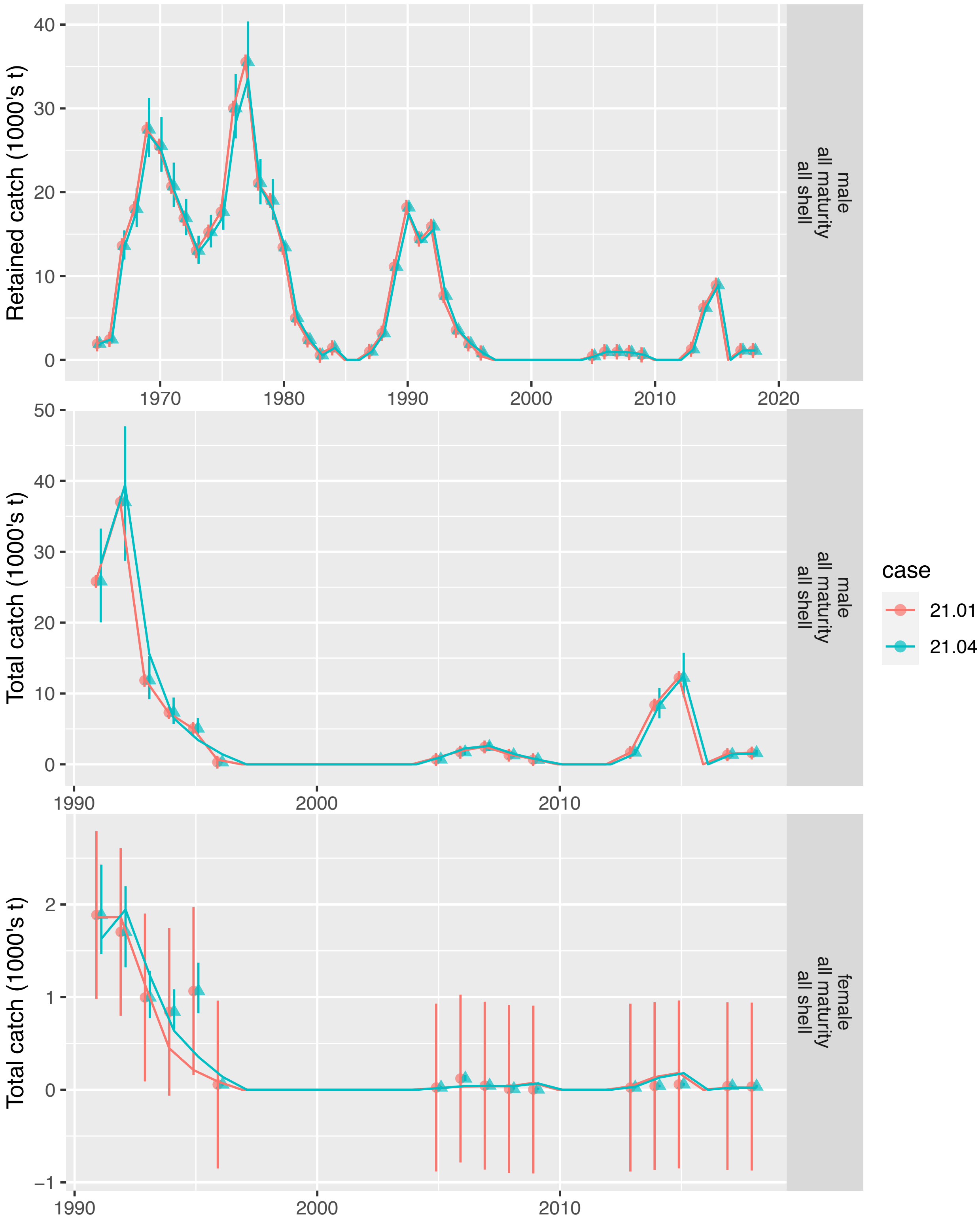


Figure 27. Fits to retained catch and total catch biomass time series in the directed fishery.

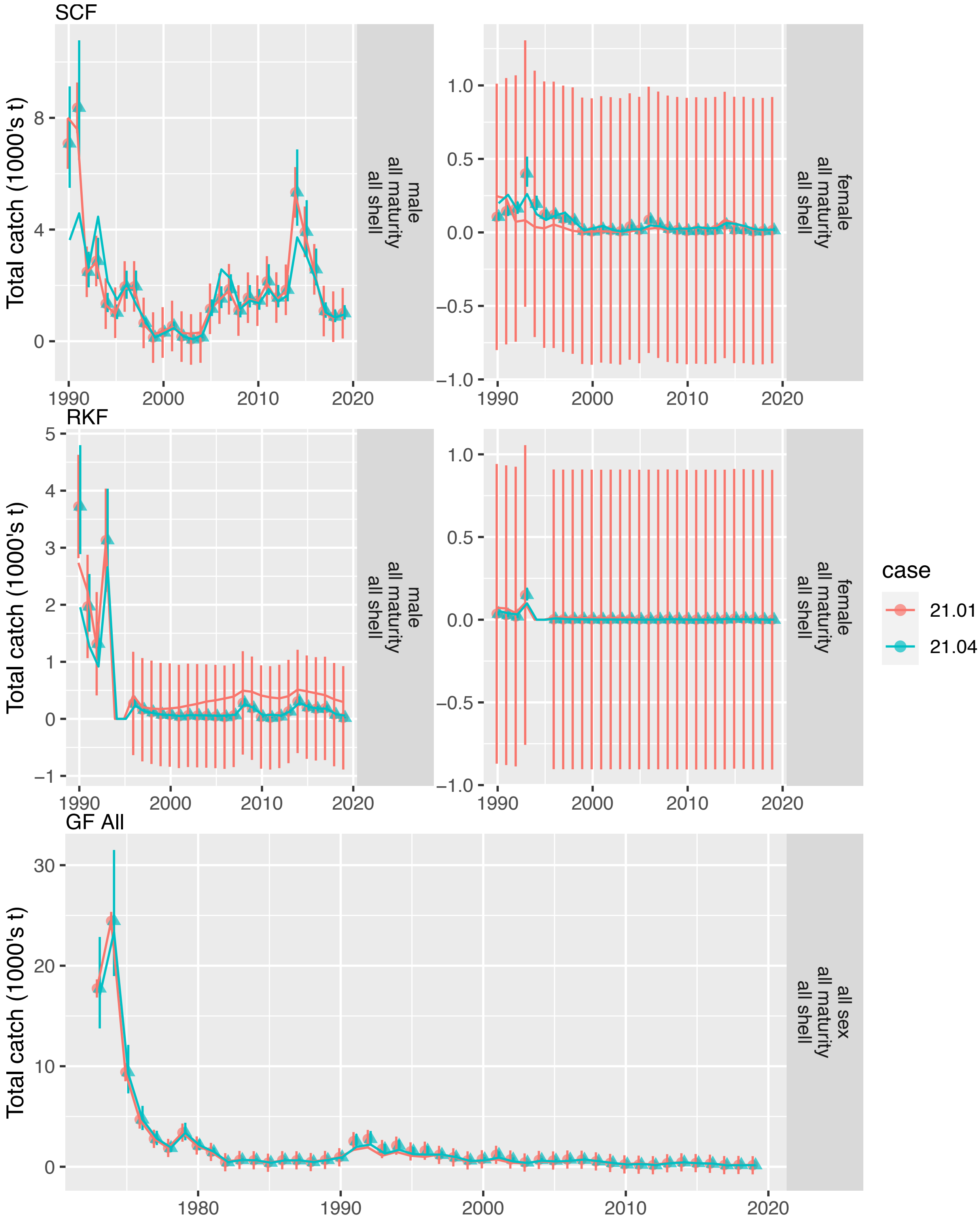


Figure 28. Fits to catch biomass time series for Tanner crab bycatch in the snow crab (“SCF”), BBRKC (“RKF”), and groundfish fisheries (“GF All”).

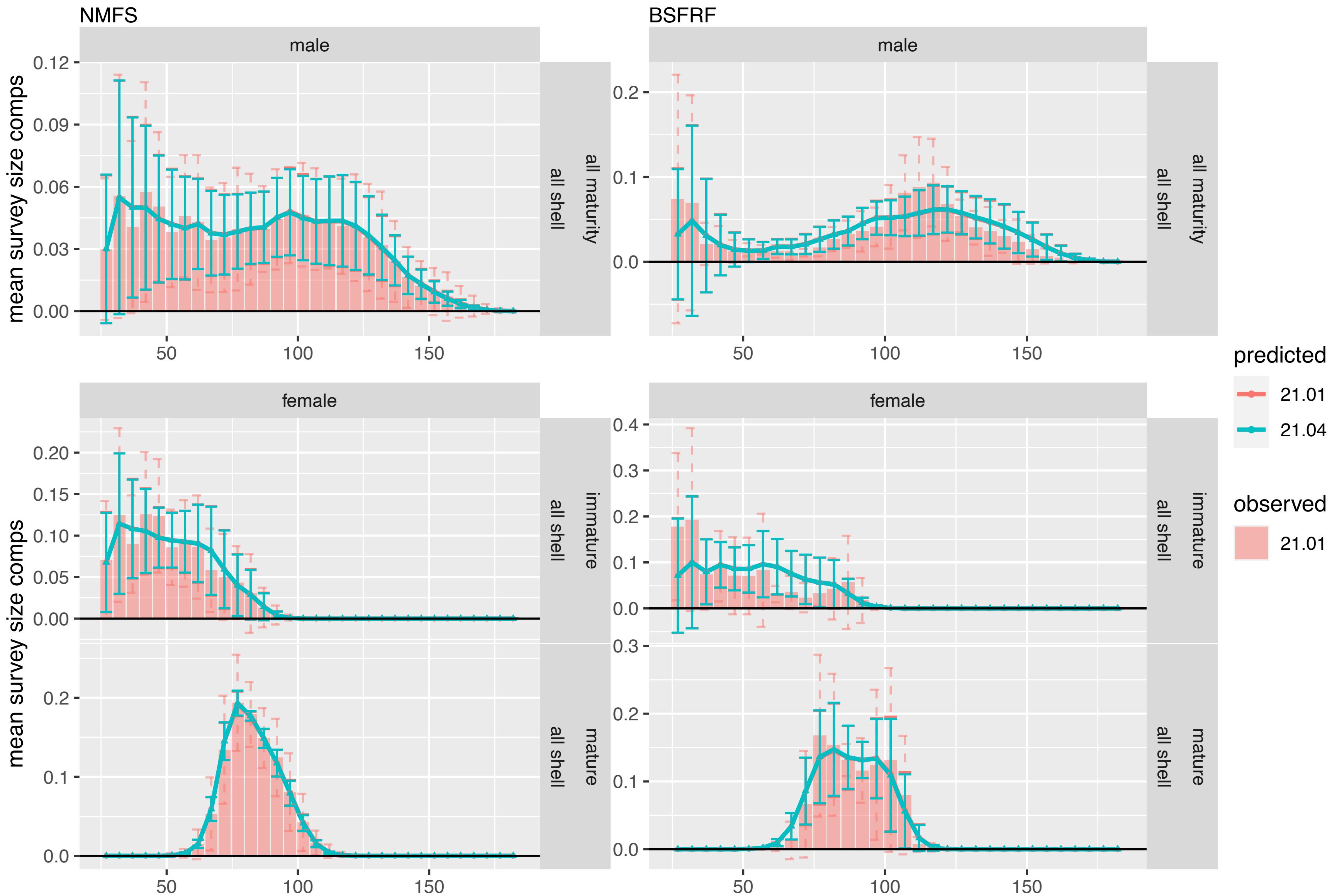


Figure 29. Fits to mean size compositions from the NMFS EBS Shelf Survey and BSFRF side-by-side surveys.

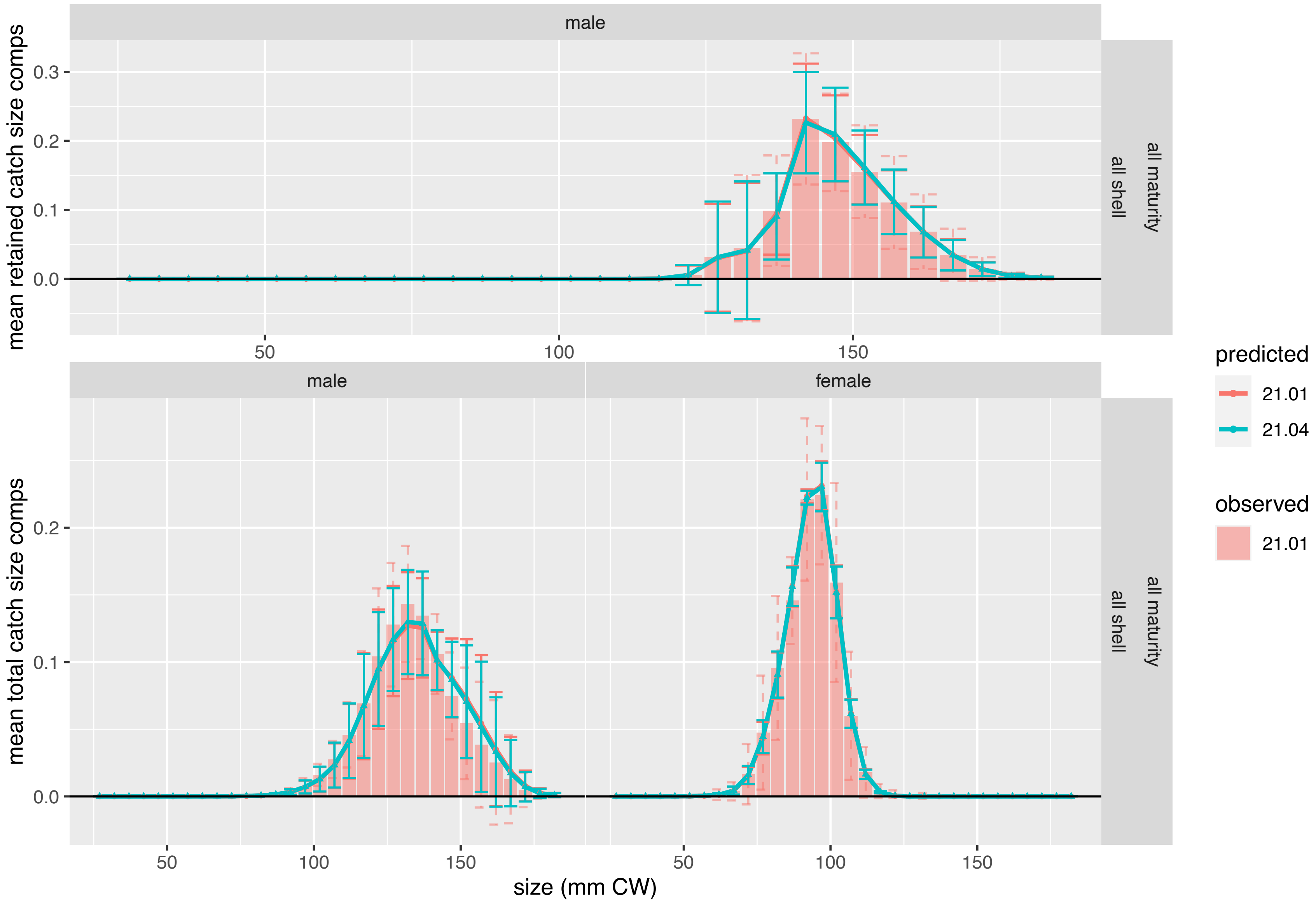


Figure 30. Fits to mean size compositions for retained catch and total catch size compositions in the directed fishery.

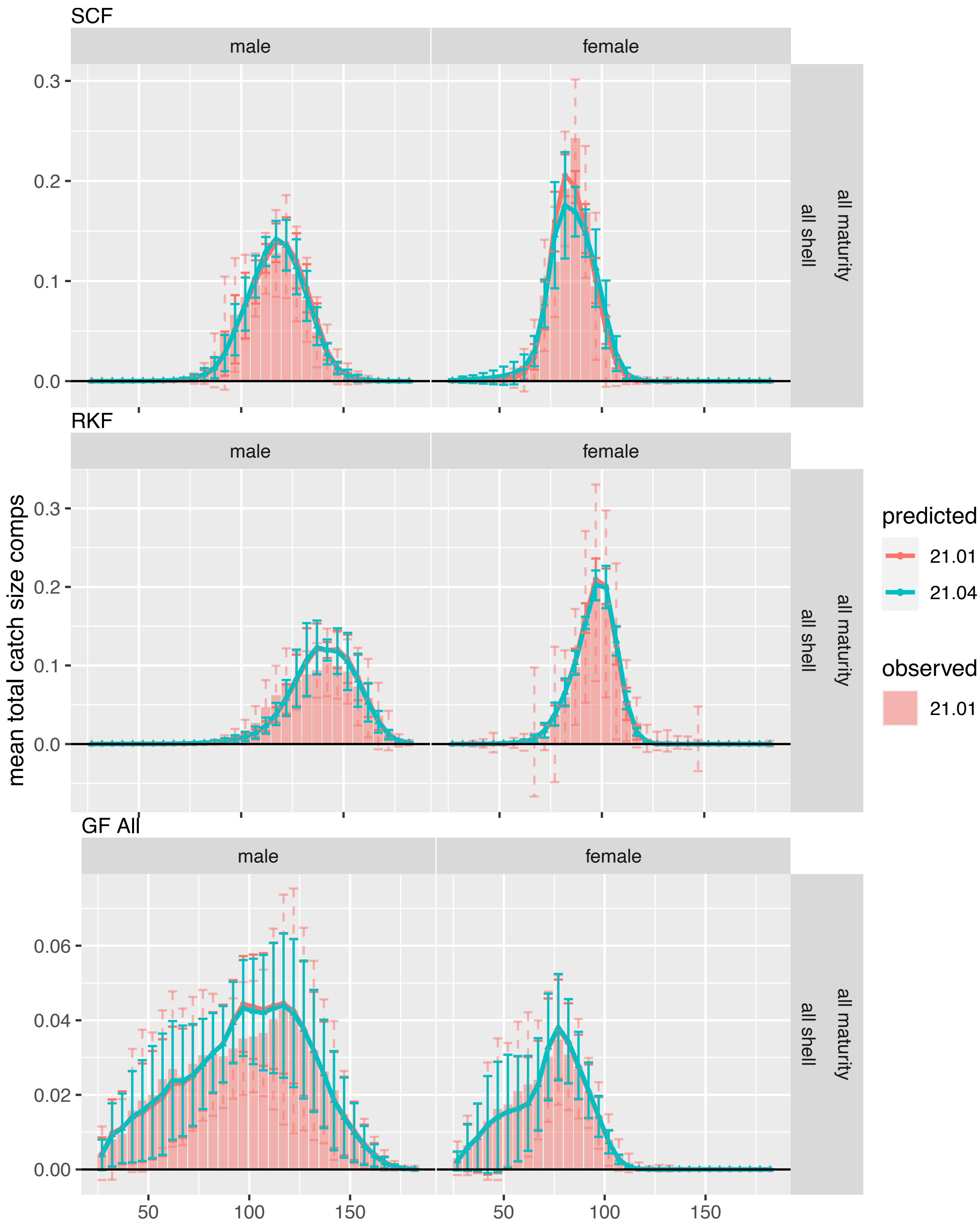


Figure 31. Fits to mean size compositions for Tanner crab bycatch in the snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

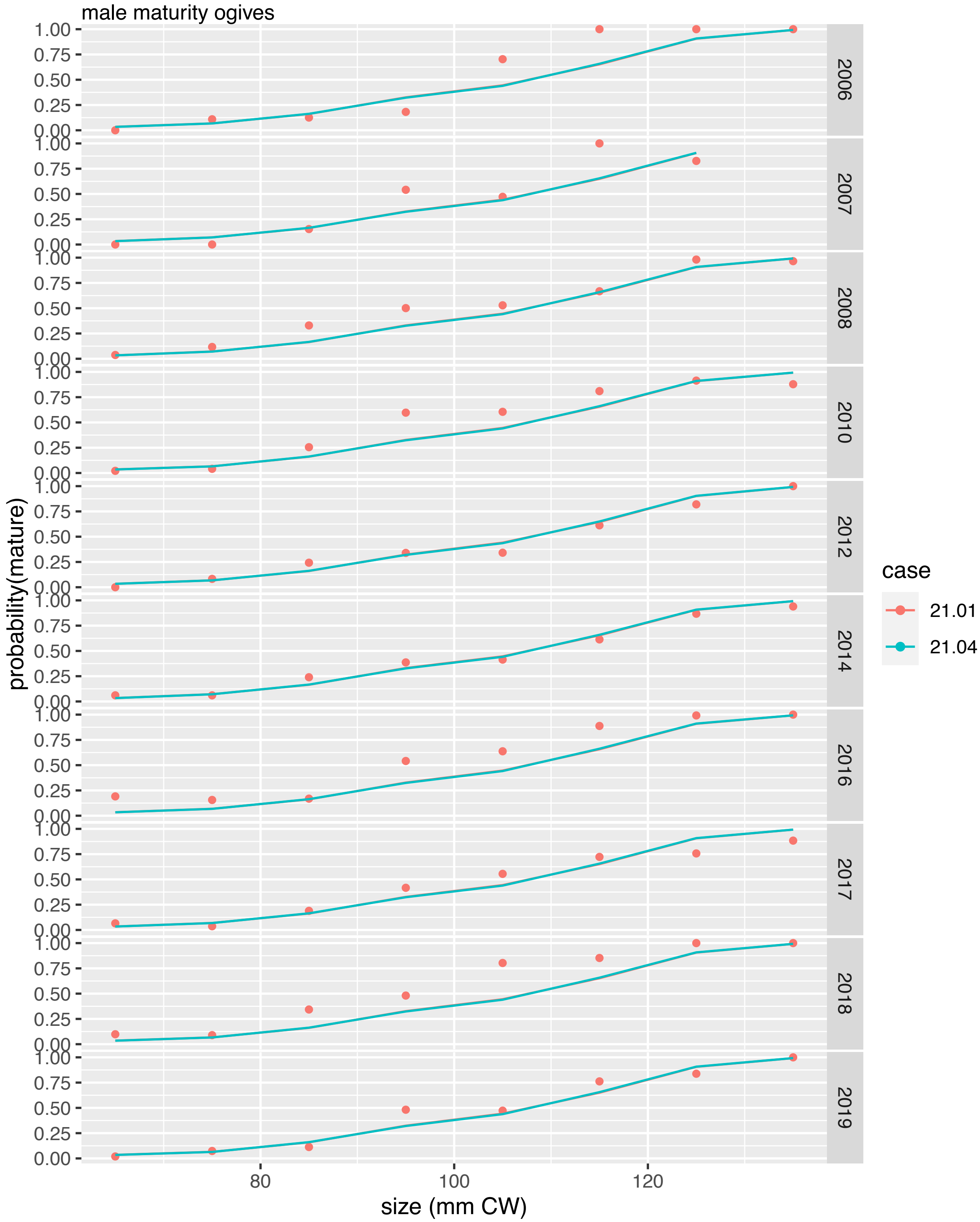


Figure 32. Model fits to maturity ogive data.

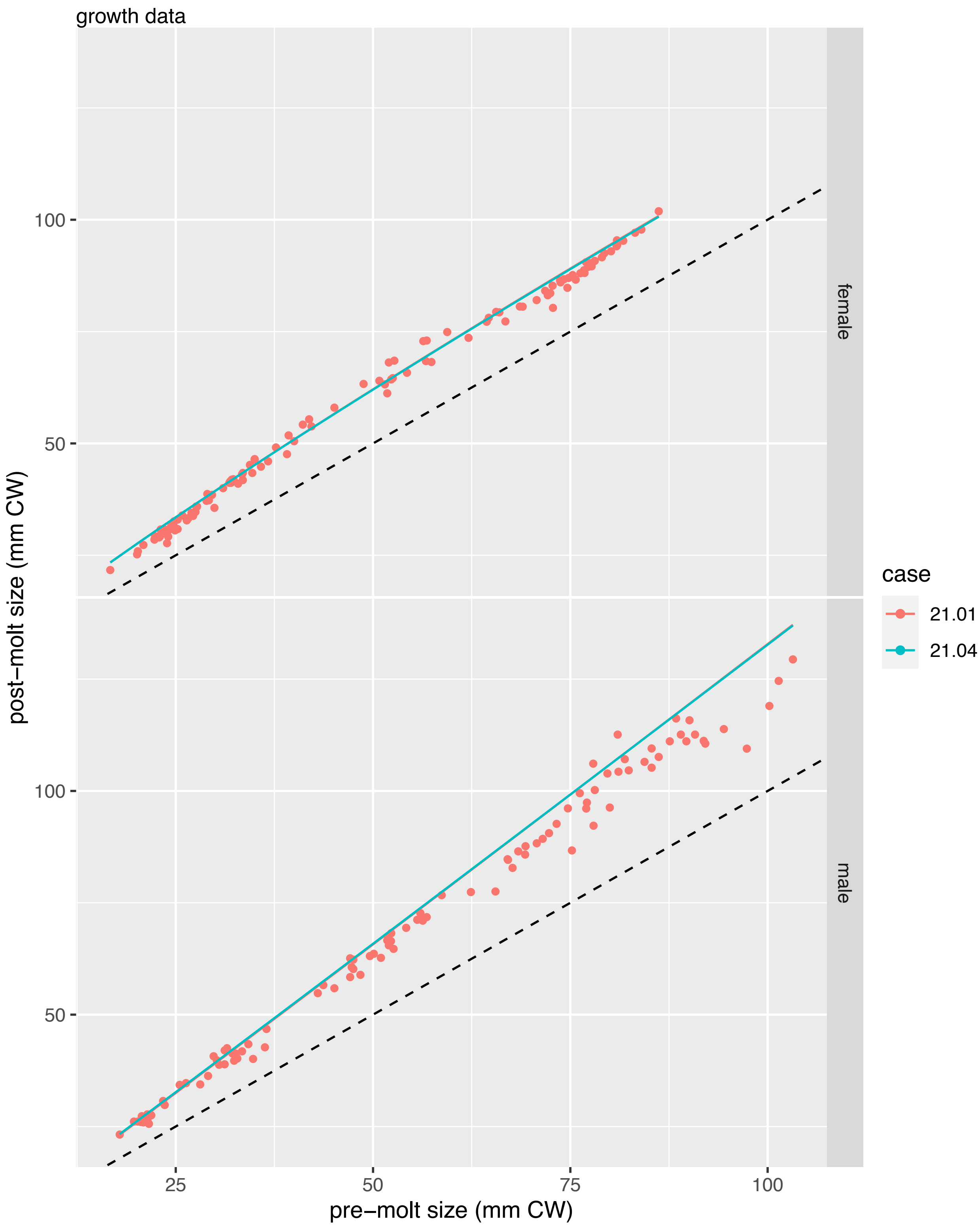


Figure 33. Model fits to maturity growth data.

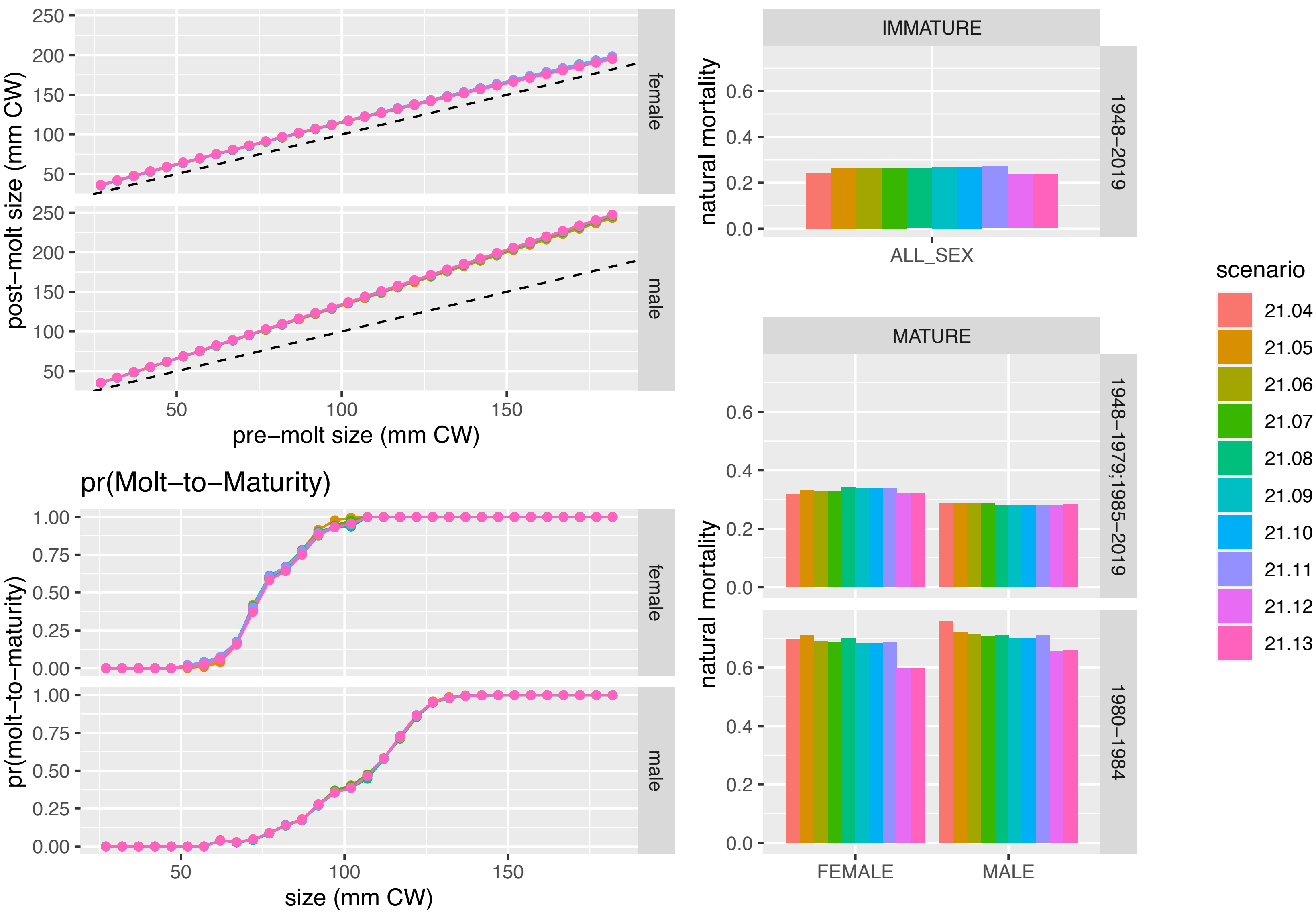


Figure 34. Estimated population processes.

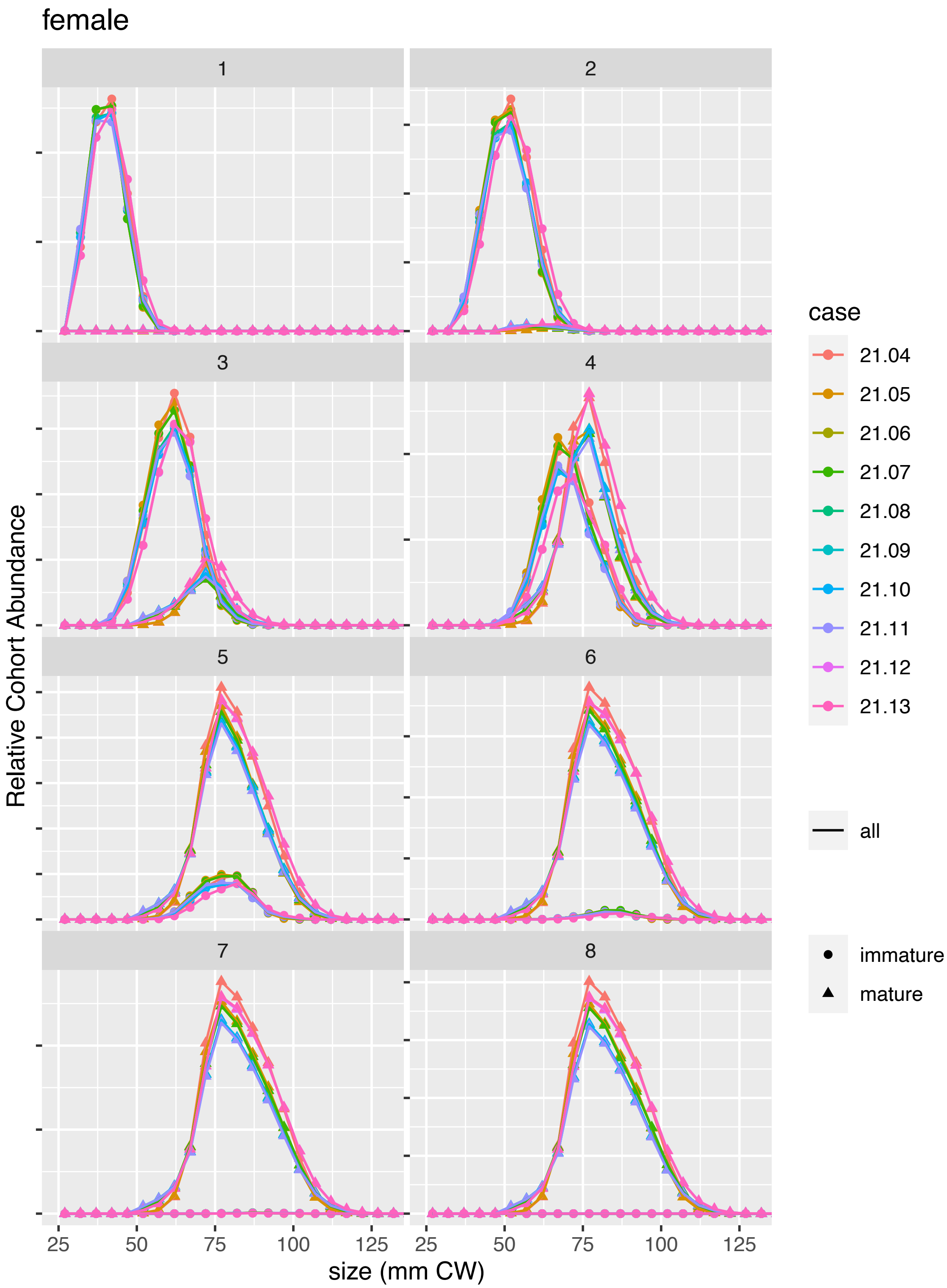


Figure 35. Estimated size progression of a cohort of female crab through time (years).

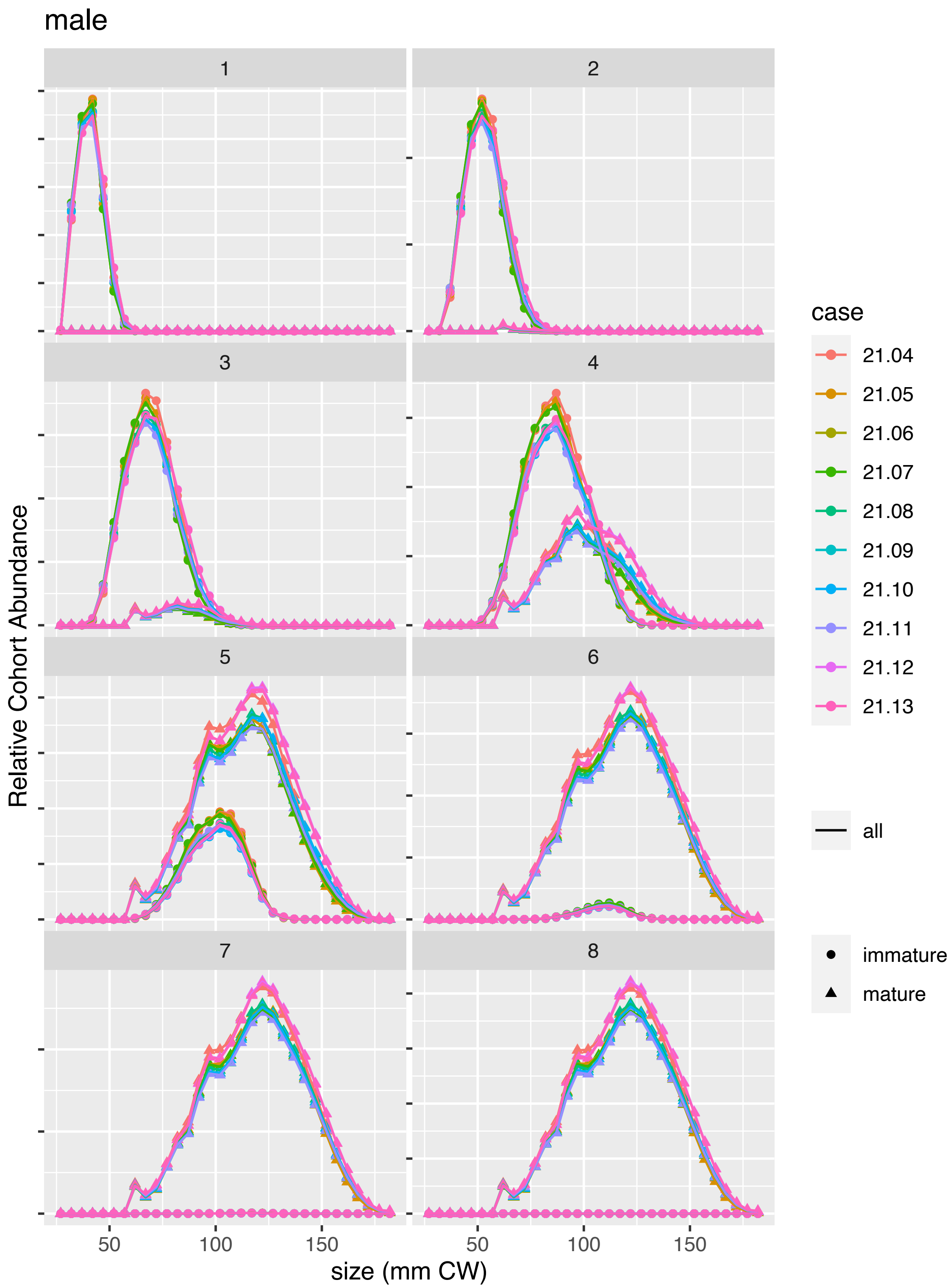


Figure 36. Estimated size progression of a cohort of male crab through time (years).

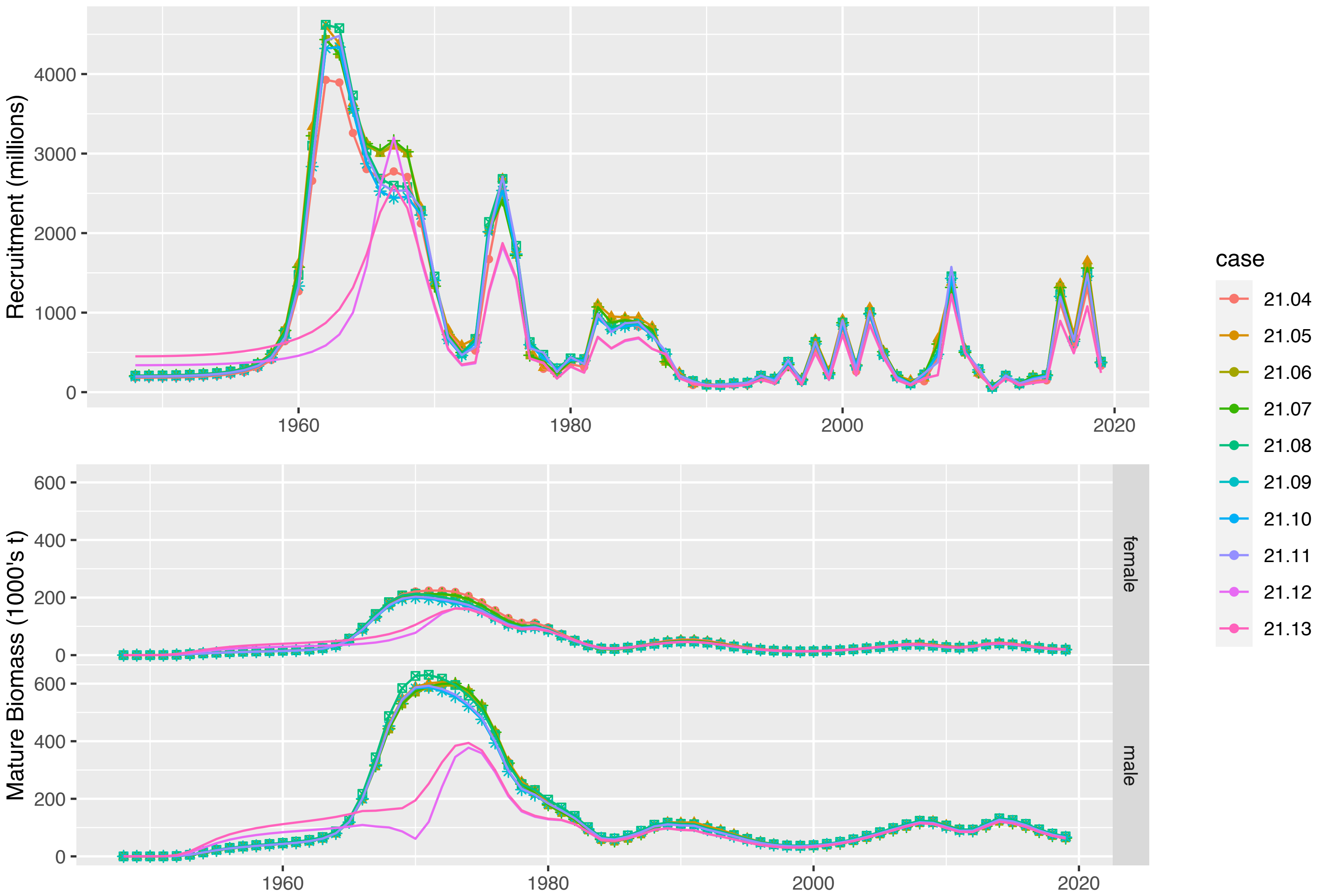


Figure 37. Estimated time series of recruitment and mature biomass.

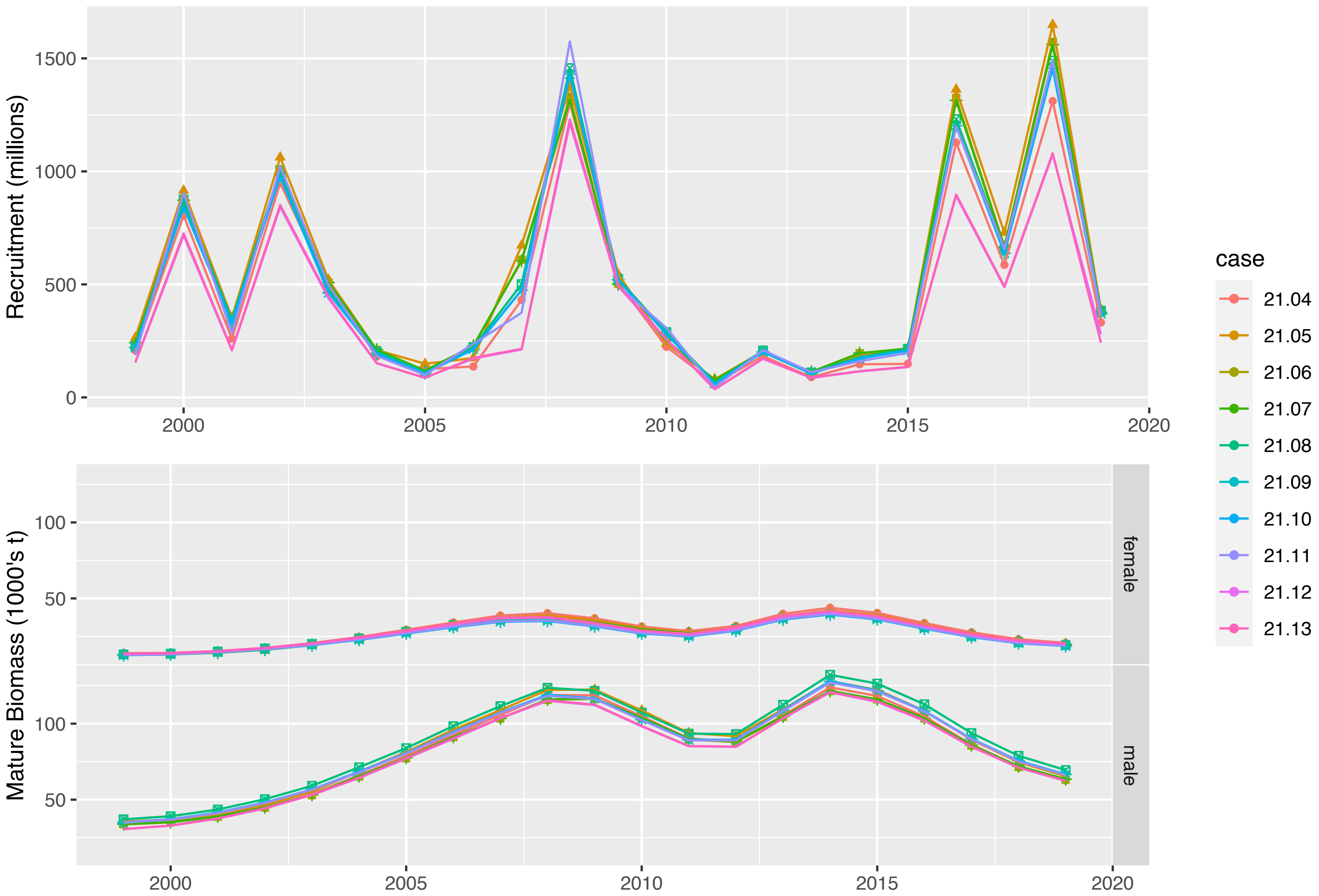


Figure 37a. Estimated time series of recruitment and mature biomass.

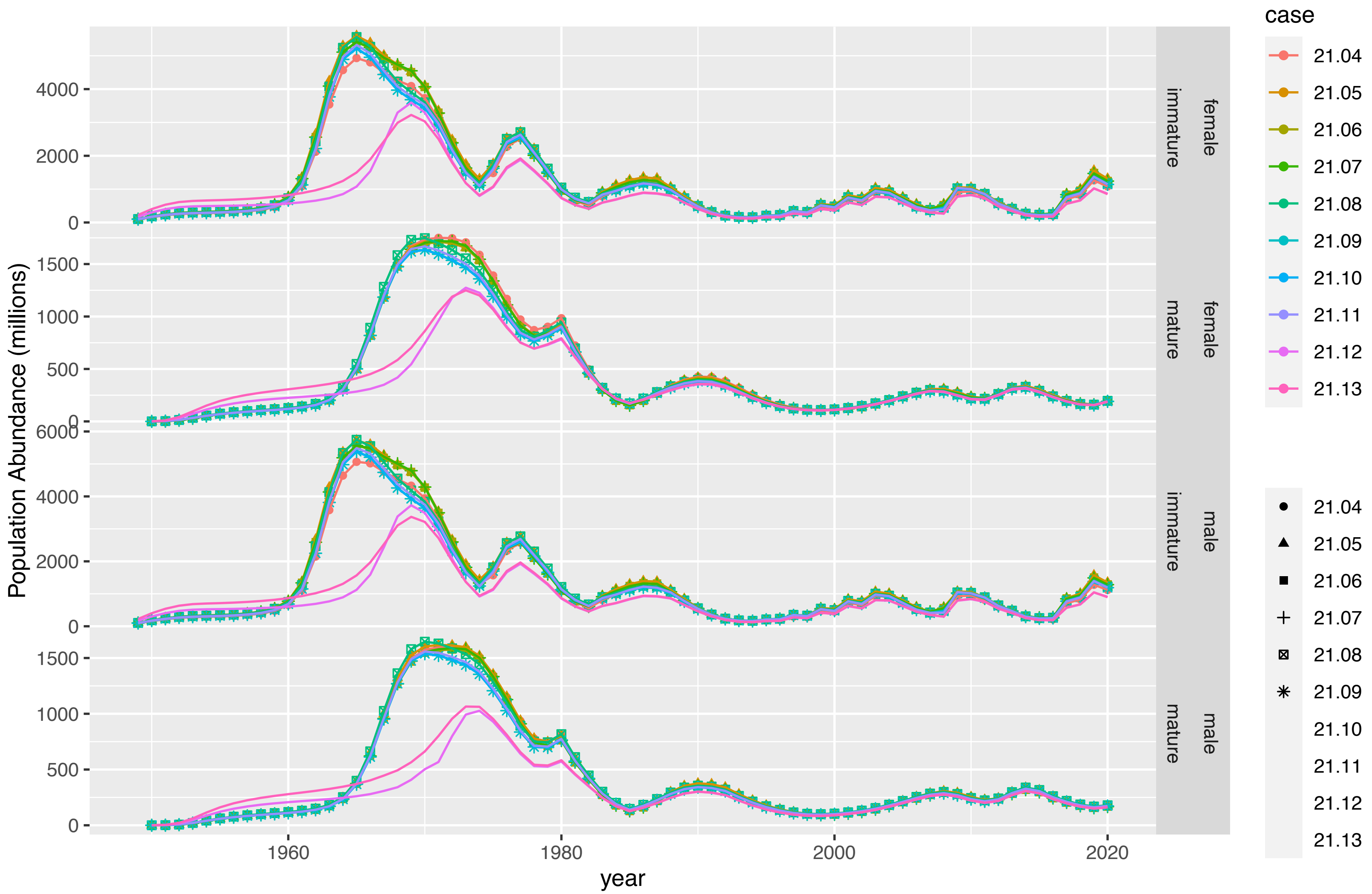


Figure 38. Estimated time series of population abundance.

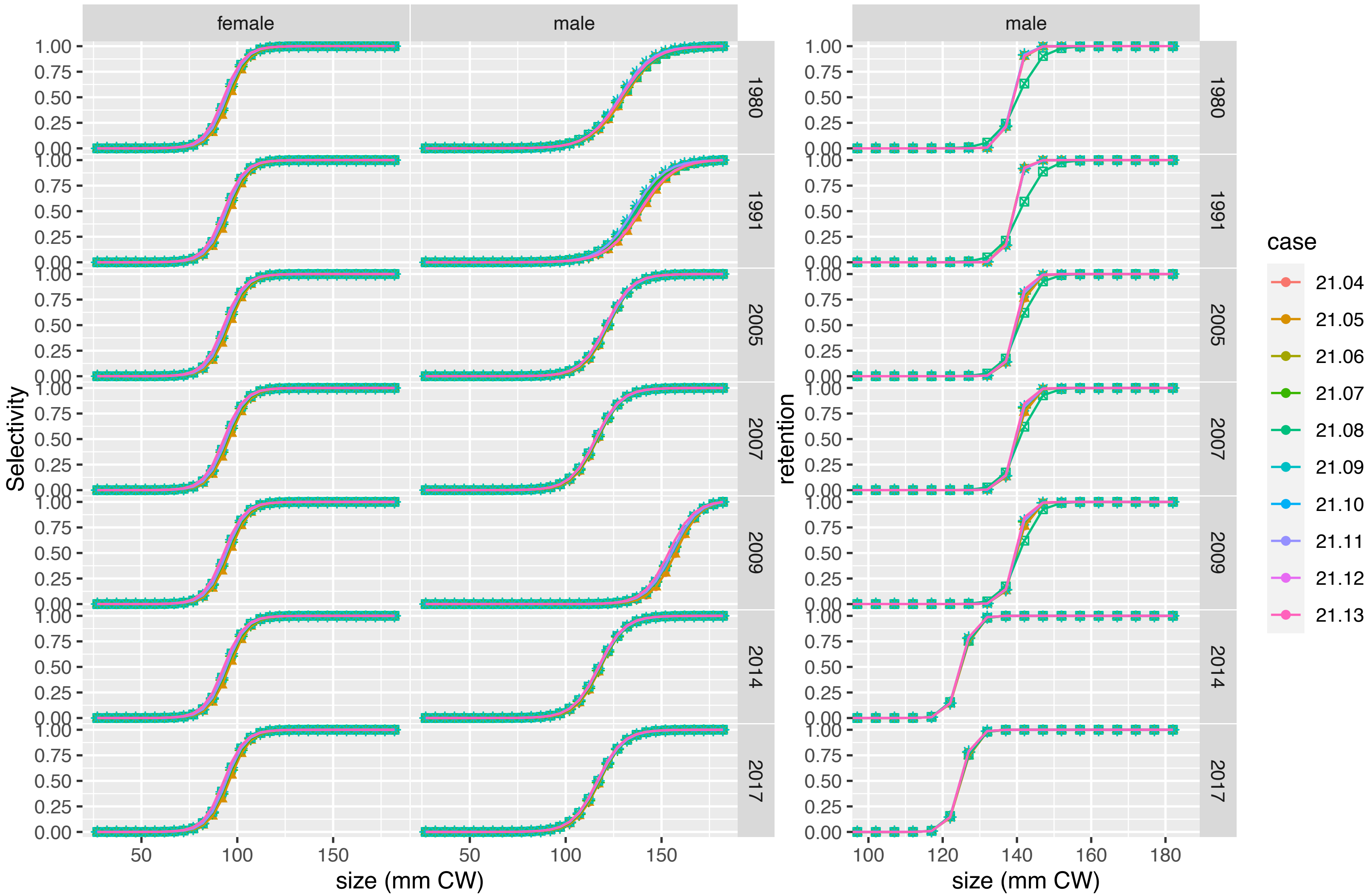


Figure 39. Estimated retention and total catch selectivity in the directed fishery ("TCF").

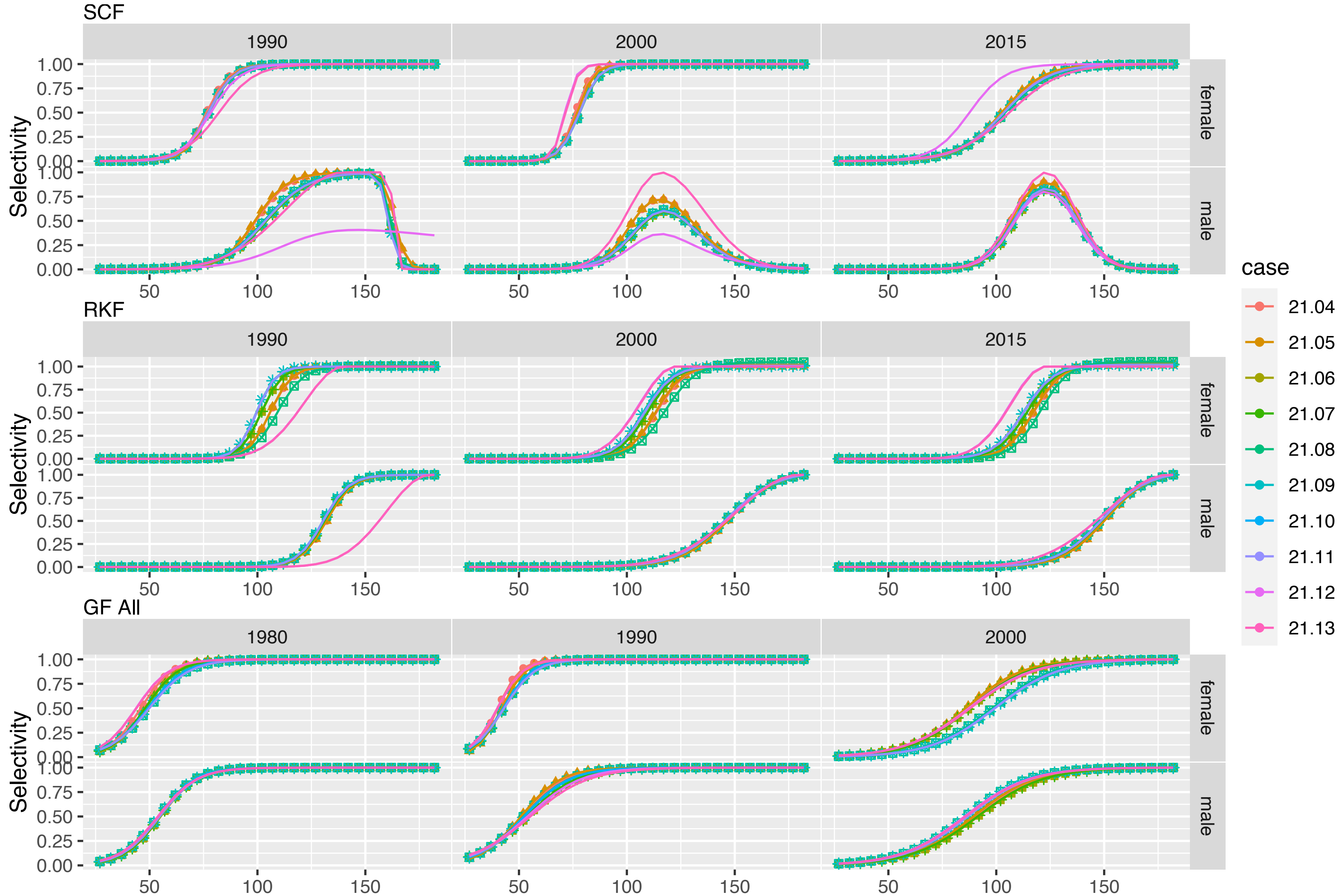


Figure 40. Estimated fishery selectivity in fisheries that take Tanner crab as bycatch: snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

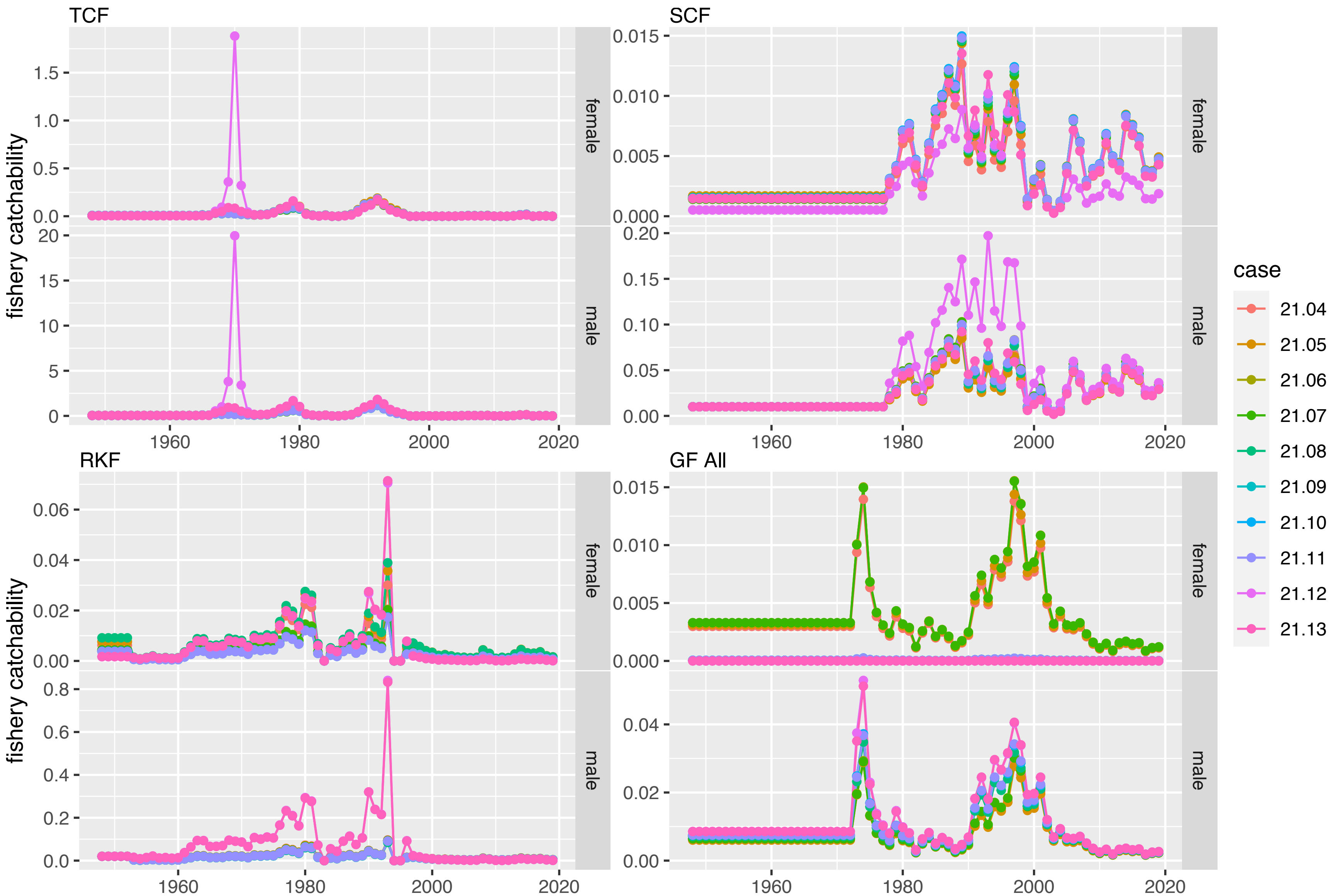


Figure 41. Estimated fishery capture rates in the directed fishery ("TCF") and other fisheries that take Tanner crab as bycatch: snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

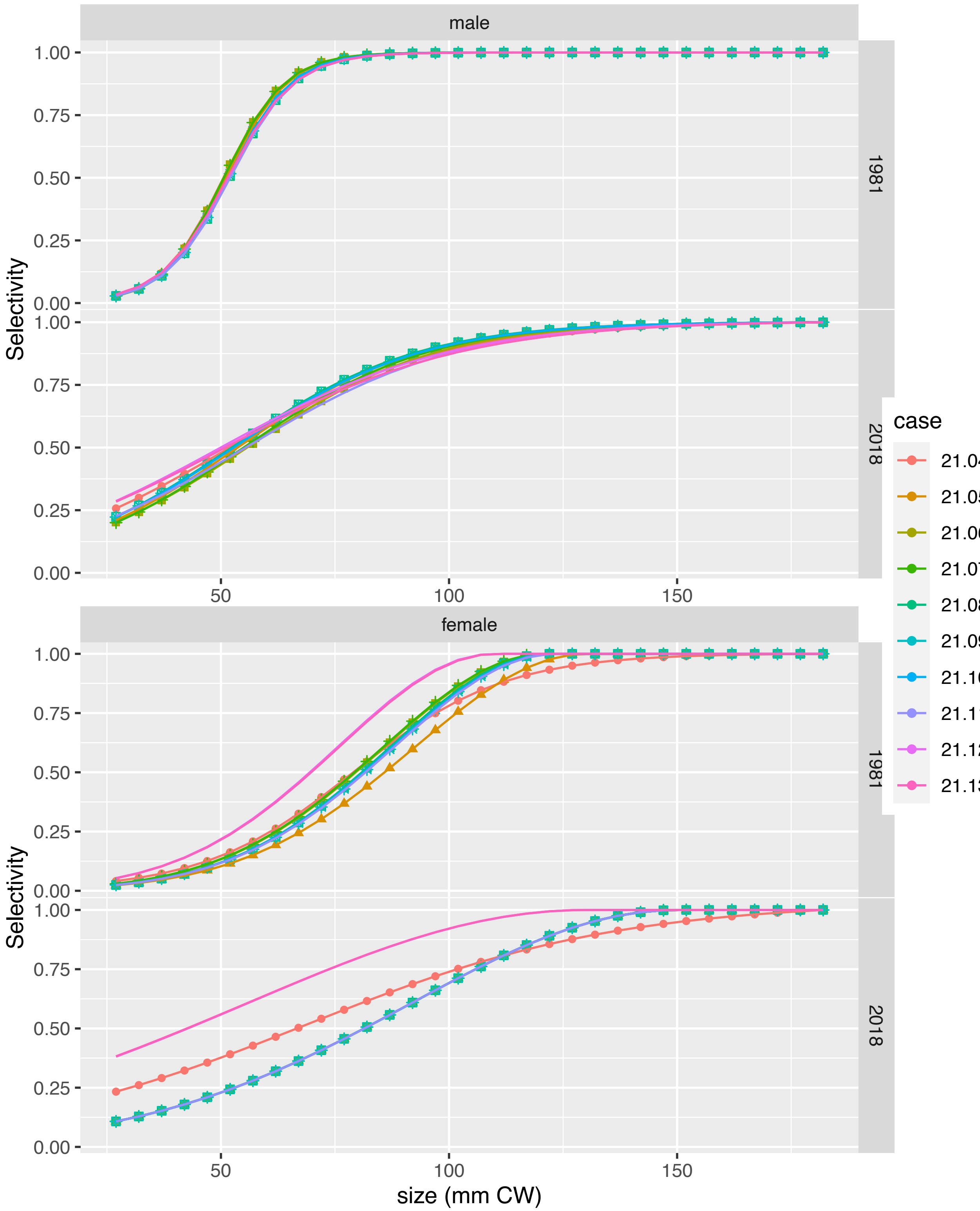


Figure 42. Estimated survey selectivity for the NMFS EBS Shelf Survey.

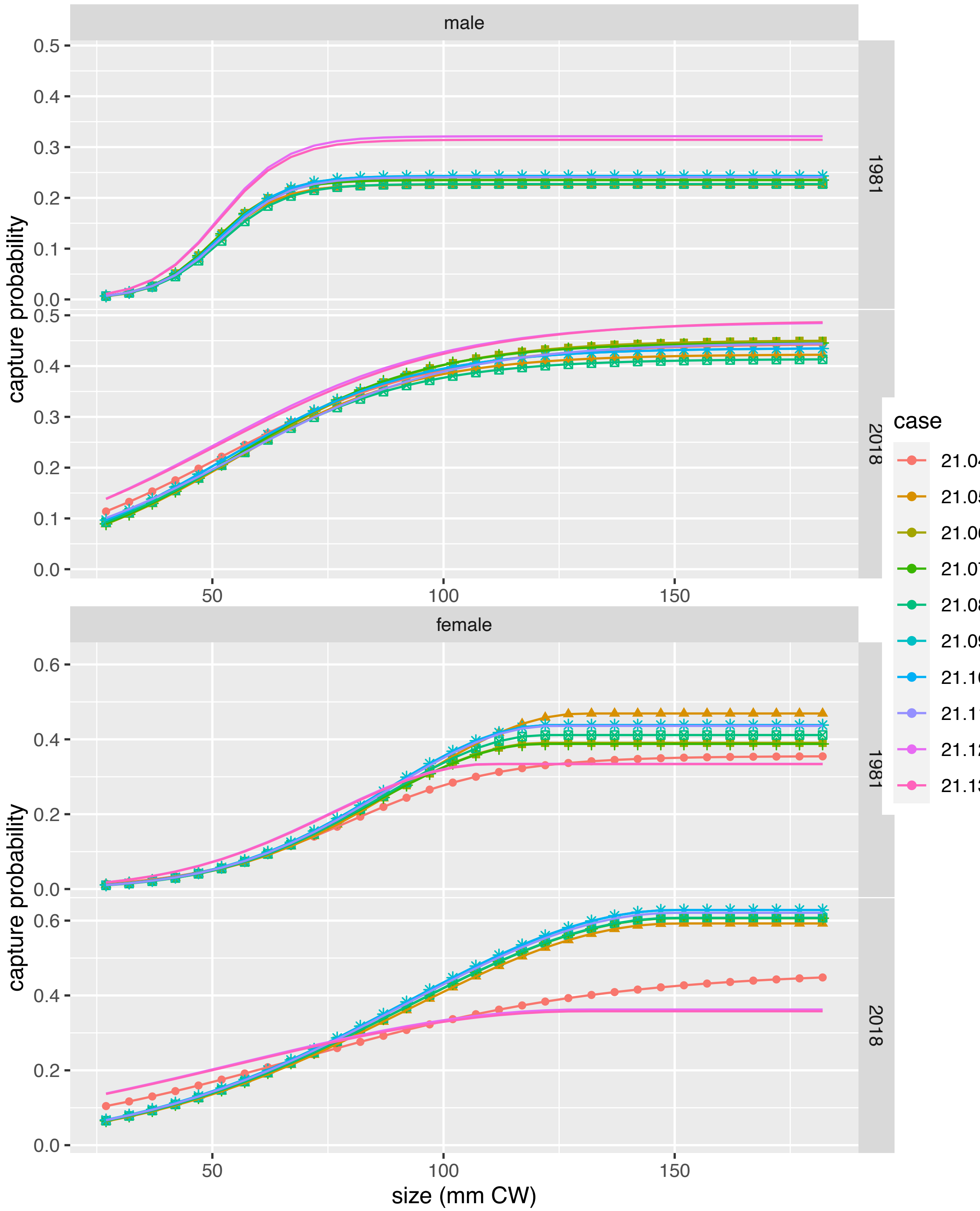


Figure 43. Estimated survey catchability for the NMFS EBS Shelf Survey.

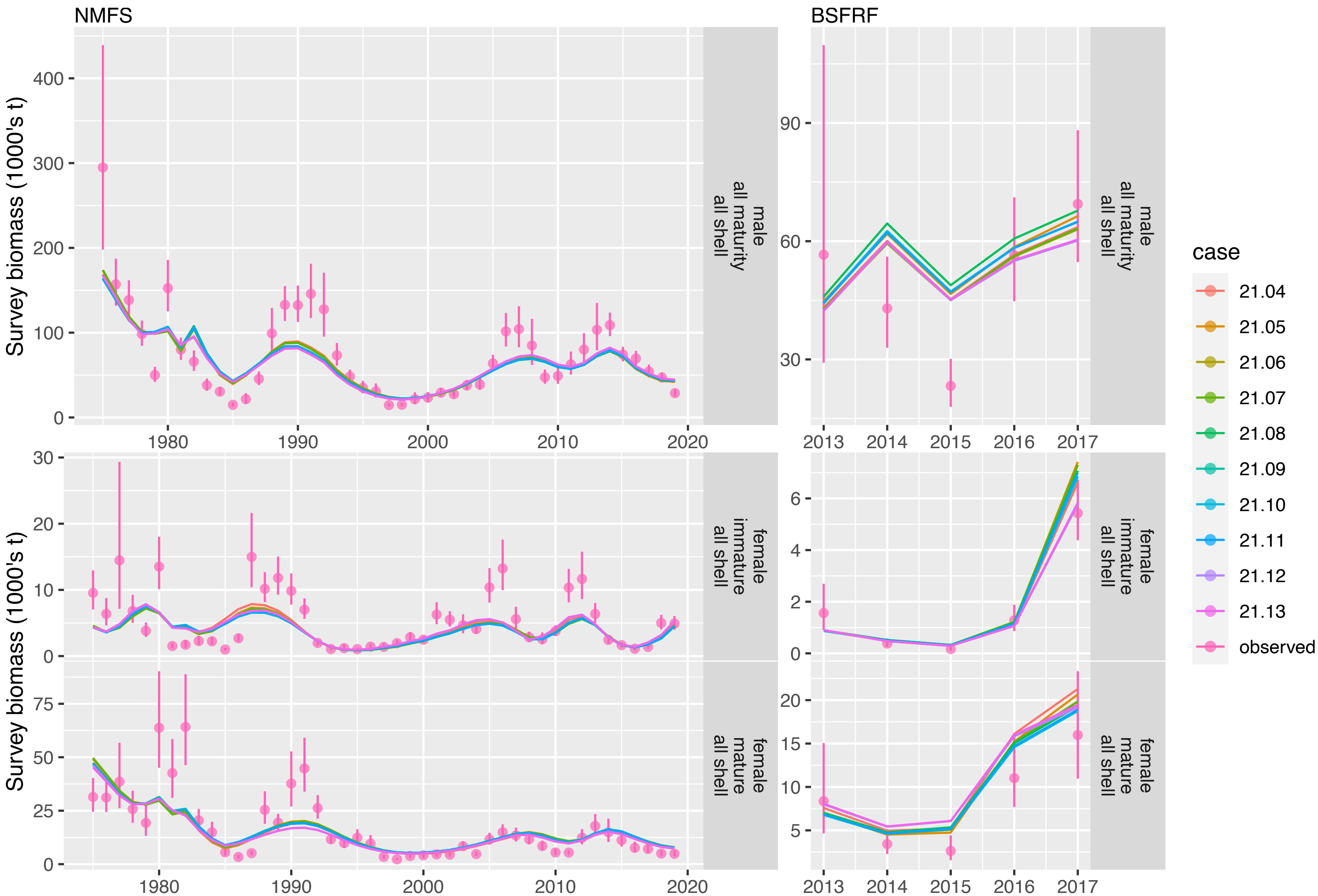


Figure 44. Fits to survey biomass time series from the NMFS EBS Shelf Survey and BSFRF side-by-side surveys.

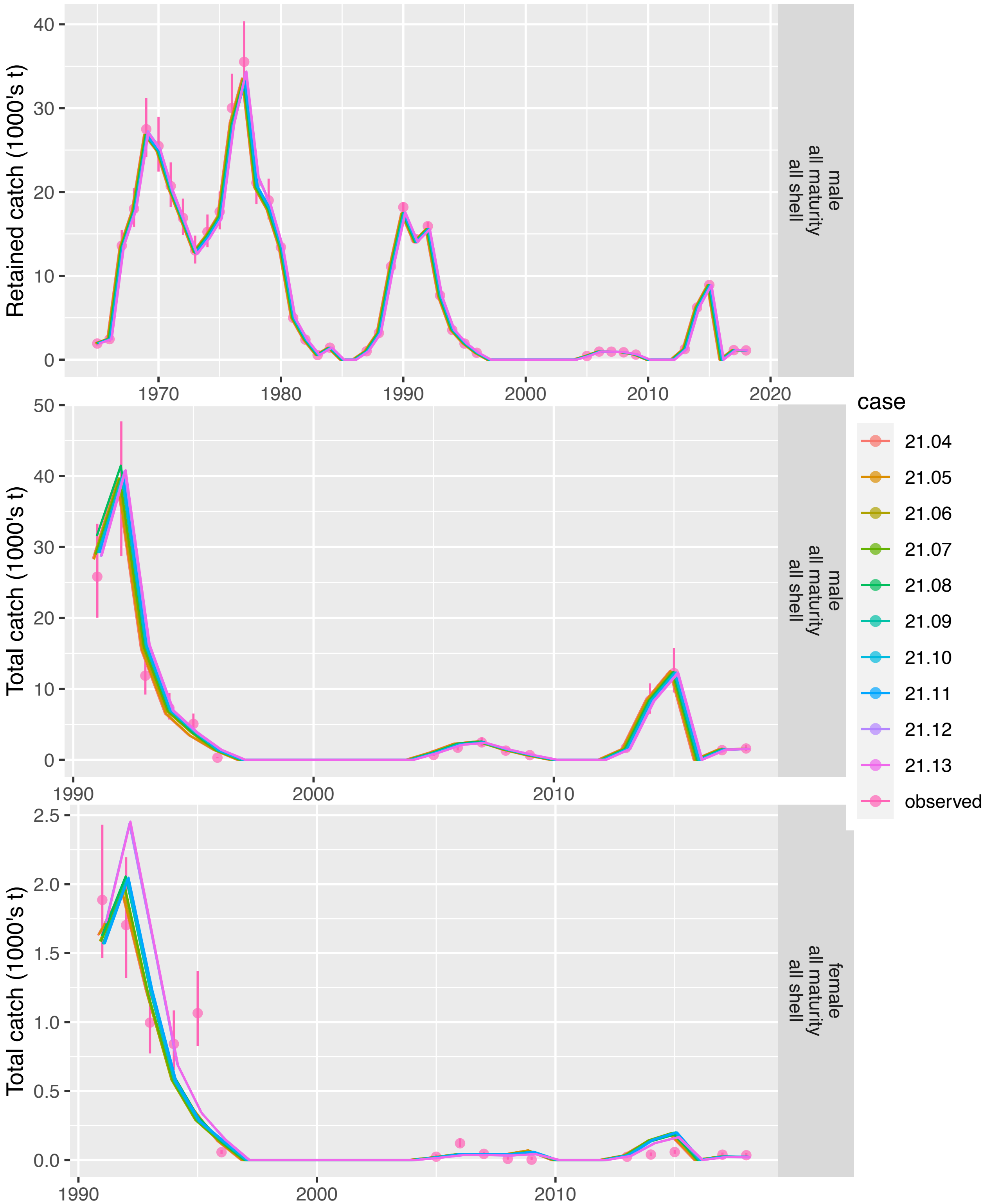


Figure 45. Fits to retained catch and total catch biomass time series in the directed fishery.

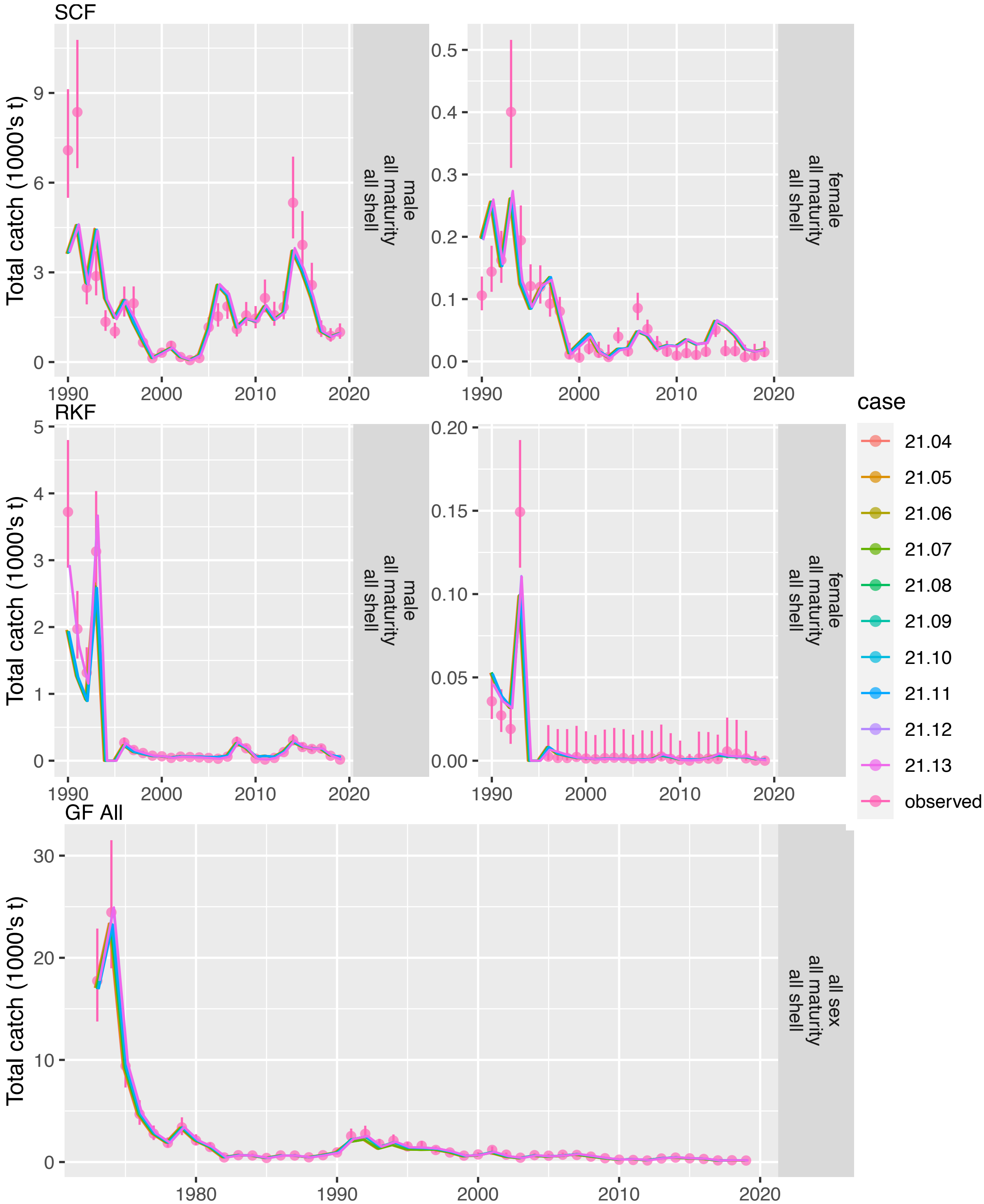


Figure 46. Fits to catch biomass time series for Tanner crab bycatch in the snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

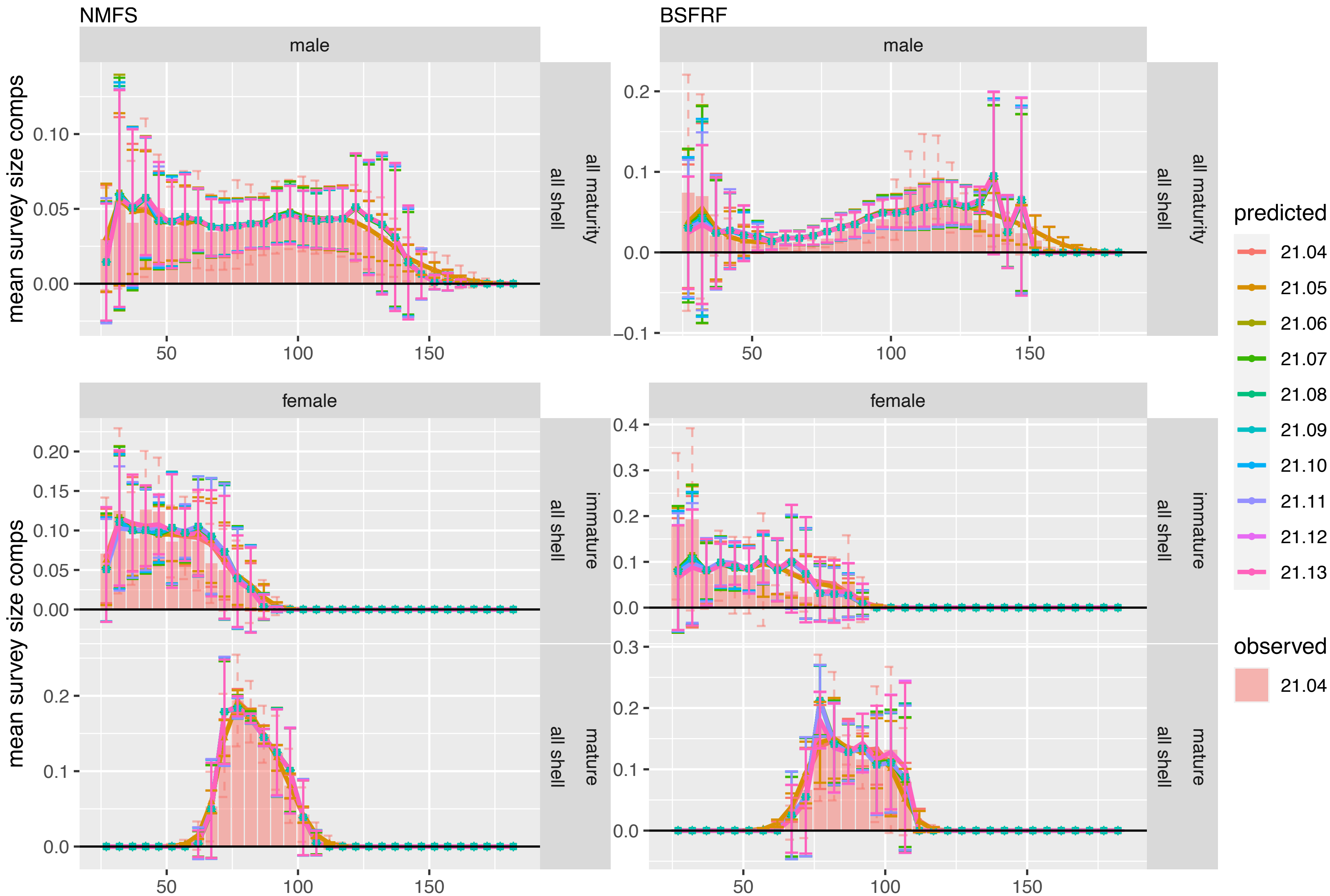


Figure 47. Fits to mean size compositions from the NMFS EBS Shelf Survey and BSFRF side-by-side surveys.

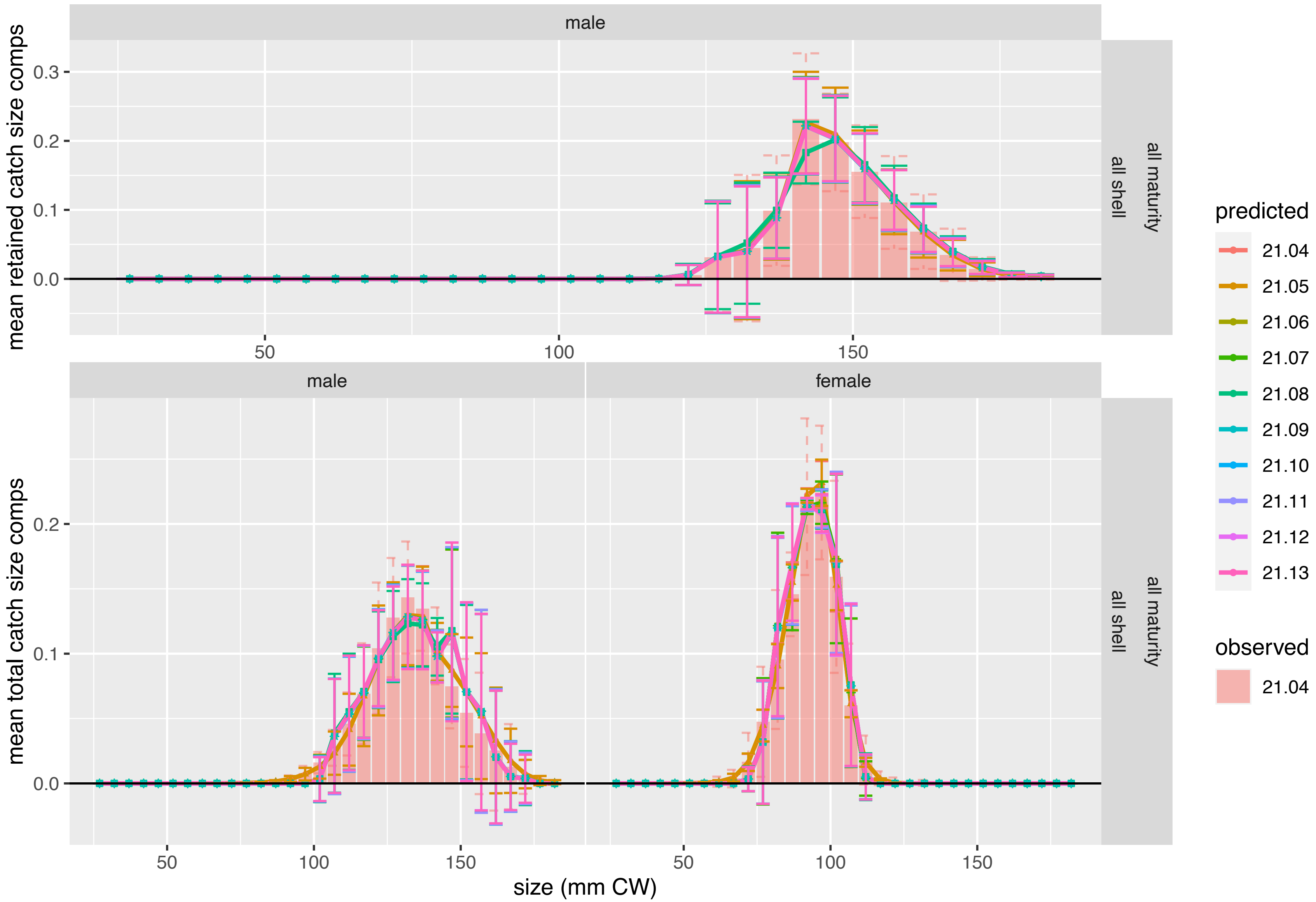


Figure 48. Fits to mean size compositions for retained catch and total catch size compositions in the directed fishery.

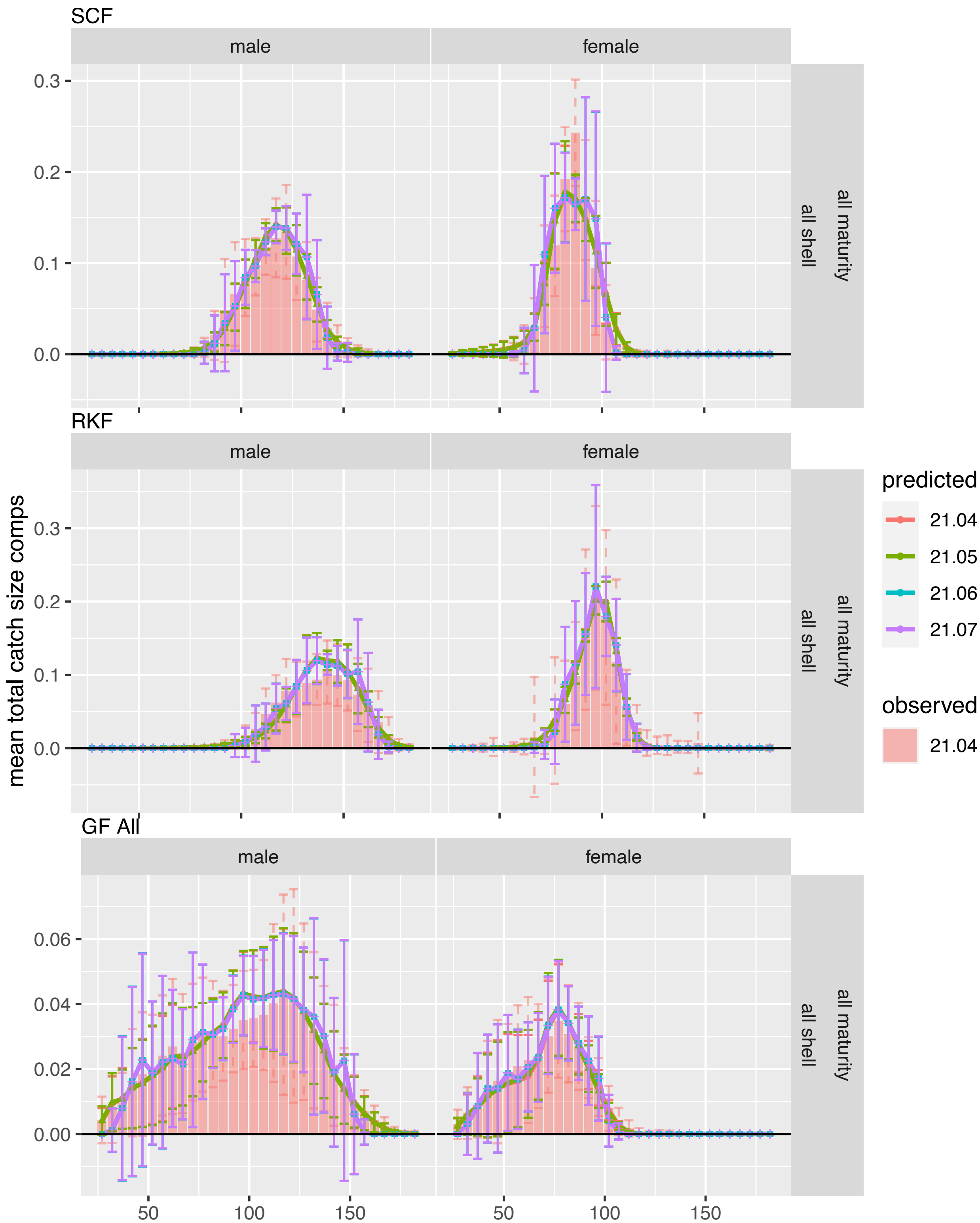


Figure 49. Fits to mean size compositions for Tanner crab bycatch in the snow crab (“SCF”), BBRKC (“RKF”), and groundfish fisheries (“GF All”) for Models 21.04-21.07.

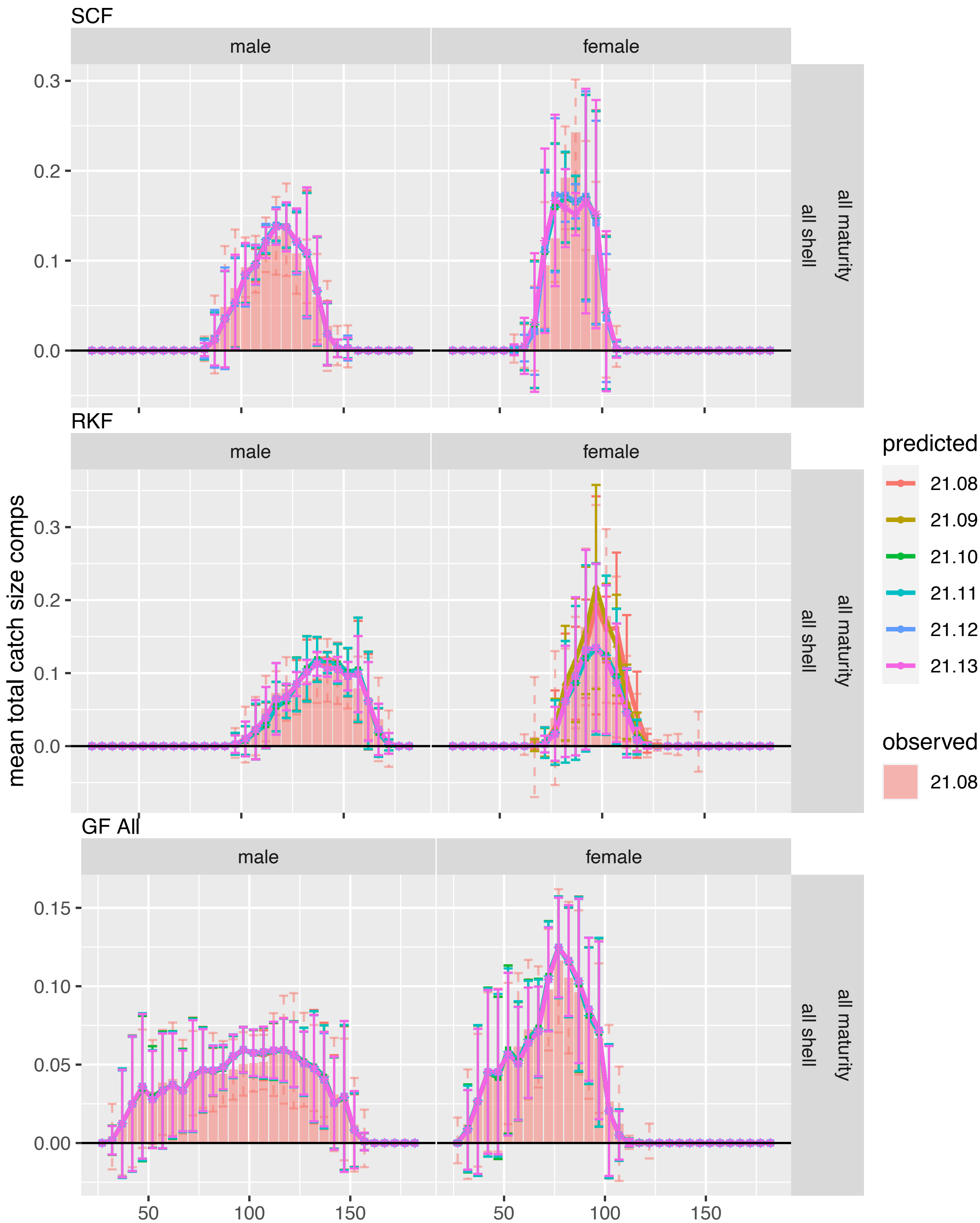


Figure 50. Fits to mean size compositions for Tanner crab bycatch in the snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All") for Models 21.08-21.13. Note that the relative sizes for the groundfish size compositions have changed due to the use of different scaling parameters in the Dirichlet-multinomial likelihoods applied.

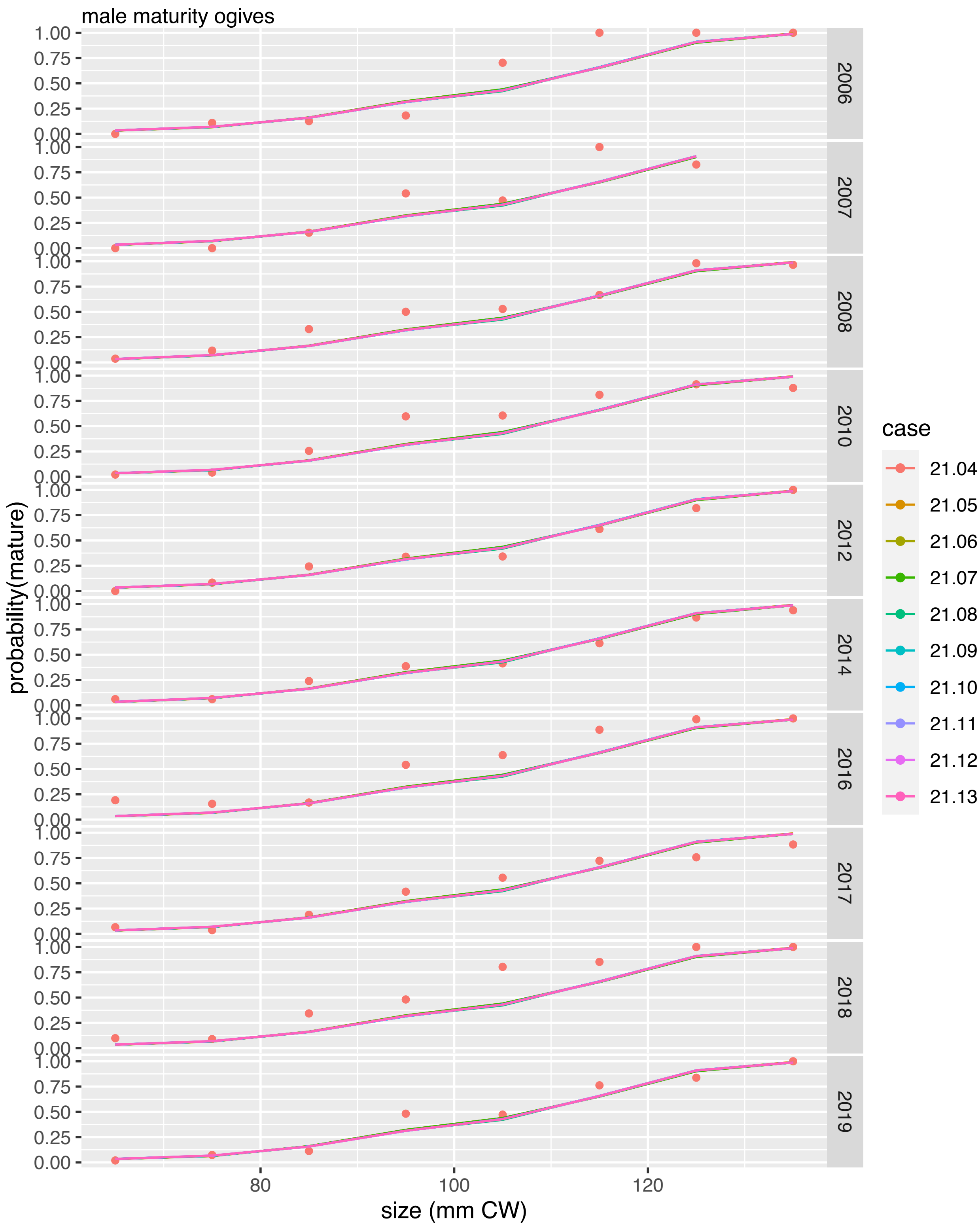


Figure 51. Model fits to maturity ogive data.

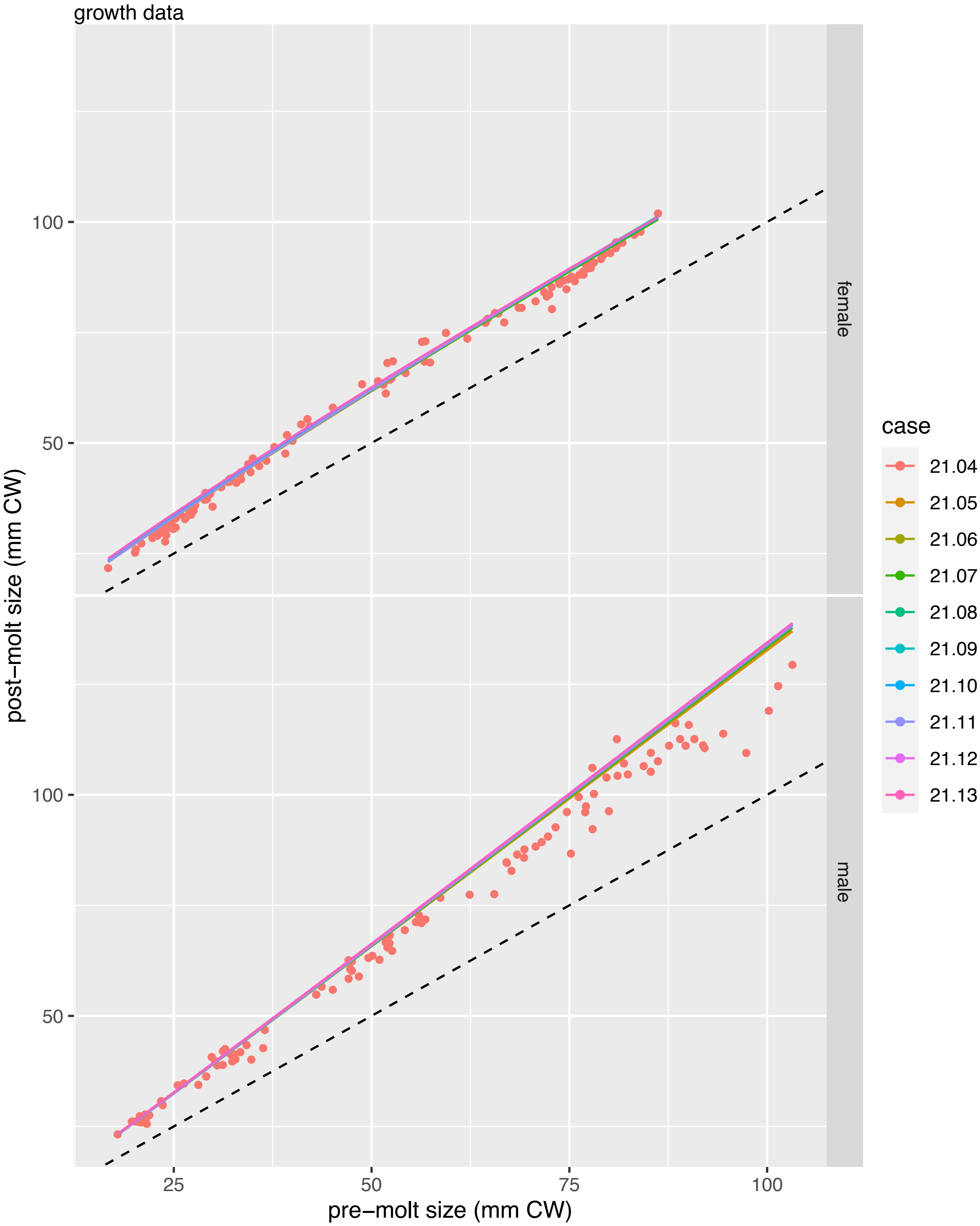
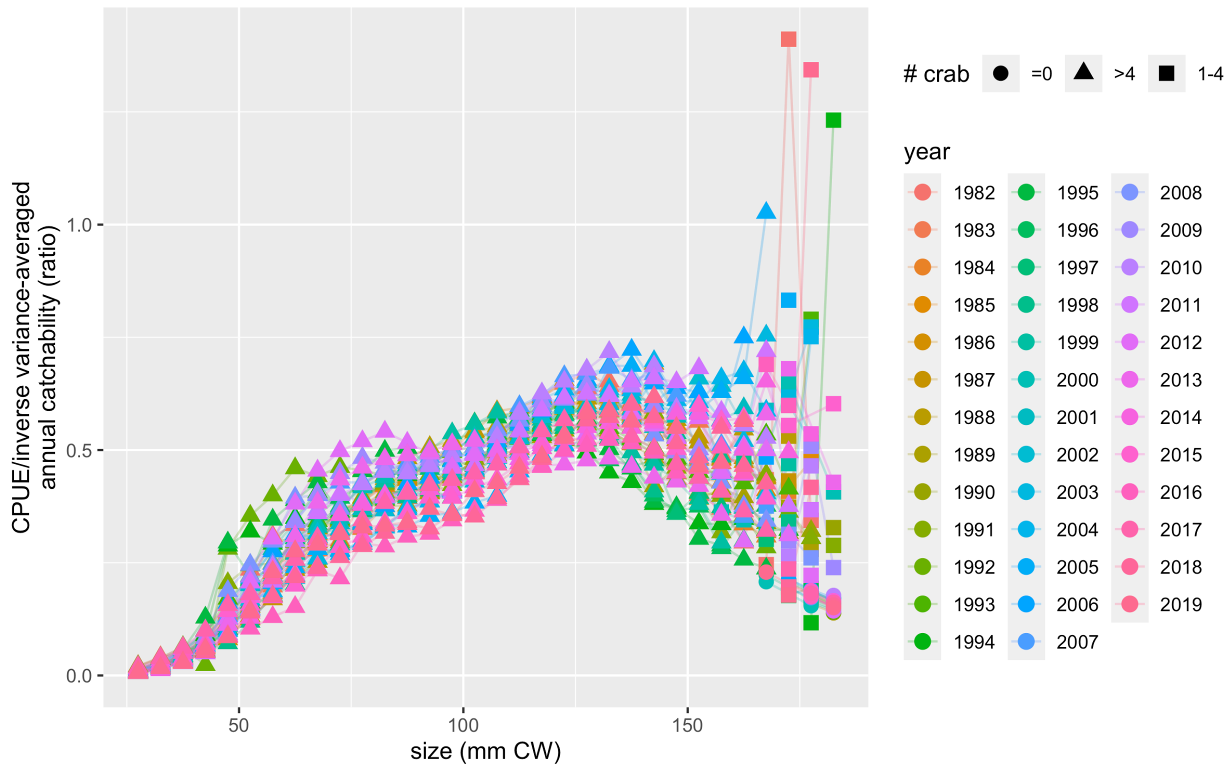


Figure 52. Model fits to maturity growth data.



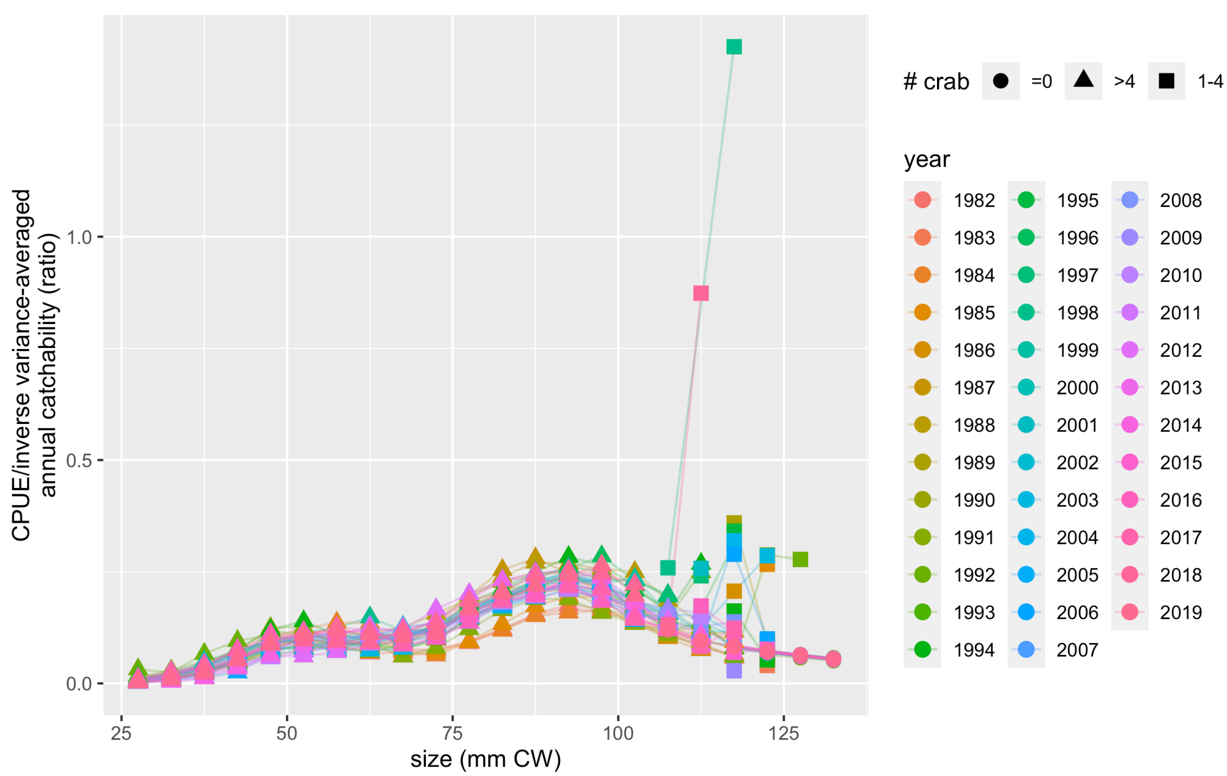


Figure 53. Annual NMFS EBS Shelf Survey catchability curves for Tanner crab estimated using the BSFRF side-by-side studies and sex-specific catch ratio analyses that incorporated bottom depth, bottom temperature, mean sediment grain size, and sediment sorting coefficients as haul-specific smoothly-varying environmental covariates. Upper plot: males. Lower plot: females.

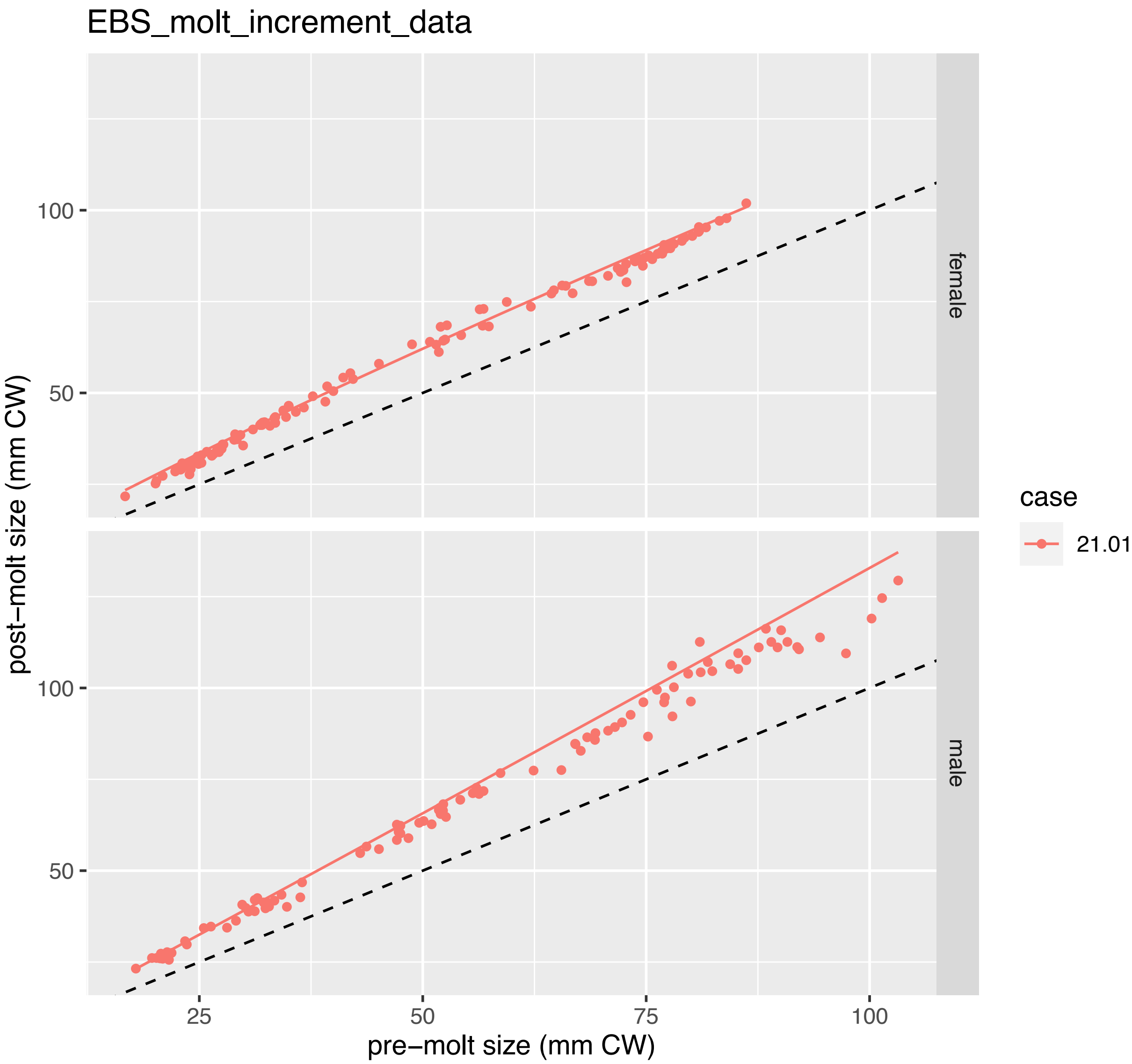


Figure 54. Fits to growth data in Model 21.01. Straight line: mean post-molt size, conditioned on pre-molt size.

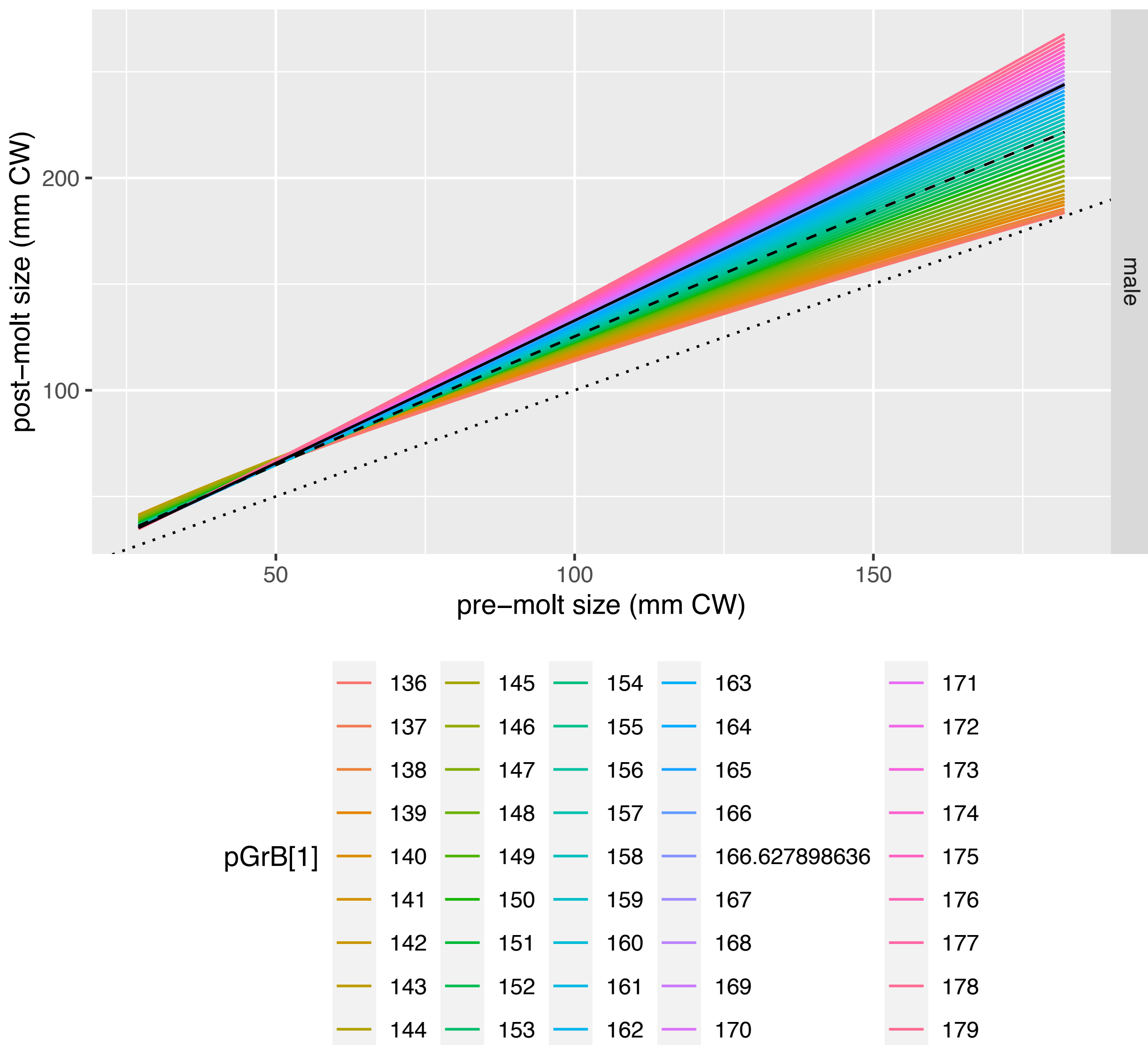


Figure 55. Mean growth curves for males as a function of pGrB[1], the mean male post-molt size conditioned on a pre-molt size of 125 mm CW. The solid black line indicates the relationship at the Model 21.01 MLE. The dashed black line indicates the relationship at the value for pGrB[1] estimated from a fit to the growth data outside the model.

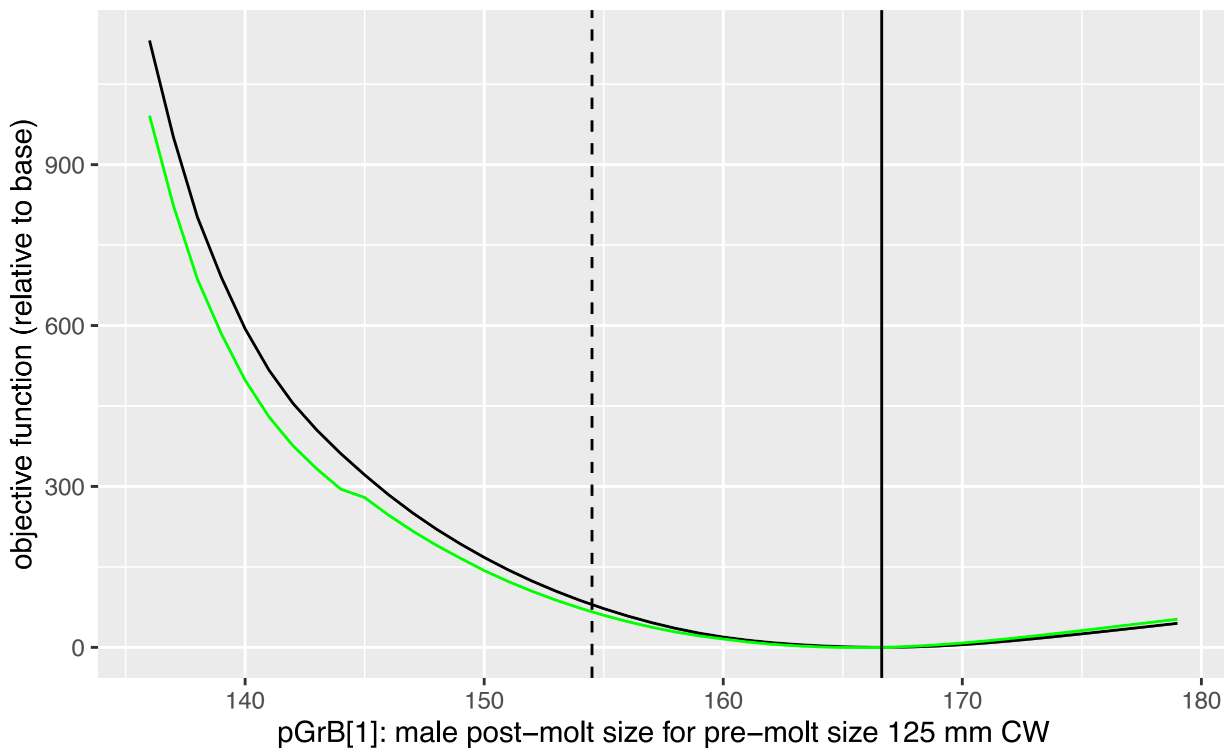


Figure 56. Total objective function (black) and data-only objective function (green) values from the likelihood profile on pGrB1[1], the mean male post-molt size given a pre-molt size of 125 mm CW. The solid vertical line indicates the estimated value from Model 21.01. The dashed vertical line indicates the estimated value from a fit to the growth data outside the model.

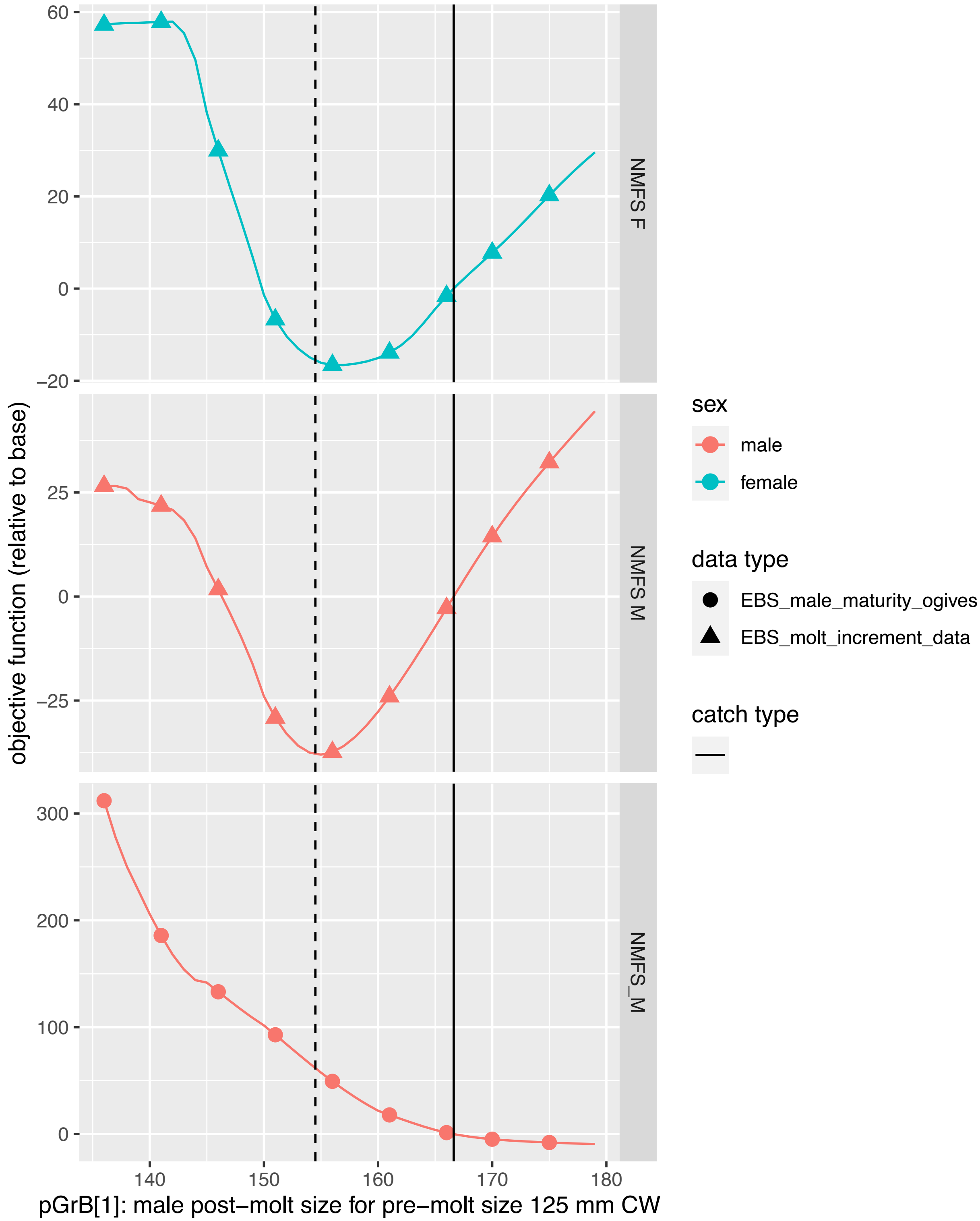


Figure 57. Component objective function values for growth and male maturity ogive data from the likelihood profile on pGrB1[1], the mean male post-molt size given a pre-molt size of 125 mm CW. The solid vertical line indicates the estimated value from Model 21.01. The dashed vertical line indicates the estimated value from a fit to the growth data outside the model.

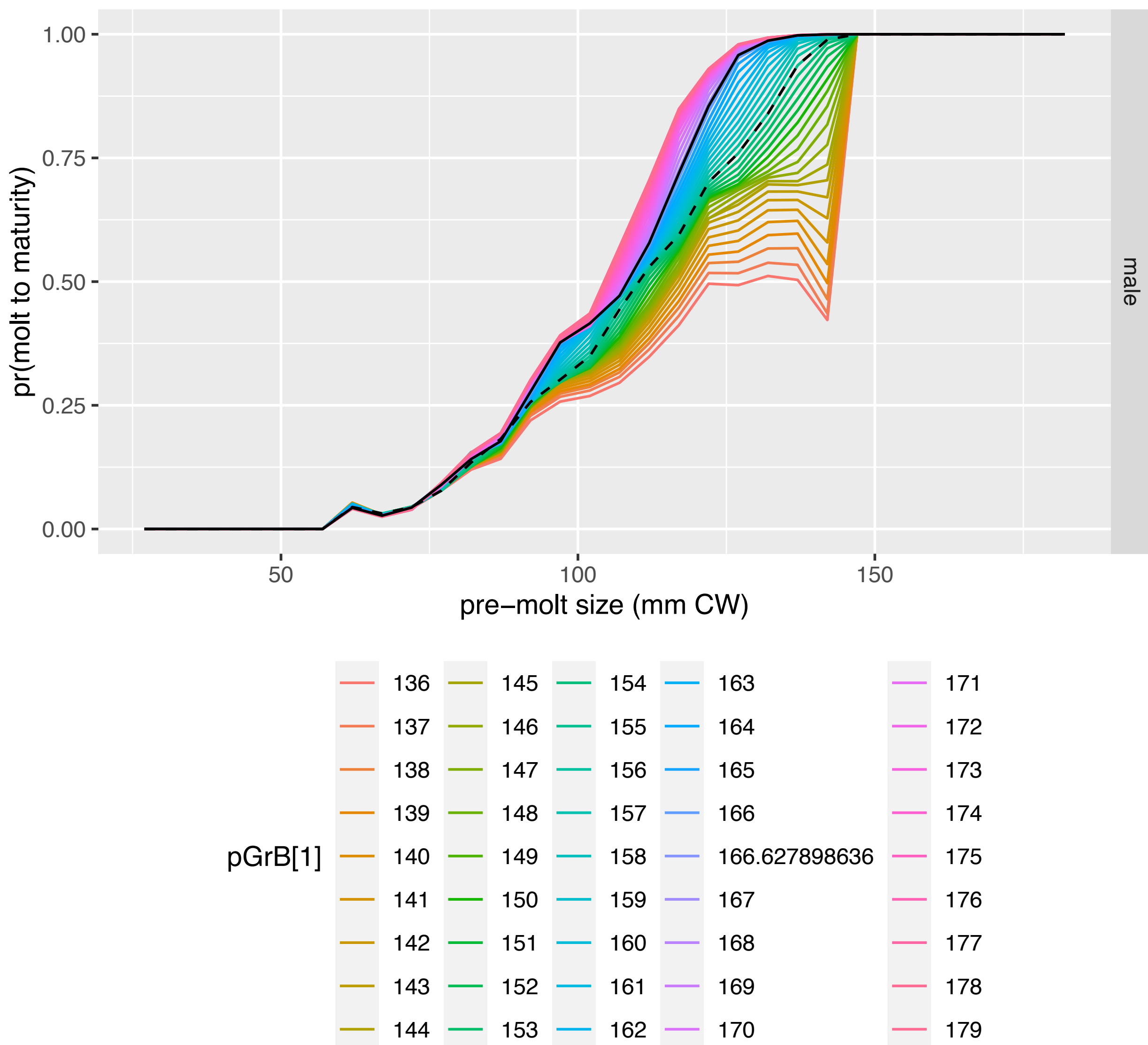


Figure 58. Curves describing the probability of the molt-to-maturity, conditioned on pre-molt size, for females (upper) and males (lower) as a function of pGrB[1], the mean male post-molt size conditioned on a pre-molt size of 125 mm CW. The solid black line indicates the relationship at the Model 20.01 MLE. The dashed black line indicates the relationship at the value for pGrB[1] estimated from a fit to the growth data outside the model. For males, the probability of the molt to maturity was assumed to be 1 for pre-molt sizes larger than 145 mm CW.

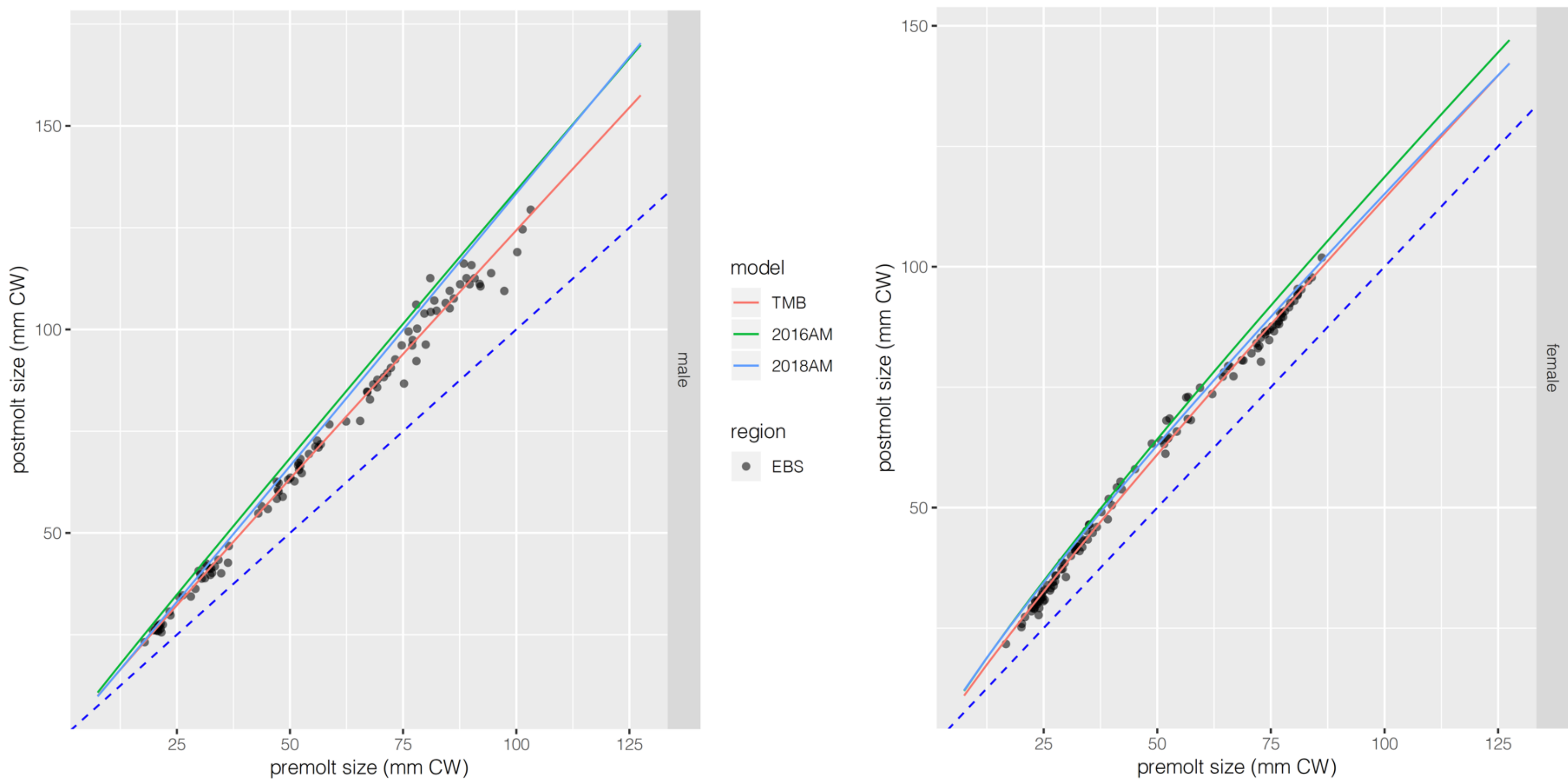


Figure 59. Growth estimated outside the assessment model (red lines) and inside the assessment model (green line: 2018 assessment, blue line: 2016 assessment).

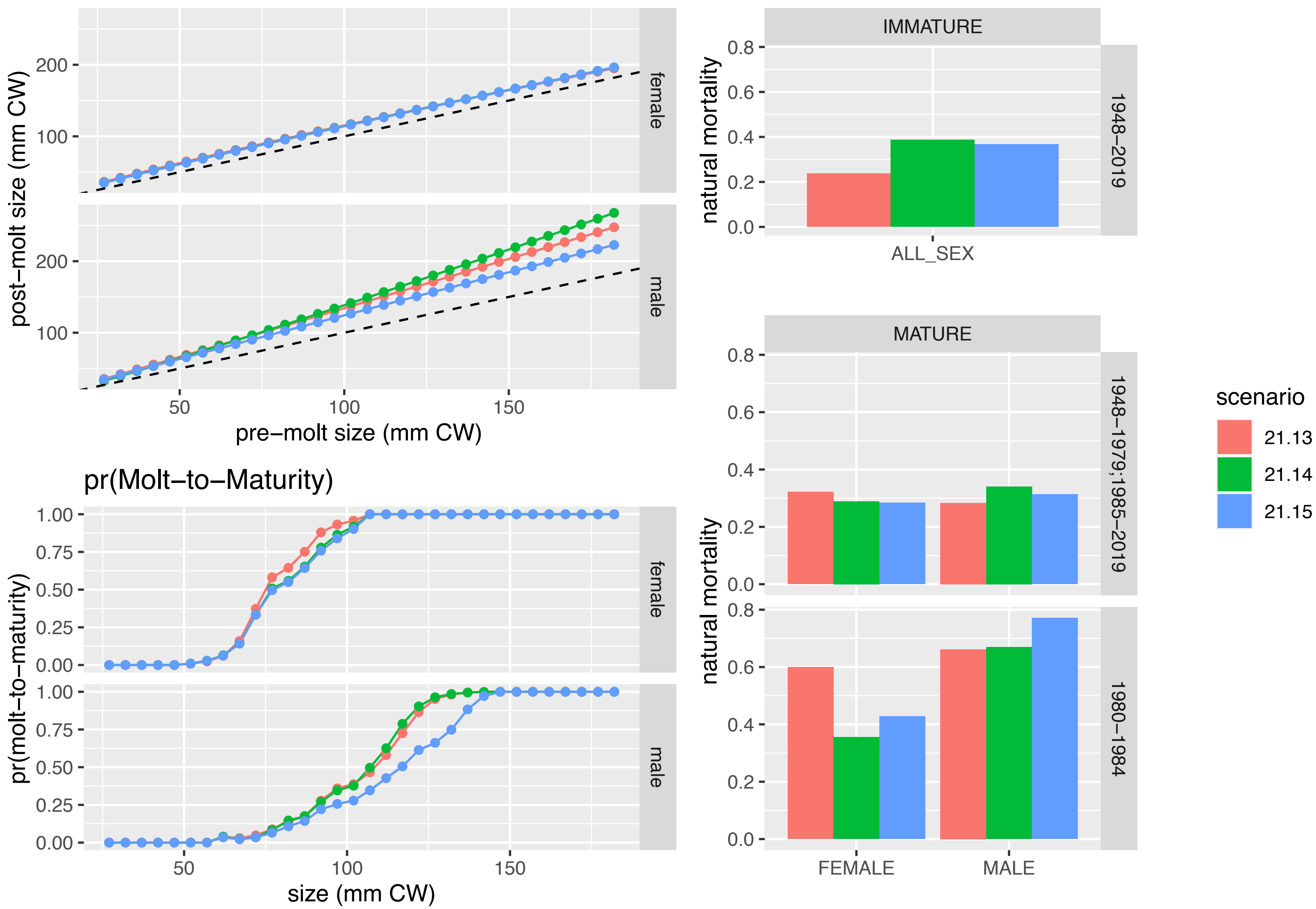


Figure 60. Estimated population processes.

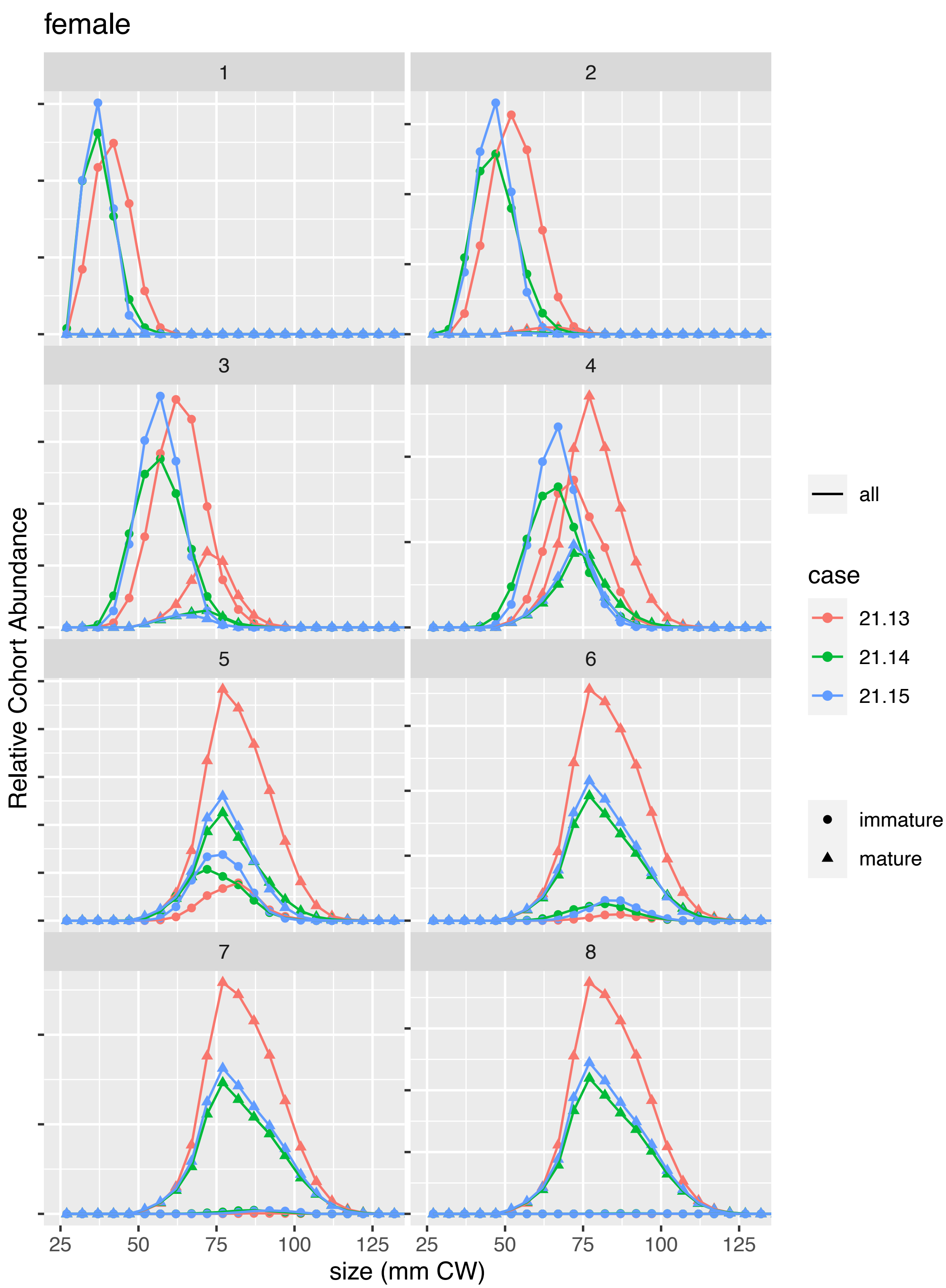


Figure 61. Estimated size progression of a cohort of female crab through time (years).

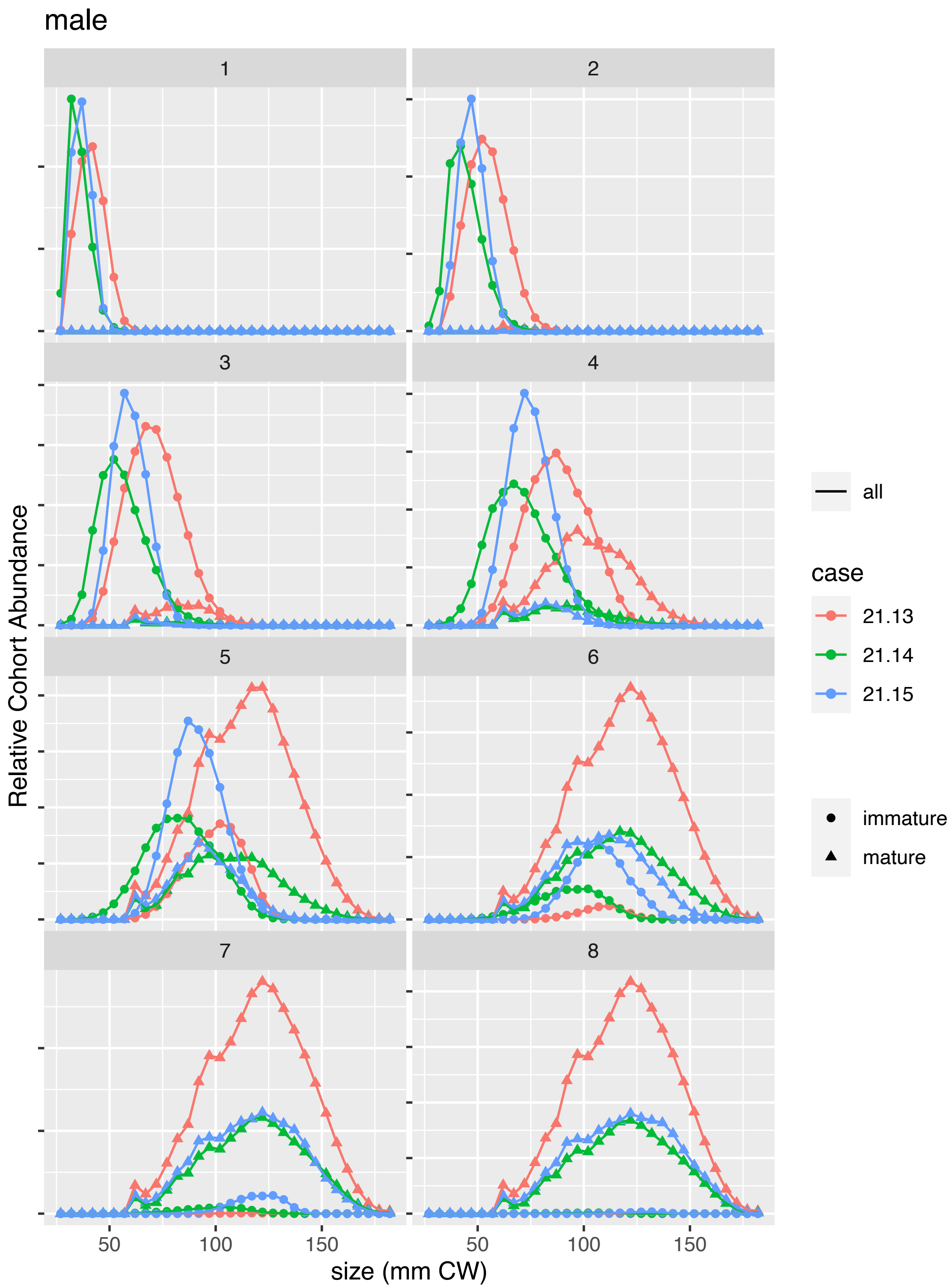


Figure 62. Estimated size progression of a cohort of male crab through time (years).

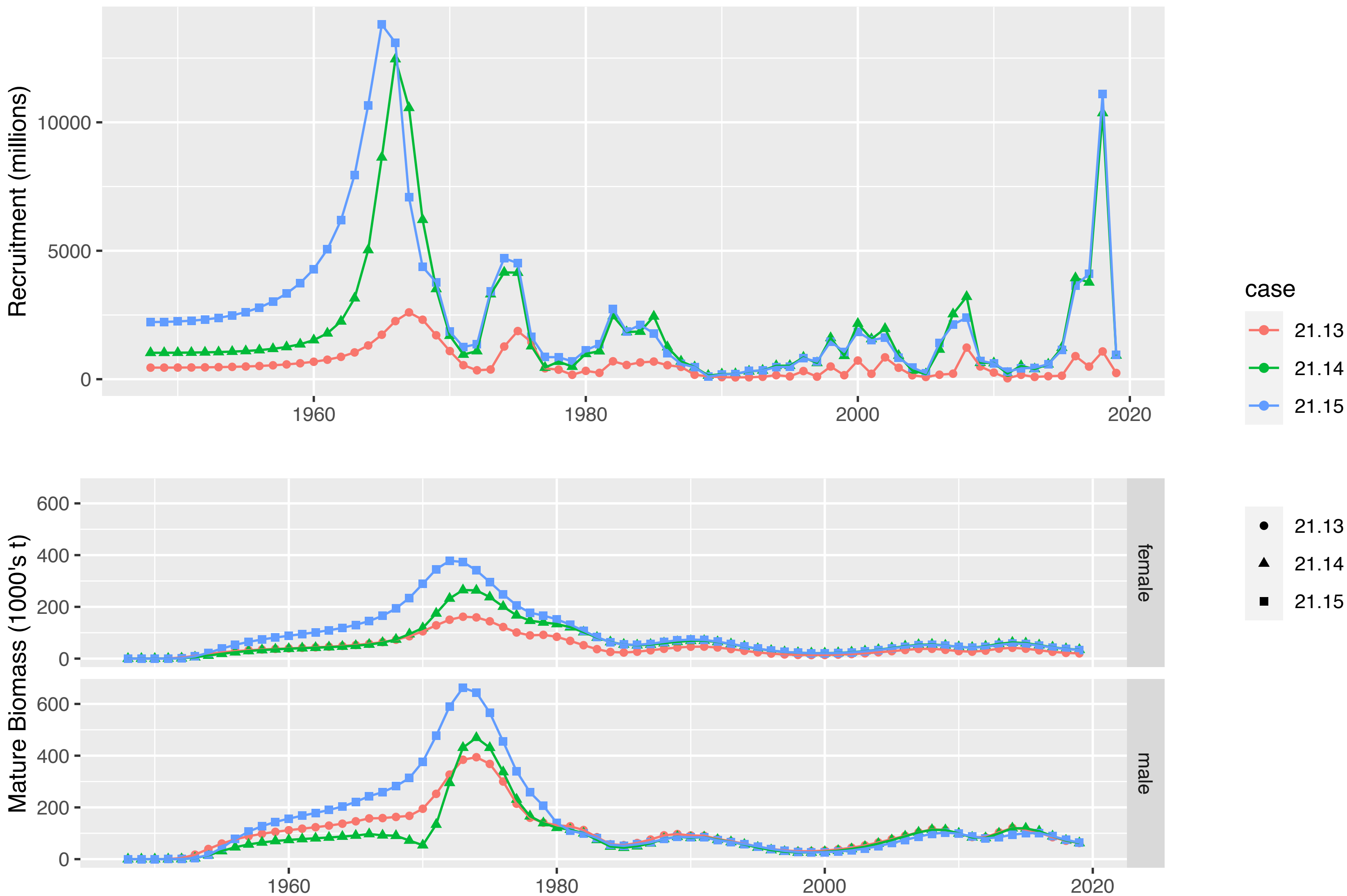


Figure 63. Estimated time series of recruitment and mature biomass.

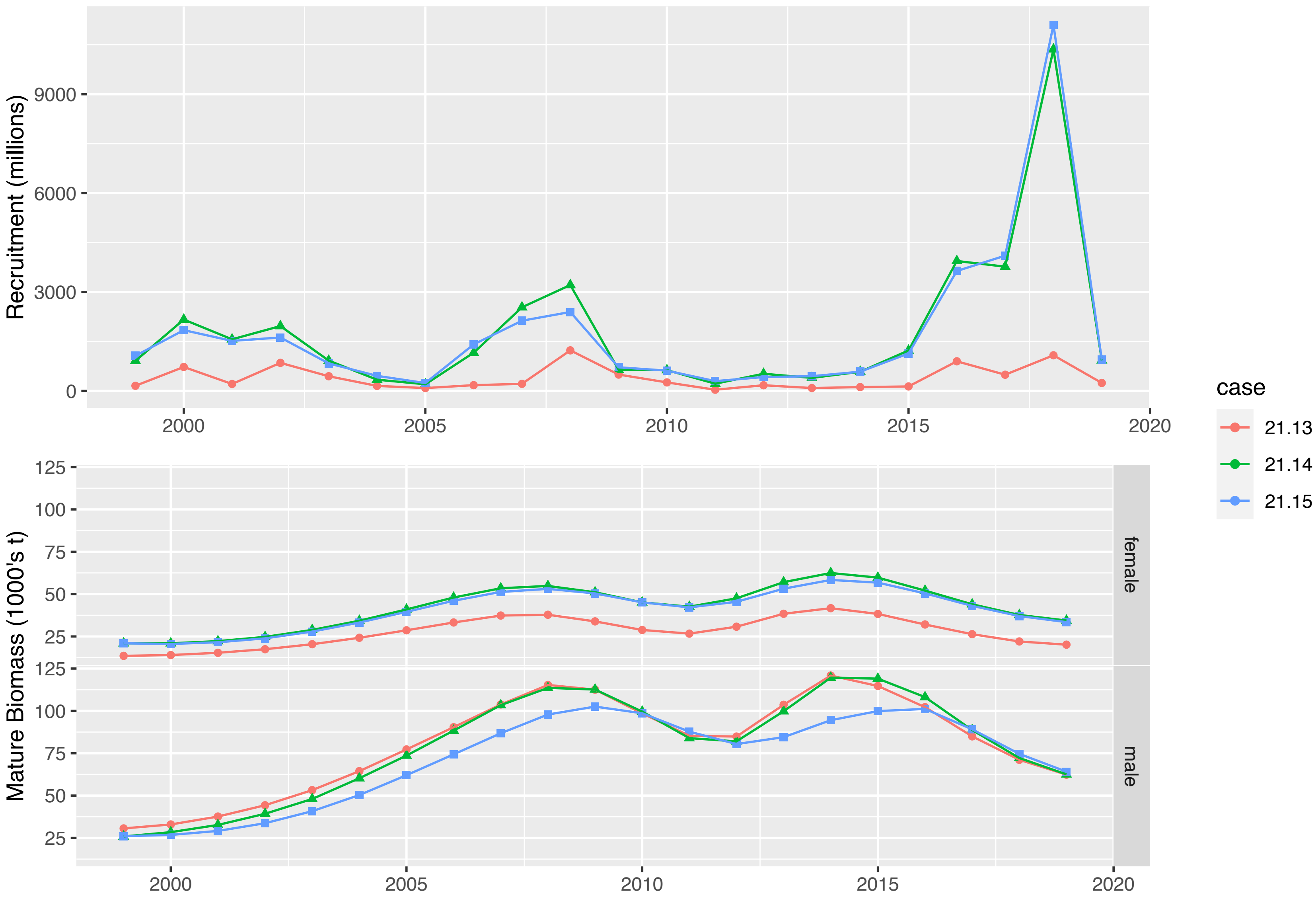


Figure 63a. Estimated time series of recruitment and mature biomass.

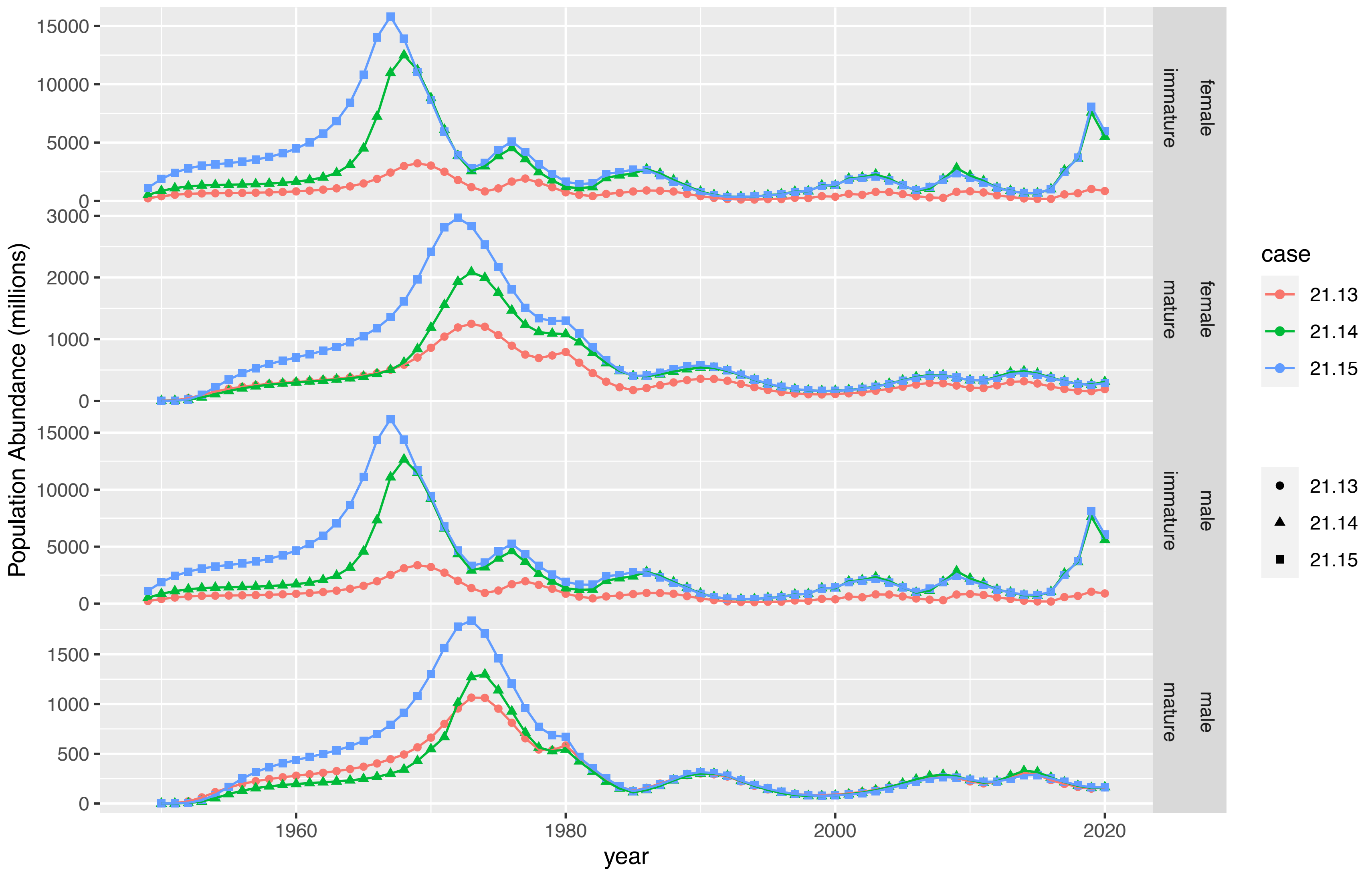


Figure 64. Estimated time series of population abundance.

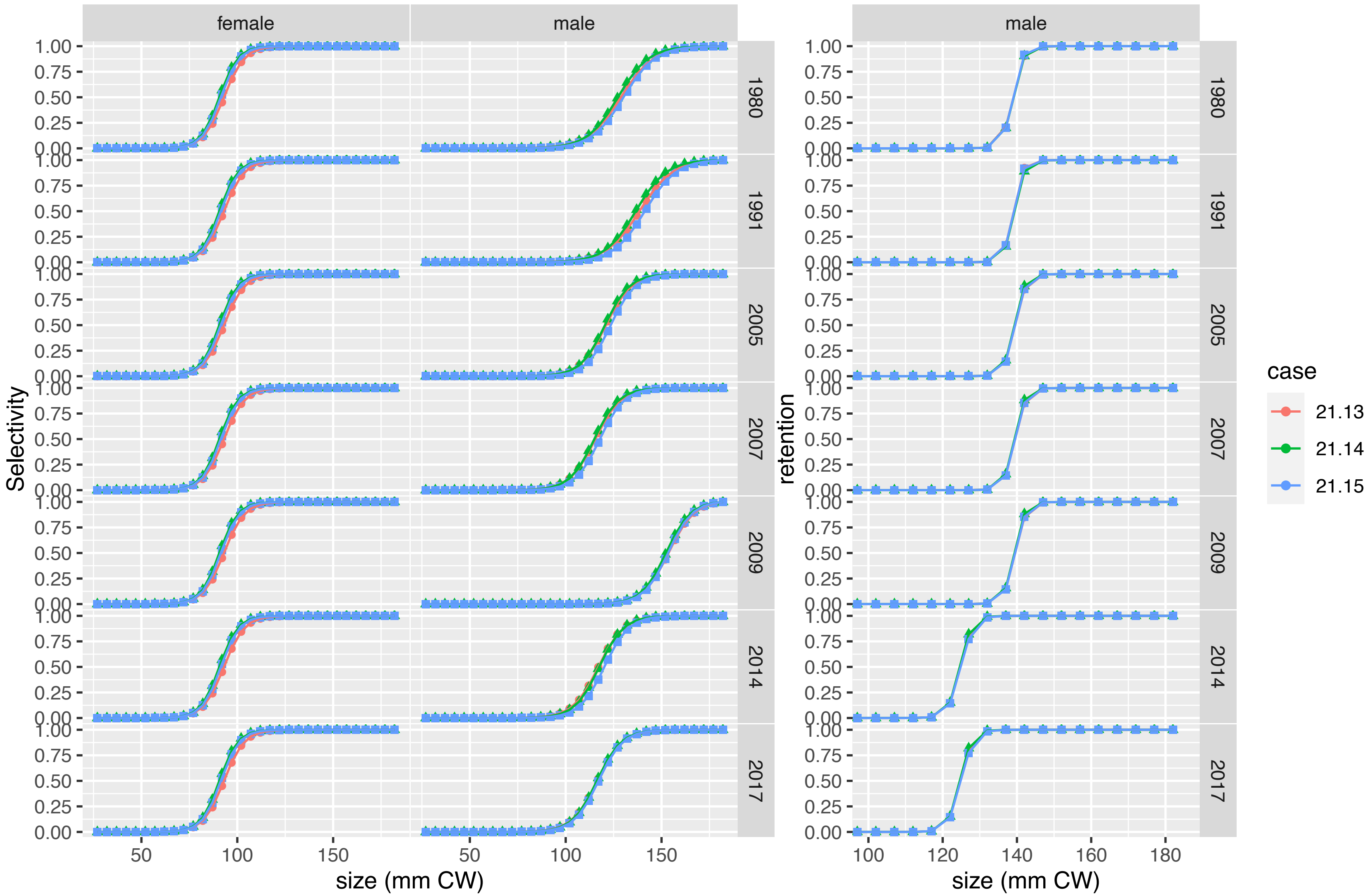


Figure 65. Estimated retention and total catch selectivity in the directed fishery (“TCF”).

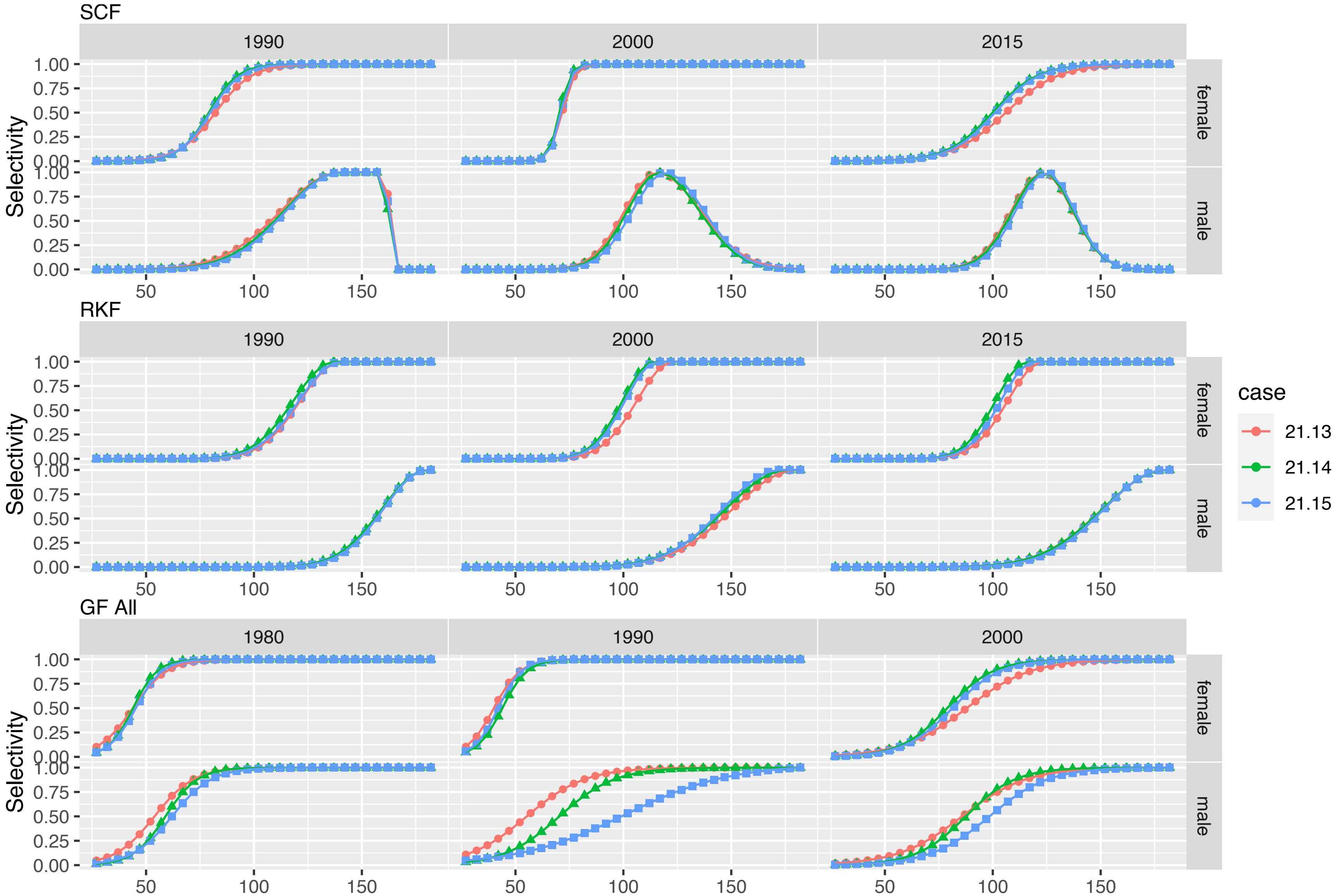


Figure 66. Estimated fishery selectivity in fisheries that take Tanner crab as bycatch: snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

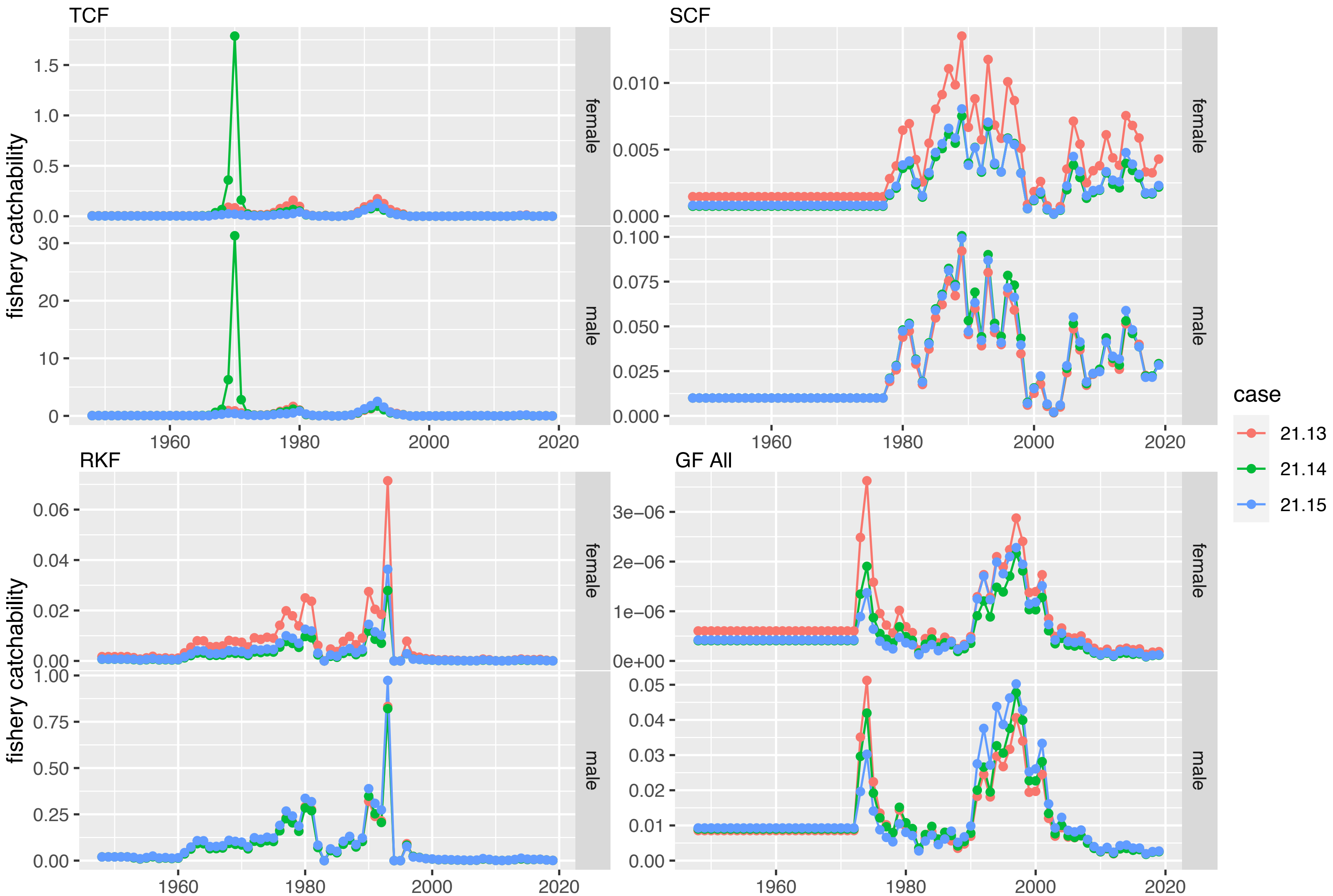


Figure 67. Estimated fishery capture rates in the directed fishery ("TCF") and other fisheries that take Tanner crab as bycatch: snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

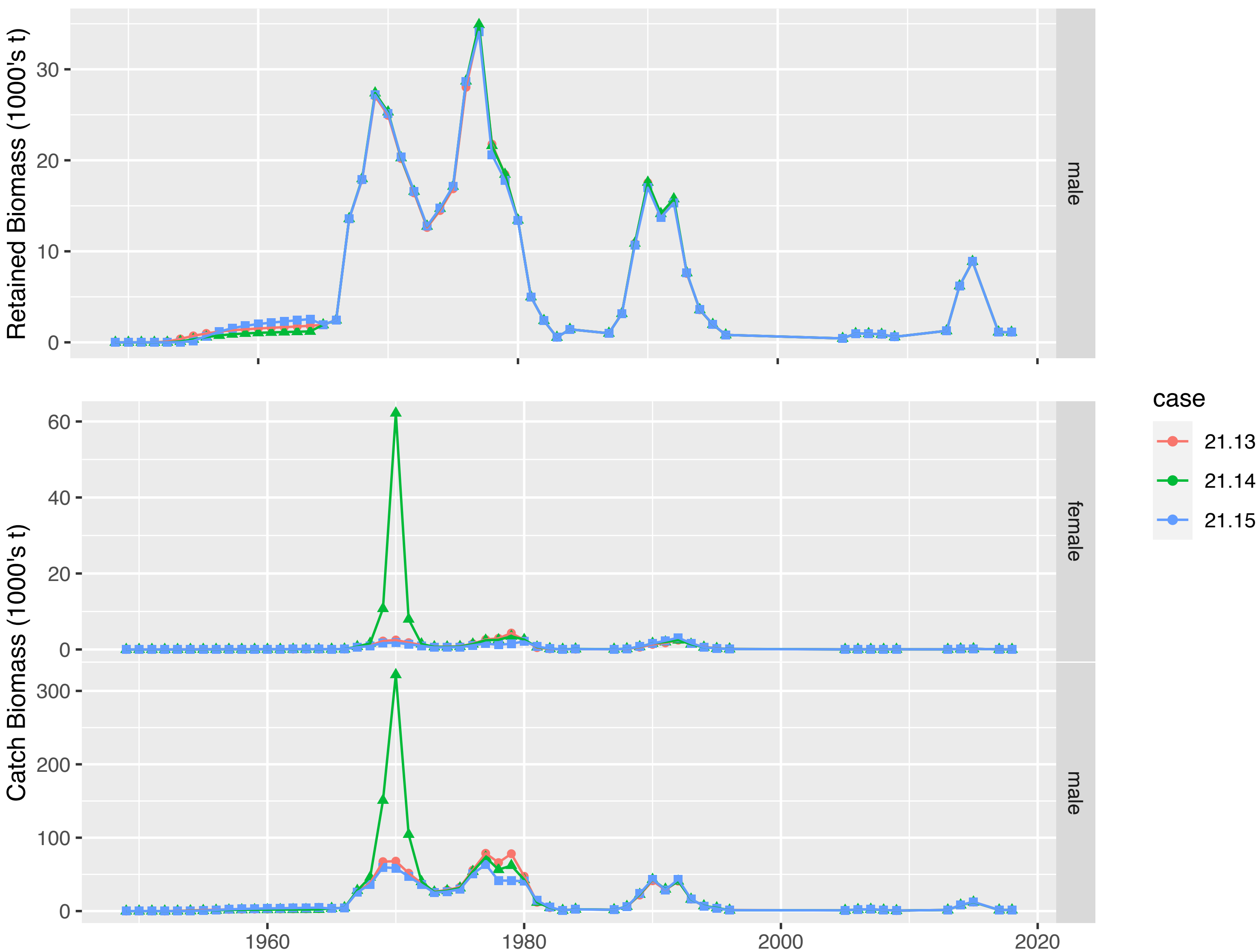


Figure 68. Model-estimated retained catch and total catch biomass in the directed fishery ("TCF").

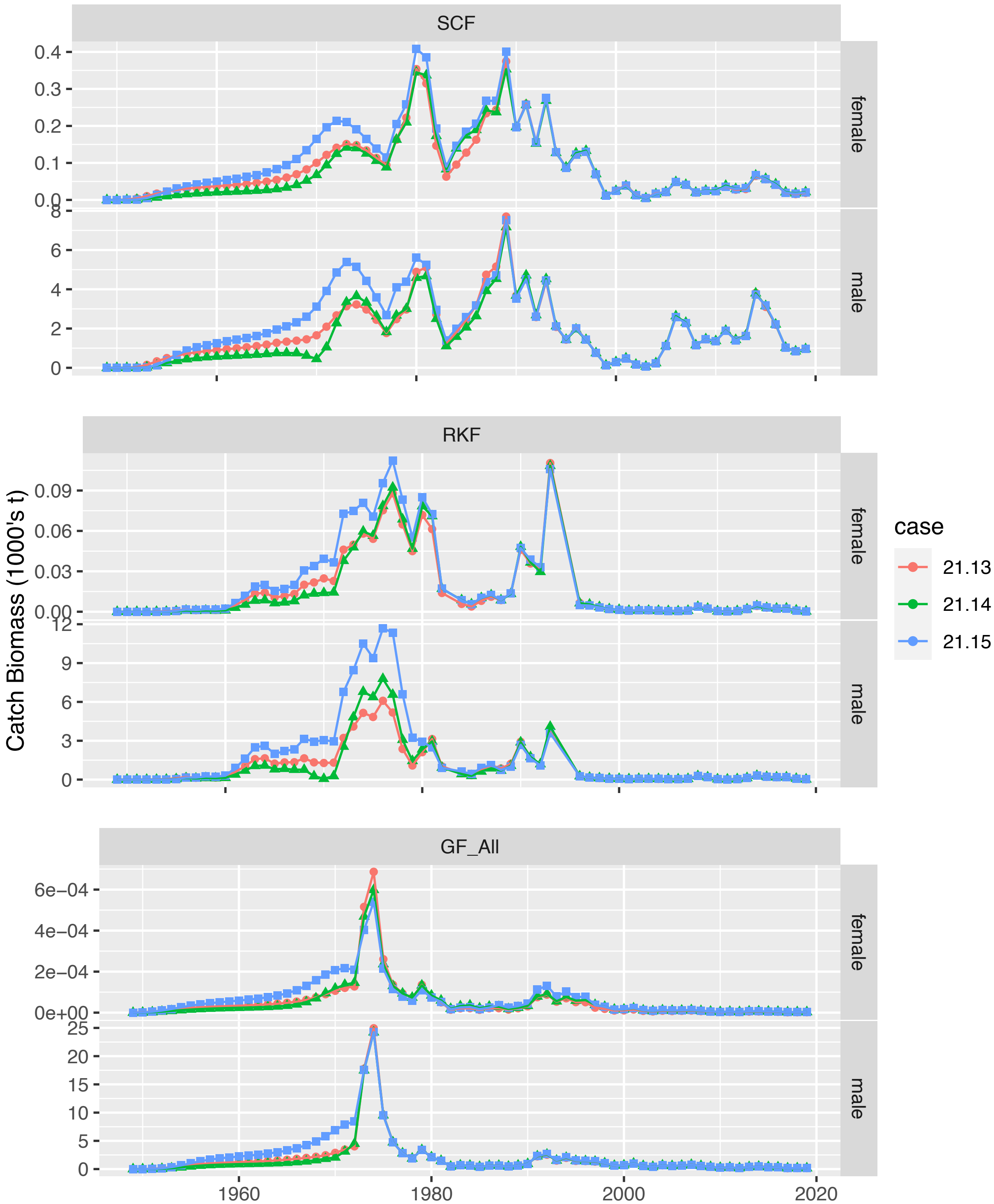


Figure 69. Model-estimated bycatch biomass in fisheries that take Tanner crab as bycatch: snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

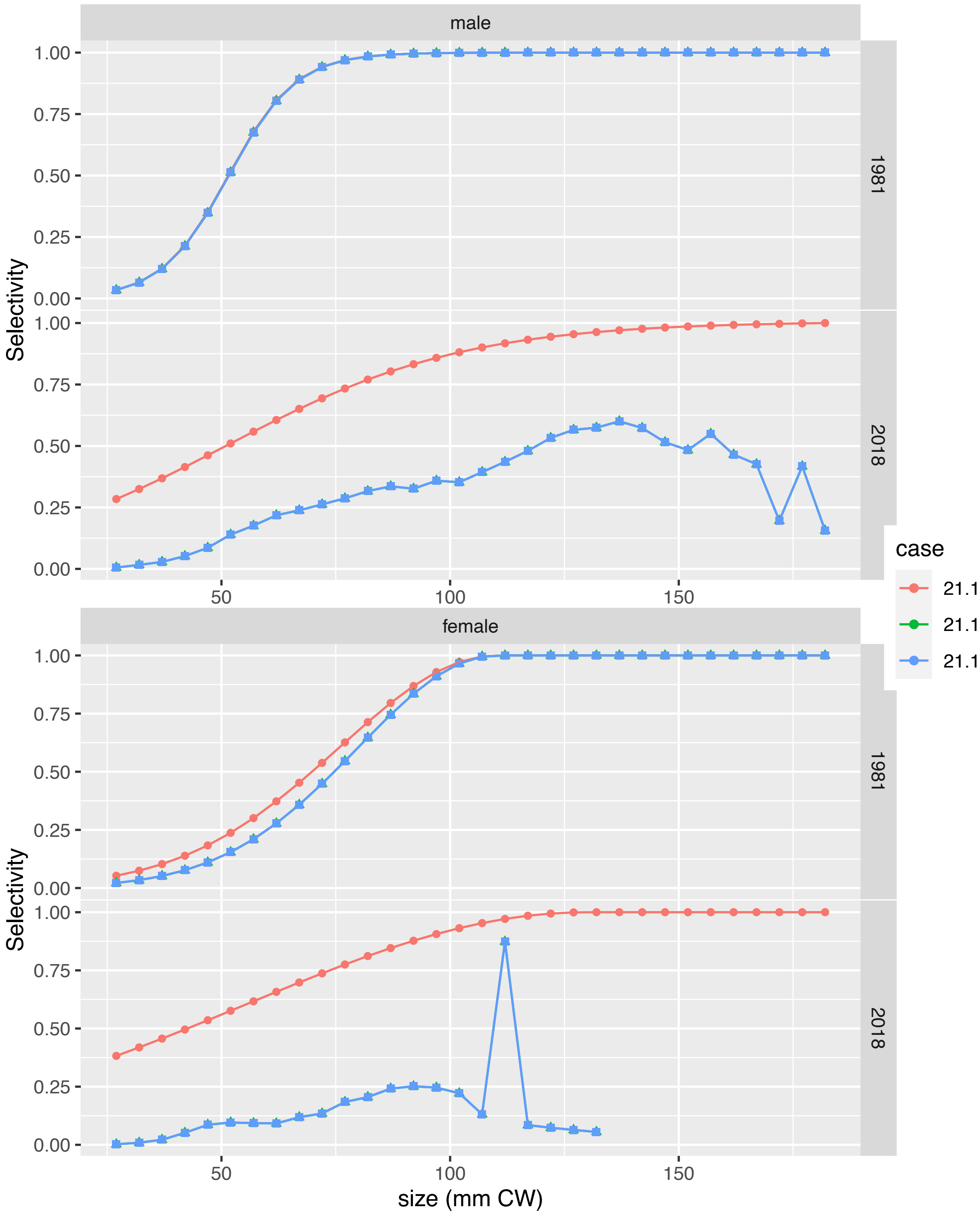


Figure 70. Estimated survey selectivity for the NMFS EBS Shelf Survey. The "selectivity" curves for 21.14 and 21.15 in the post-1981 period also include fully-selected catchability, so are not directly compared with those from 21.13.

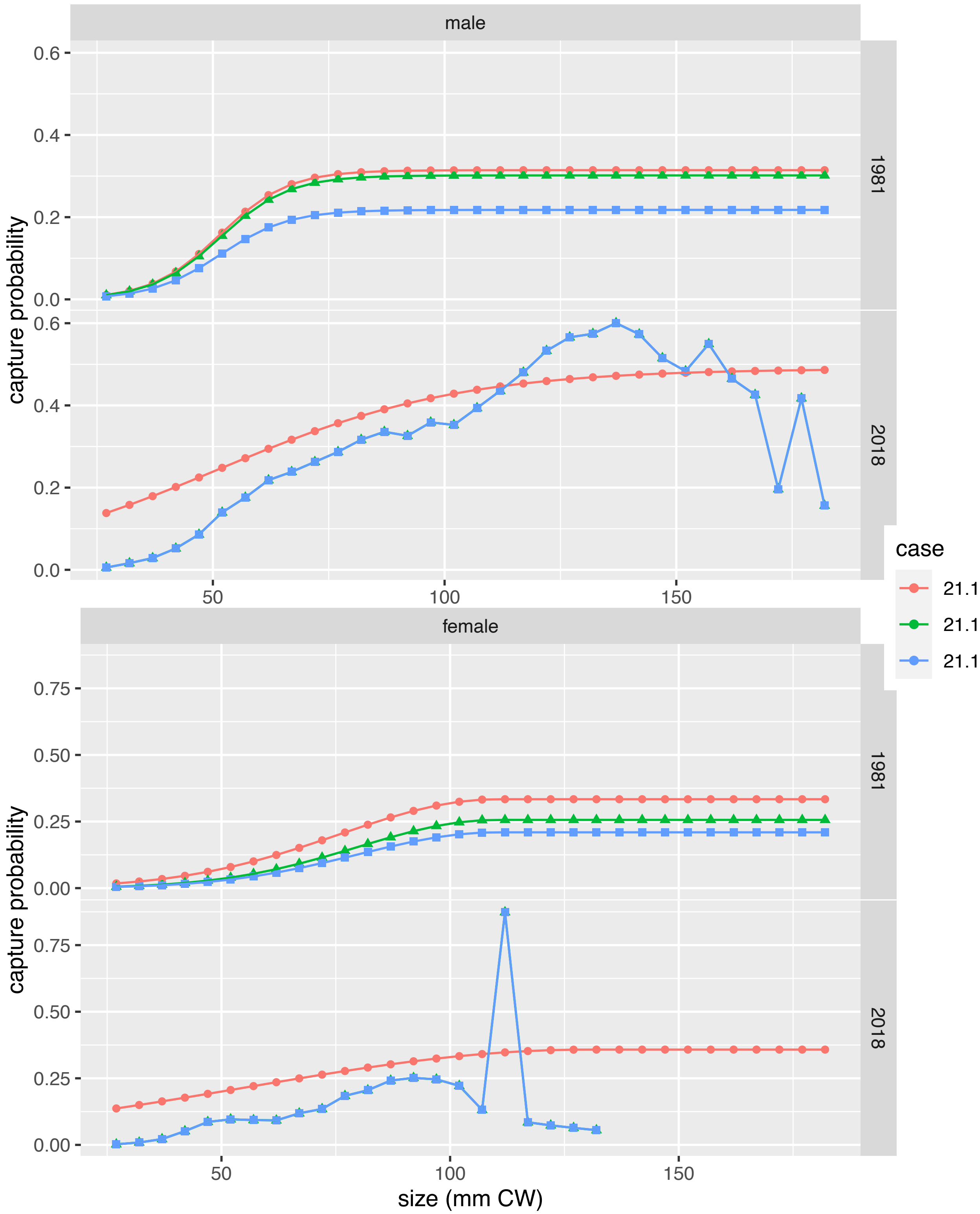


Figure 71. Estimated survey catchability for the NMFS EBS Shelf Survey. Catchability functions vary annually for Models 21.14 and 21.15. Example function functions from 2018 are shown here.

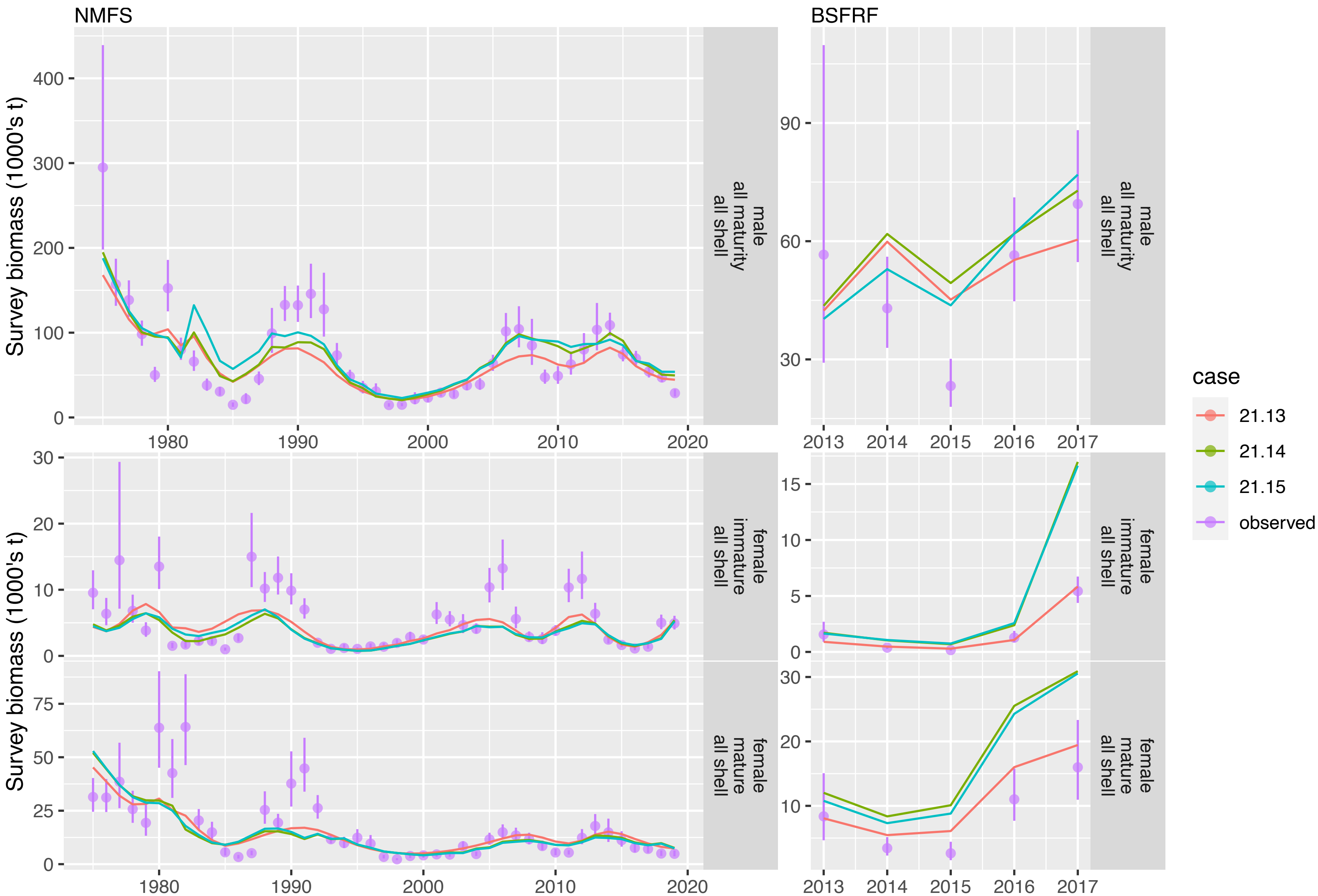


Figure 72. Fits to survey biomass time series from the NMFS EBS Shelf Survey and BSFRF side-by-side surveys.

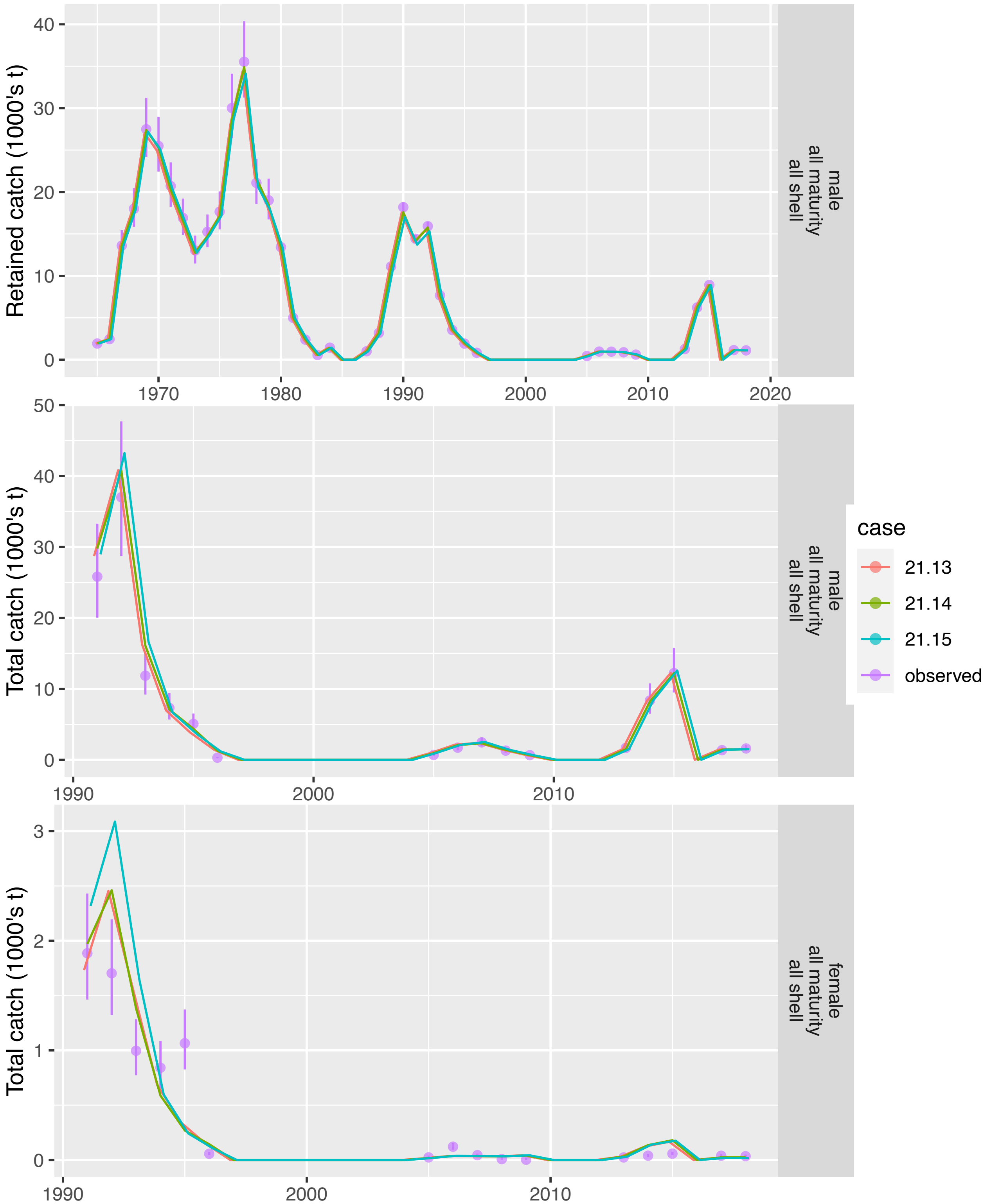


Figure 73. Fits to retained catch and total catch biomass time series in the directed fishery.

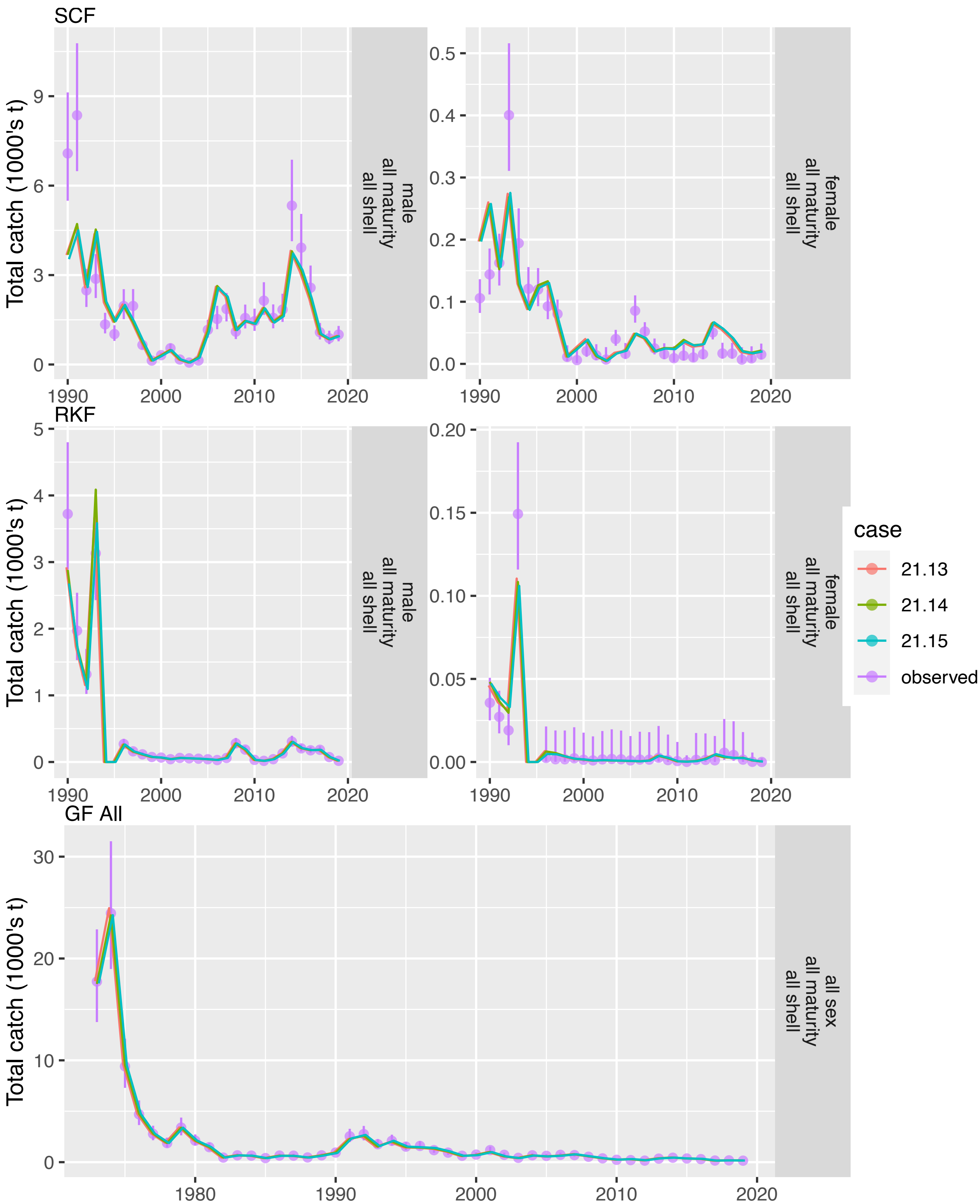


Figure 74. Fits to catch biomass time series for Tanner crab bycatch in the snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

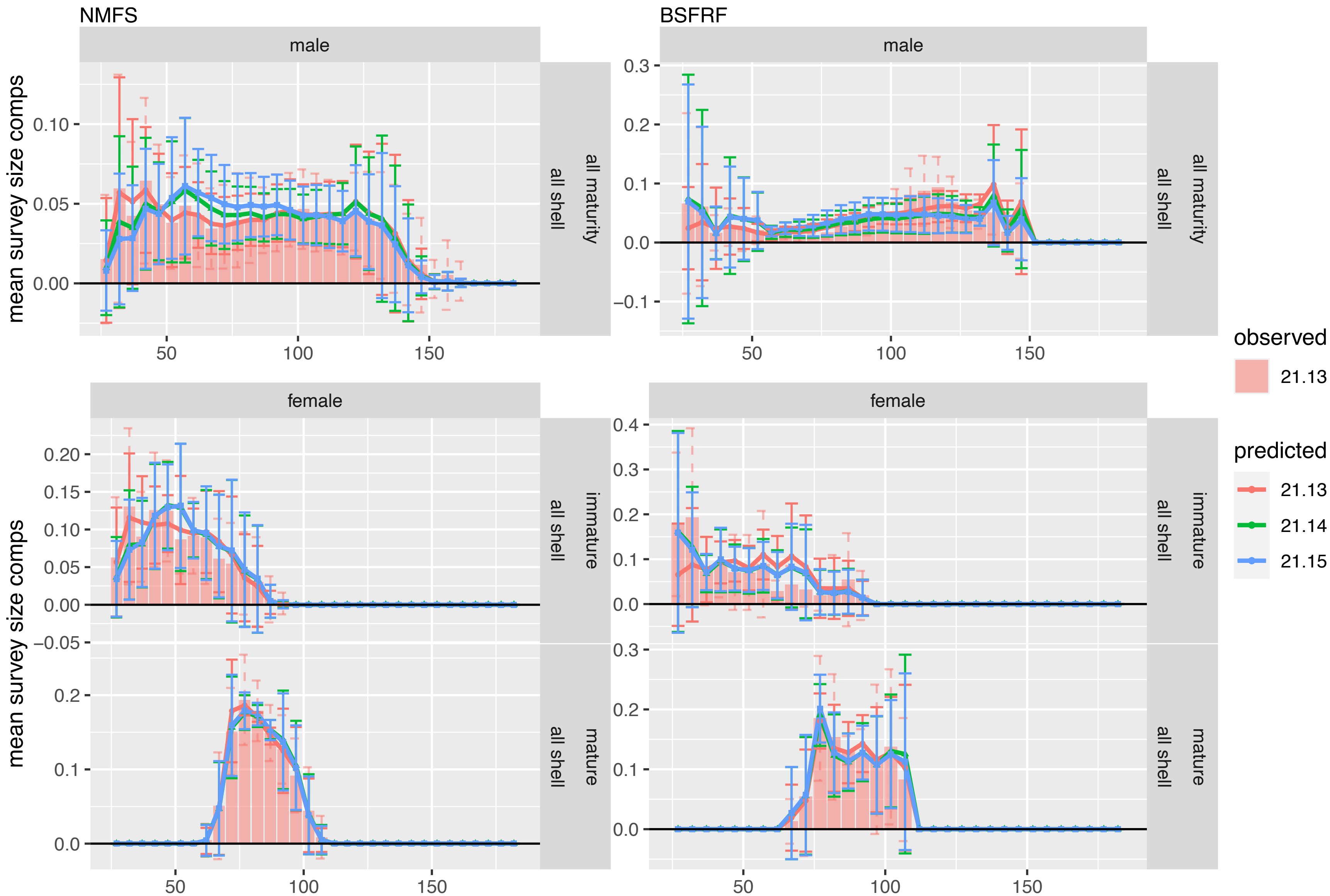


Figure 75. Fits to mean size compositions from the NMFS EBS Shelf Survey and BSFRF side-by-side surveys.

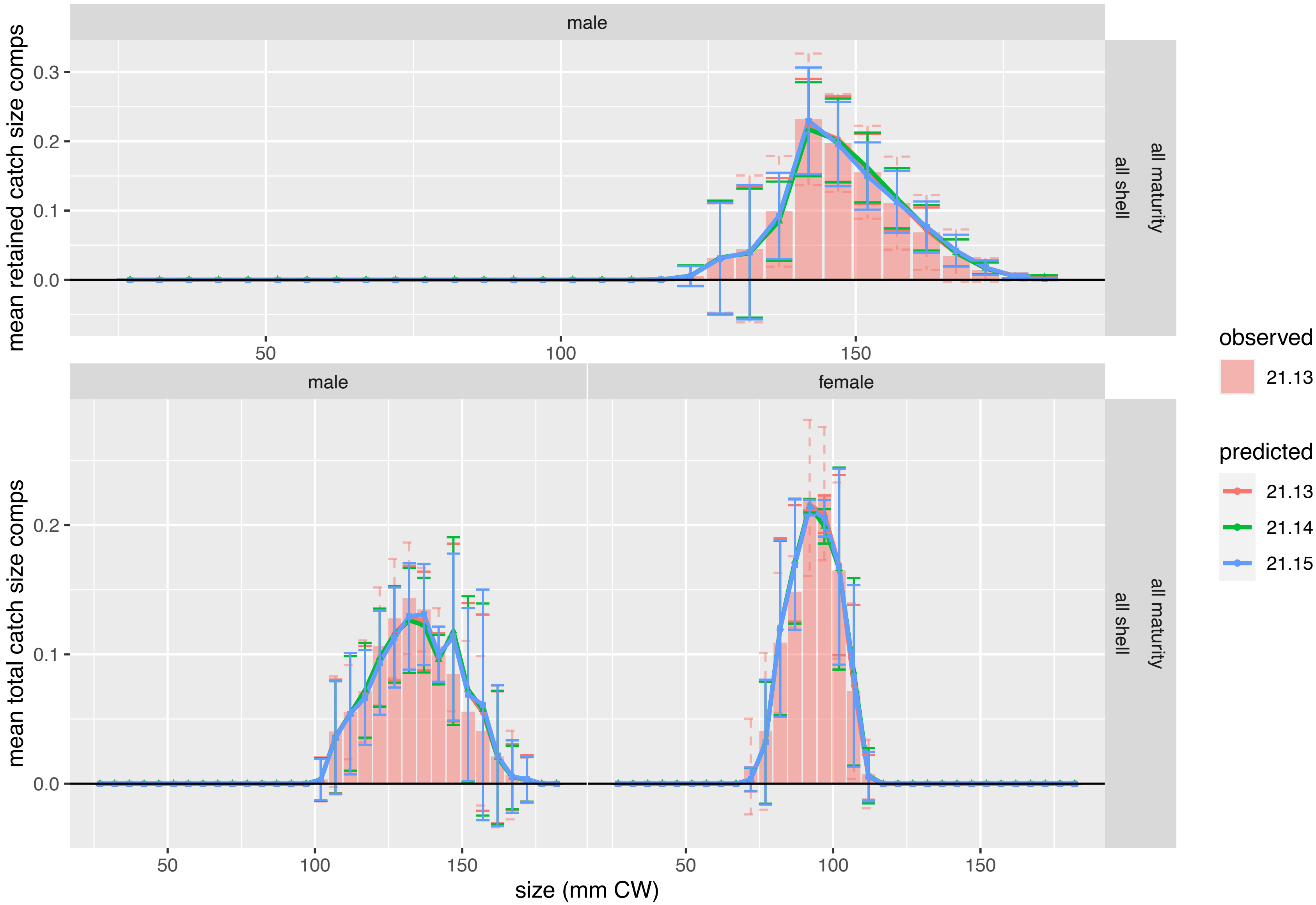


Figure 76. Fits to mean size compositions for retained catch and total catch size compositions in the directed fishery.

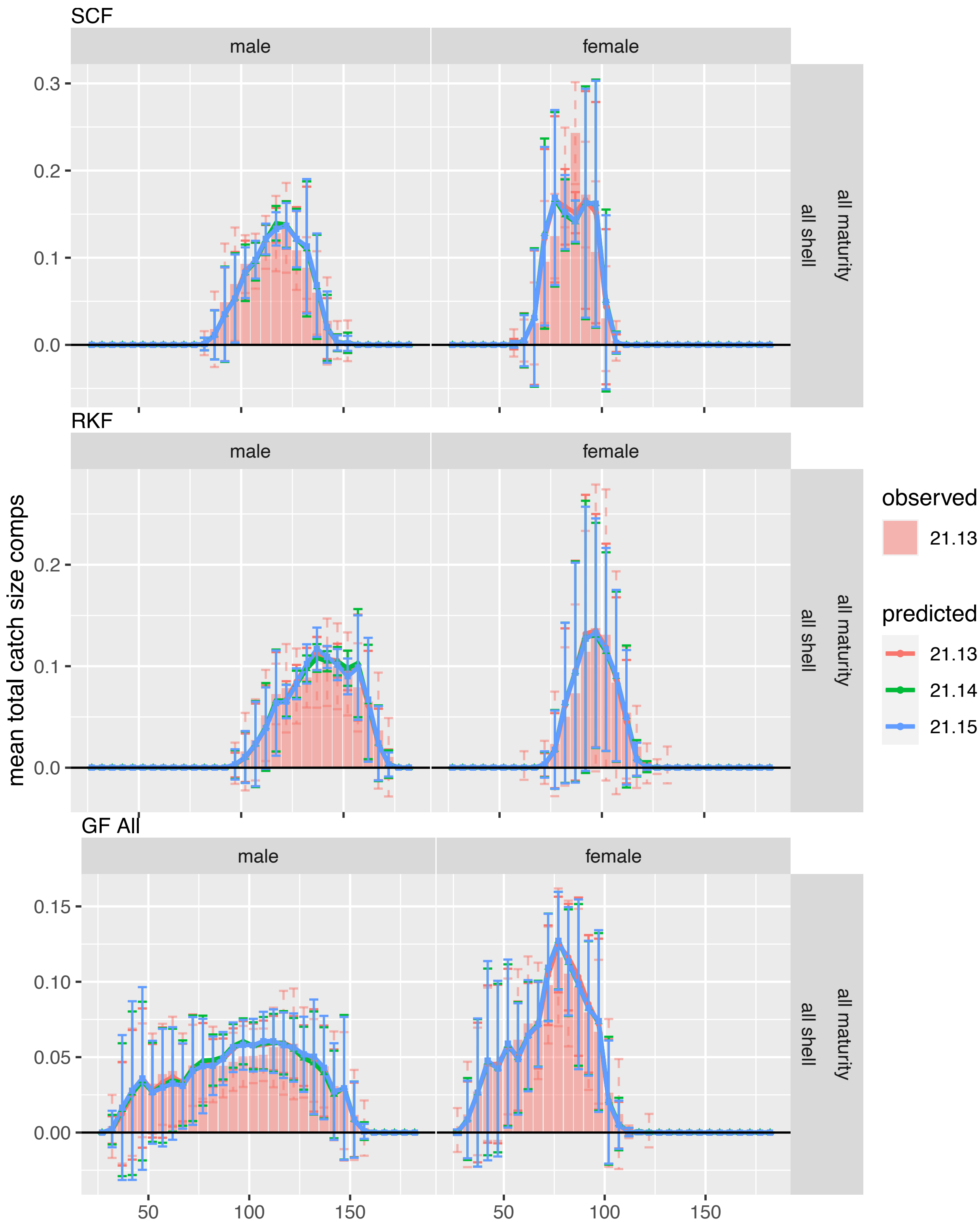


Figure 77. Fits to mean size compositions for Tanner crab bycatch in the snow crab ("SCF"), BBRKC ("RKF"), and groundfish fisheries ("GF All").

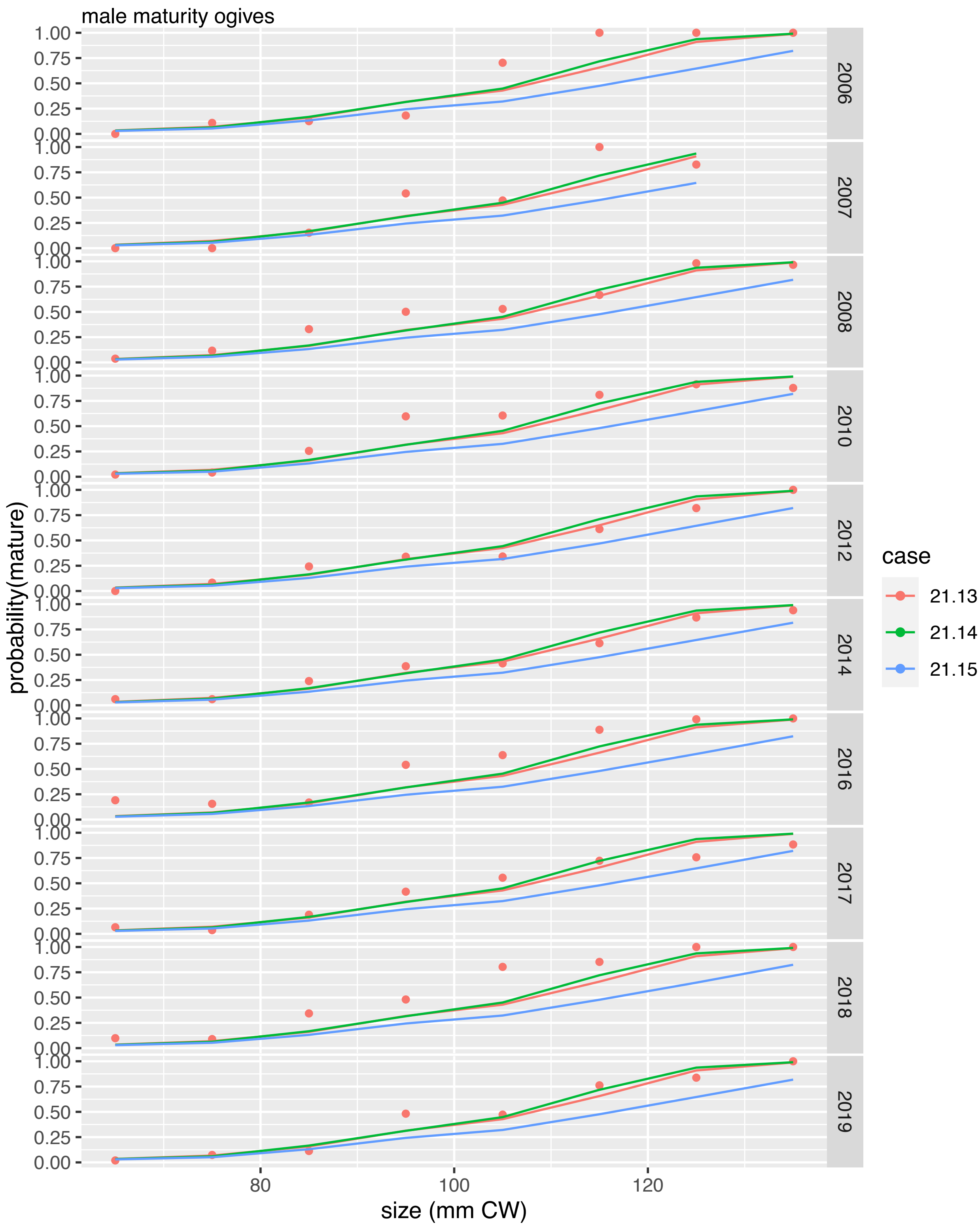


Figure 78. Model fits to maturity ogive data.

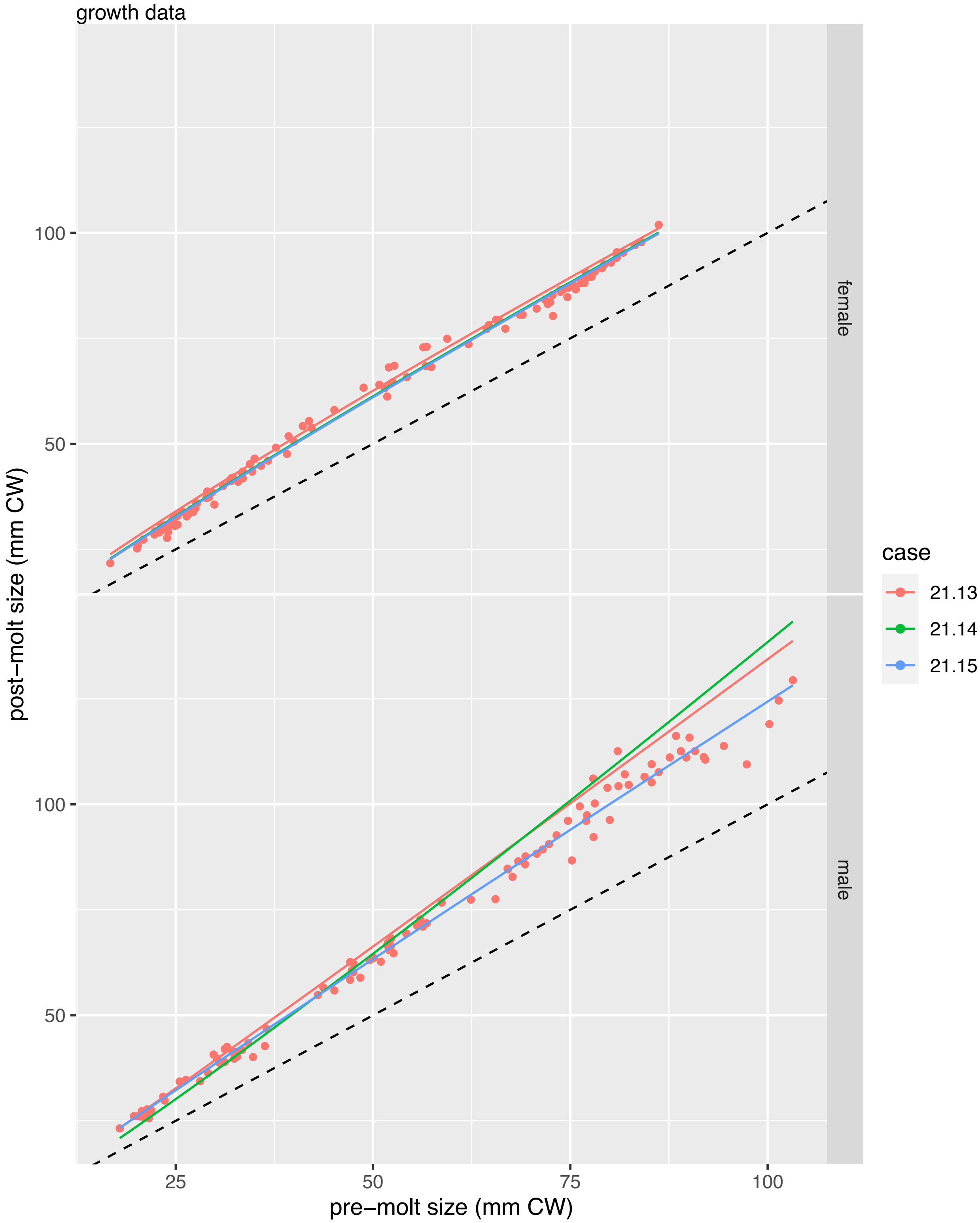


Figure 79. Model fits to maturity growth data.