

May 2016 Tanner Crab Stock Assessment Activities Report: Part 1

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Executive Summary

Stock: species/area.

Southern Tanner crab (*Chionoecetes bairdi*) in the eastern Bering Sea (EBS).

Fishery update

Legal-sized male Tanner crab are caught and retained in the directed (male-only) Tanner crab fishery in the EBS. Directed fisheries in the State of Alaska's (SOA) Bering Sea District were opened in 2013/14 for the first time since 2009/10 because the stock was not overfished in 2012/13 (Stockhausen et al., 2013) and stock metrics met the State of Alaska (SOA) criteria for opening the fisheries in 2013/14. Currently, Total Allowable Catch (TAC) is set for two areas in the District, one west of 166° W longitude and one between 163° W and 166° W longitude, and the fisheries open on October 15 and close on March 31. Prior to the closures in 2010/11, the retained catch averaged 770 t per year between 2005/06-2009/10. In 2013/14, 80% (593.6 t) of the TAC in the western area (1,645,000 lbs; 746.2 t) was taken, while 99% (654.3 t) of the TAC (1,463,000 lbs; 663.6 t) was taken in the eastern area.

In 2014/15, TAC was set at 6,625,000 lbs (~3,000 t) for the western area and at 8,480,000 lbs (~3,900 t) for the eastern area. On closing, 78% (5,248,887 lbs; ~2,400 t) of the TAC was taken in the western area while almost 100% (8,459,998 lbs; ~3,800 t) was taken in the eastern area.

In 2015/16, TAC was set at 8,396,000 lbs (~3,800 t) for the western and at 11,272,000 lbs (~5,100 t) for the eastern area. On closing, 100% of the TAC was taken in both areas.

Recent changes (if any) to the management of the fishery.

At the March, 2015 SOA Board of Fish meeting, the Board adopted a revised harvest strategy for Tanner crab in the Bering Sea District¹, wherein the TAC for the area east of 166° W longitude would be based on a minimum preferred harvest size of 127 mm CW (5.0 inches), including the lateral spines. Formerly, this calculation was based on a minimum preferred size of 140 mm CW (5.5 inches). The TAC in the area west of 166° W longitude continues to be based on a minimum preferred harvest size of 127 mm CW (including lateral spines).

¹ <https://aws.state.ak.us/OnlinePublicNotices/Notices/Attachment.aspx?id=100244>

Responses to SSC and CPT Comments

1. *Responses to recent SSC and CPT comments.* [Note: for continuity with previous assessments, the following includes comments prior to the most recent two sets of comments.]

October 2015 SSC Meeting

Comment: “The SSC endorses all of the CPT recommendations with respect to the poor fits to some of the retained catch time series, poor fits to the size composition data for retained catch and survey data, and issues with the total directed fishery selectivity curve for males (in particular the 1996 ‘outlier’).”

Response: See responses to CPT comments below.

Comment: “The SSC was unable to fully compare models, as the summary tables in the assessment did not include the number of model parameters for evaluating differences in likelihoods.”

Response: A good point, and an oversight on my part. The number of model parameters will be included in at least one summary table (e.g., Table 3 here).

Comment: “The SSC would have liked to have seen residual diagnostic plots for models assuming a log-normal likelihood (B and D) to assess more fully the rationale for not further considering these models.”

Response: Residual diagnostic output (z-scores) have been added to model output, and z-score plots are now included in the standard plots produced following a converged model run. Examples are available in the “online” model results, but have not been included in this report.

Comment: “There are continuing concerns about the most appropriate weights to use for different data components (CVs, effective N, etc.), and the SSC looks forward to recommendations from the data-weighting workshop.”

Response: The author was unable to attend the workshop and looks to the CPT for specific recommendations to follow.

Comment: “Strong residual patterns in numbers at size remain a concern and suggest model misspecification with respect to growth.”

Response: Growth increment data for Tanner crab in the Bering Sea was collected in 2015 for sub-adults and is being collected now (April 2016) for smaller crab. Despite several requests to the concerned parties, the author has not yet been able to obtain data already collected (including those from the Gulf of Alaska), which is rather frustrating.

Comment: “The period with elevated M differs between male (1981-1985) and female crab (1980-84).”

Response: This was a mistake (now corrected) in the code that produced the plot. The periods are the same (1980).

Comment: “The model overestimates female bycatch mortality in the snow crab fishery.”

Response: This issue is addressed more fully in the report. One factor responsible for this observation was that the estimated male fishing mortality rate in each fishery was equally applied to females, with only changes in selectivity available to better fit female bycatch. The option to estimate female-specific offsets to (log-scale mean) male fishing mortality rates has been added to the model (model change C in this report) and reduces this problem. Fits were also improved using a lognormal likelihood (with assumed cv 's, model changes L0 and L1), rather than the standard normal likelihood.

September 2015 CPT Meeting

Comment: “The model fits total catch well, but does a poorer job in fitting retained catch, catch of females, and catch in the bycatch fisheries.”

Response: There appears to be a conflict in the model between fitting total (male) catch and retained catch in the directed fishery. Fitting discard catch rather than total catch (model change D in the report) improved the fit to retained catch. This may also be an issue related to treating retained and total catch

with equal uncertainty in the standard model likelihood. Fits to female bycatch improved upon estimating a female-specific offset to (log-scale male) mean fishing mortality (model change C in the report). Fits to bycatch improved, in general, using a lognormal likelihood assumption for fishery catch data (model changes L0 and L1 in the report), but it is unclear what are reasonable cv's to use.

Comment: “Strong residual patterns exist in fits of male survey and retained-catch size composition...”

Response: See response to SSC comment regarding collection of growth increment data.

Comment: “It was not clear why the model estimates full selection [for males in the directed fishery] in 1996 at roughly 100 cm...”

Response: This result occurred because the 2015 assessment model was apparently not fully-converged, even though it appeared to be (small maximum gradient, invertible hessian). Based on 200 model runs jittering initial parameters, the minimum objective function for the converged model (Model 0 here) is only 0.39 likelihood units smaller than the 2015 model, consequently the two results are essentially indistinguishable on a likelihood basis. B_{MSY} for Model 0 is slightly smaller than the assessment model result (25.7 vs. 26.8 thousand t), F_{MSY} is slightly higher (0.71 vs. 0.64), and the OFL would have been almost the same (27.9 vs. 27.7 thousand t).

Comment: “The poor fit of the models with lognormal fishery catch likelihoods (Models B and D [in the 2015 assessment] ... was surprising to some CPT members.”

Response: These models exhibited questionable convergence in the 2015 assessment. From results obtained for this report using similar models, it is clear those models had not converged and the results were spurious (as was suggested by the author at the time). For this report, we ran each model scenario 100-200 times with randomly-selected (jittered) initial parameter values to improve confidence in obtaining a “converged” model result. The models with lognormal fishery likelihoods (models including changes L0 and L1 in the report) now fit the data well—perhaps too well, in some cases.

Comment: “The author should consider fitting retained catch exactly.”

Response: Time did not allow exploring this possibility.

June 2015 SSC Meeting

No unaddressed comments.

May 2015 Crab Plan Team Meeting

Comment: “Future exploration...should consider the impact of handling mortality on the estimate of natural mortality and how the model behaves if Q for the most recent years is assumed known rather than being estimated.”

Response: This remains to be addressed.

Comment: “The CPT would like to see the results of analyses based on this (new) model at its September 2015 meeting”.

Response: The new model code (TCSAM2015) is presented in this report.

Comment: “The CPT reiterates its suggestions from the September 2014 meeting, in particular that the sensitivity of the results to the prior on Q should be explored.”

Response: This remains to be addressed.

October 2014 SSC Meeting

Comment: “The SSC encourages authors to explore alternative models such as time-varying growth to help address retrospective bias and patterns in other residuals.”

Response: This can be addressed in the future with the new model code (TCSAM2015).

Comment: “The SSC also encourages authors to explore model alternatives without time-varying selectivity for the groundfish fishery.”

Response: This can be addressed in the future with the new model code (TCSAM2015).

June 2014 SSC Meeting

Comment: “Examine retrospective patterns of models being brought forward.”

Response: This will be possible using the new model code (TCSAM2015).

May 2014 Crab Plan Team Meeting

No unaddressed comments.

Introduction

This chapter reports on work undertaken since the (September) 2015 assessment of the BSAI tanner crab stock (Stockhausen, 2015) to improve the Tanner crab stock assessment model (TCSAM). It also proposes a limited number of scenarios to be evaluated for status determination and OFL setting at the next assessment (September, 2016).

The principal emphasis of the work completed thus far has been two-fold: 1) to update the assessment model code used in the 2015 assessment (TCSAM2013) to incorporate potential improvements to that assessment and to evaluate these improvements relative to the previous version of the model and 2) to evaluate a completely new version of the assessment code (TCSAM2015) that constitutes a “bridge” between a future GMACS assessment model and the current (TCSAM2013) model. As discussed below, TCSAM2015 incorporates the GMACS fishing mortality model. It also eliminates all of the “hard-wired” components of TCSAM2013 in favor of setting model configuration details completely using input files rather than editing model code (e.g., specifying time periods or priors on parameters). Some model parameters are re-scaled (e.g., from arithmetic to log scale) to improve model convergence and a revised growth model algorithm is available as an option. The new code also provides more extensive model fitting options and diagnostic output. Finally, Tier 3-type OFL calculations are incorporated directly in the model code, rather than as standalone code for post-processing model results (as with TCSAM2013). In addition, a companion simulation tool (rsimTCSAM) has been developed as an R package to test and debug TCSAM2015, as has a companion diagnostic tool (rTCSAM2015) to make multiple model runs and plot model output. It is anticipated that future improvements to the Tanner crab model (e.g., incorporating BSFRF surveys, chela height data, and growth data) will be incorporated into TCSAM2015 and that TCSAM2013 will not be further updated.

TCSAM2013 updates

The TCSAM2013 model is discussed in detail in Appendix A to this chapter. Model code is available on github (<https://github.com/wStockhausen/wtsTCSAM2013>; the current branch is ‘dev20160316’). Although the author would like to drop this code in favor of the more-flexible TCSAM2015 (discussed in Part 2 to this report), a substantial amount of work has been done since Sept. 2015 as part of the transition to TCSAM2015 to implement alternative approaches to model parameterization and data-fitting in the code. In addition, more model options can now be specified in a “control file” and are no longer “hard-wired” in the model code. The changes to the code are summarized in Table 1. The changes involved in setting model options in the control file simplify running the model under different scenarios, mainly because the model code no longer needs to be edited and recompiled to obtain the desired model configuration. Options in the control file also allow the user to individually select the new parameterization and data-fitting options or use the old ones. The implementation changes (highlighted in Table 1) represent changes that might affect the model results. The effects of these alternatives have been evaluated, to some extent, in this report except for the one (highlighted in orange in Table 1) involving estimating the scalars used to extrapolate fishing mortality rates using effort data, which time did not permit.

Specific individual changes to a jittered version of the 2015 assessment model (“Model 0”) considered in this report are listed in Table 2. The impact of the individual changes were evaluated in 23 different model scenarios both as single changes to Model 0 (Tables 3, 5) and as incrementally-combined changes (Tables 3, 6, 7). For each model scenario, the model was run a number of times (Table 3, # of jitter runs) with initial values for all estimated parameters randomly-selected (“jittered”) to evaluate model convergence. Typically, only 10-20% of the runs converged to the lowest objective function value (indicating the importance of jittering to evaluate convergence). The run with the smallest objective function value and maximum gradient was subsequently selected as the run most likely to have truly converged to the minimum objective function value. This model was re-run (using the jittered initial values) to invert the hessian and obtain uncertainty estimates (standard deviations) for the parameters.

Model 0 was run 200 times jittering the initial values for its parameters to evaluate convergence of the 2015 assessment model to the global minimum. As a result, it was discovered that the 2015 assessment model, while the diagnostics examined (small maximum gradient, invertible hessian) suggested the model had converged, it had done so to a local minimum and not the global minimum. While there is no guarantee that Model 0 converged to the global minimum either, the large number of runs with random starting locations provides enhanced confidence that this is indeed the case. Model 0 converged to an objective function value of 2048.68 likelihood units, while the 2015 assessment model converged to 2049.07, a difference of 0.39 units (Table 4). From an overall likelihood standpoint, the 2015 model is almost as credible as Model 0. However, examining values for the individual components included in the total objective function reveals several larger (2-5 likelihood units) offsetting changes. The driver for most of the changes appears to be the estimated selectivity curve for total male mortality in the directed fishery in 1996 (Figure 1). The curve in the 2015 assessment is shifted towards much smaller crab than any other year, while the corresponding curve from Model 0 is not. Furthermore, this change also affected the total selectivity curve pre-1991, which is based on the average post-1990 curve. The 1996 total selectivity curve was identified during the assessment as an issue to follow up on (and apparently now resolved). B_{MSY} for Model 0 is slightly smaller than the assessment model result (25.7 vs. 26.8 thousand t), F_{MSY} is slightly higher (0.71 vs. 0.64), and the OFL would have been almost the same (27.9 vs. 27.7 thousand t). More comparisons between the 2015 assessment model and Model 0 are available in the accompanying online material in the file “ModelComparisons.2015vs0.zip”. [NOTE: In subsequent figures, “2015 Model” refers to Model 0, not the 2015 assessment model.]

Comprehensive graphical comparisons between Model 0 and the single-change models are available in the accompanying online material in the files “ModelComparisons.SingleChanges.A-D.zip” and “ModelComparisons.SingleChanges.E-I.zip”.

Model change “A” consisted of changing the beginning of the “current” period for estimating log-scale mean recruitment and deviation parameters from 1974 to 1975. This change was considered because, prior to 2015, the beginning of the “current” recruitment period coincided with the first year of the NMFS bottom trawl survey data series used in the assessment. In 2015, the survey time series was revised and now starts in 1975, but the start of “current” recruitment was not changed to 1975. The effect of this change, to be consistent with the rationale used in previous assessments, was thus evaluated. Relative to the assessment model, this change had negligible impact on the results (Tables 3, 5 and 8).

Change “B” consisted of revising the normalization used in TCSAM2013 to combine sex-specific size frequency data from observer bycatch sampling in the groundfish fisheries. The fits to the female size compositions starting in 1997 in previous assessments (Figure 2) were particularly poor. Subsequent investigation revealed that the observed male and female size compositions, when fit, were being combined in an extended fashion using the sex-specific input *effective* sample sizes, not the original sample sizes, to weight the sex-specific contributions to the extended composition. However, because of the algorithm used to calculate them, the input effective sample sizes don’t necessarily reflect the overall ratio of males to females in the original data. Consequently, an option was added to the code to normalize the groundfish fisheries bycatch size compositions using the original sample size, rather than the input sample, and evaluated as change “B”. Model 0 and models including change B are not directly comparable because the data being fit is different (due to the different normalizations), so the objective function values cannot be directly compared to evaluate the models from a likelihood standpoint (Tables 3, 5, and 8). However, it is apparent (Figure 2) that incorporating change B is the correct approach. This change somewhat reduced estimated mortality rates for the bycatch in the groundfish fisheries and historically (pre-1980) in the directed fishery. Final MMB-at-mating is ~7% larger with Model B, compared to Model 0, while average recruitment (1982+) is 1% smaller.

To address model change “C”, parameters to estimate log-scale offsets for females to mean fishing mortality (or capture, see below) rates were added to the model. This change stemmed from what appeared to be poor fits to female bycatch in previous assessments (Figure 4, lefthand plot). Relative to Model 0, this single change (Model C) improved the model fit by almost 40 likelihood units (Tables 3, 5) while adding only 3 model parameters (bycatch mortality rates were not estimated for males or females for the BBRKC fishery in Models 0 or C). The improved fit is clearly apparent in Model C (Figure 4, righthand plot). Interestingly, this change had larger positive effects on fits to size compositions in the fisheries, as well as size compositions for mature crab in the survey, than it did on fits to fishery bycatch mortality. This was due to concomitant changes in estimated fishery selectivity for females (Figure 5).

Change “D” was implemented in the model code as an option to fit discard mortality (biomass) for males in the directed fishery, rather than total mortality. It was hypothesized that fitting to discard mortality only might be more accurate/effective, because “observed” total mortality simply combined observed discard mortality and observed retained mortality. Although the total objective function values for Model 0 and Model D (Table 3) are not directly comparable because the directed fishery total/discard mortality data being fit are different, making this change did substantially improve the fit to retained catch biomass (~23 likelihood units) but also substantially degraded fits to retained catch size compositions (~28 units) and total catch size compositions (~16 units) for the directed fishery (Table 5). The influence of the choice on fitting total or discard mortality in the directed fishery on fishery size composition fits probably reflects the fact that the total catch size compositions (from observer sampling) reflect total capture size compositions, not discard compositions. Total catch size compositions are fit because it was felt that observers were not distinguishing crab that would either be retained or discarded accurately enough to allow use of “discard” size compositions. However, as has been noted previously, this introduces a logical inconsistency into the model because the model estimates size compositions for total mortality in the directed fishery, not total *capture*. It should also be noted that using the GMACS fishing mortality model (see below) eliminates this inconsistency because it can estimate total capture size compositions, as well as discard and retained compositions. Changes to final MMB-at-mating and average recruitment, relative to Model 0, were very small.

Model change “E” turned on estimation of parameters related to bycatch fishing mortality rates in the BBRKC fishery. In previous assessments, these rates have been fixed at nominal values—although selectivity curves have been estimated. Estimating these parameters (including a log-scale female offset) results in an improvement of almost 10 likelihood units over Model 0 (Table 3), but at the expense of estimating 25 additional parameters. Somewhat surprisingly, estimating these parameters actually degrades the “fit” bycatch mortality in the BBRKC fishery (Table 5)—however, the bycatch mortality during the time period over which data is available (1992-present) is quite small and below any ability to fit well using the model’s standard log-likelihood model for fishery mortality, which assumes that bycatch mortality has an associated (but un-estimated) standard deviation of ~1000 t. Instead, the improvement in overall model fit, which comes mainly through better fits to mature male and immature female size compositions in the survey (Table 5), is probably related to a different extrapolation of pre-1992 bycatch mortality rates in the BBRKC fishery using effort data.

In previous assessments, the log-scale parameter reflecting mean “historic” (1949-1973) recruitment was initialized with a value of 0. Model change “F” was to evaluate the effect of setting the initial value for this parameter to the same value as that used for the “current” recruitment period—with the concern that the initial value might affect the convergence. For a single model run without jittering initial parameter values, it turned out this change had no effect. For jittered model runs, the concern was irrelevant.

In previous assessments, the log-scale parameters associated with estimating the size dependence of the probability of molting to maturity hit their upper bounds for larger crab because the probability had to be ≤ 1 . In the 2015 assessment, 9 of the 32 parameters for males hit the upper bound (0, log-scale). This was

a concern because of indirect effects this behavior might have on model convergence and inverting the model hessian to obtain parameter uncertainty estimates. Model change “G” introduced an option to estimate these parameters on a logit, rather than log, scale. For Model G, only 1 out of 32 parameters for males hit the upper bound (15, logit-scale). The estimated size-specific probabilities of molt-to-maturity with model G were very similar to those obtained with Model, but lacked the decline seen in Model 0 for the largest male crab (Figure 6). However, the overall model fit decreased by 3.2 likelihood units.

In the 2015 assessment, as in other recent ones, the model began building up the population in 1949 from zero abundance using only “historic” recruitment. This led to speculation that an earlier start might allow the model to “spin-up” more effectively prior to being informed by data (retained catch data starts in 1965). Consequently, the model code was revised to use an input from a model configuration file as the model start year. In addition, the year to start estimating log-scale “historic” recruitment deviations was added as an input in the control file. That way, recruitment deviations did not necessarily start in the same year the model started. Change “H” addressed this issue by starting the model in 1930 under constant recruitment until 1949, at which time “historic” deviations were added. This change apparently made almost no difference whatsoever (Table 3).

As illustrated in Figure 5 (left plot), several logistic selectivity curves in the 2015 assessment failed to reach 1 by the largest size bin included in the model. While this is not necessarily a problem, it complicates comparison of (for example) fishing rates based on the concept of “full selection” to a fishing gear. It can also indicate the existence of structural conflicts between data and model, such as widely-different fishing mortality rates on males and females in the same fishery. As such, the model code was revised to provide the option (set in the control file) to normalize logistic curves used to describe selectivity processes in the fisheries and surveys. For change “I”, this option was invoked for all the logistic selectivity curves used in the model (i.e., for the surveys and all fisheries except male bycatch in the snow crab fishery). Perhaps surprisingly, Model I was the only model scenario for which parameter uncertainty information (i.e., an “std” file) was not produced. However, given that estimating fishing mortality offsets for females in Model C led to female bycatch selectivity curves that were essentially 1 at sizes less than 150 mm CW (Figure 5, righthand plot), there were clearly structural inconsistencies in Model 0 and the data that were resolved by scaling “fully-selected” fishing mortality differently for males and females. Requiring that female selectivity curves reached 1 by the largest size bin simply exacerbated the inconsistencies between Model 0 and the data.

As described above, each of the individual changes A-I was evaluated singly against the 2015 assessment model. These changes were also applied and evaluated incrementally, with accumulated changes progressing from Model A to Model A-I, which included all “intermediate” changes B, C, D, E, F, G, and H. Components of the objective function for most of the incremental models are compared in Table 6. A subset of comparisons of fits to biomass time series, MMB-at-mating, and recruitment from the models are compared in Figures 7-26. Selectivity curves are compared in Figures 27-32. Because Model A and Model 0 were nearly identical, and because Model B and Model 0 are not strictly comparable on the basis of likelihood considerations, the progression in models starts with B, moves to A-C and proceeds incrementally to A-I. Comprehensive graphical comparisons between Model 0 and the incremental-change models are available in the accompanying online material in the file “ModelComparisons.IncrementalChanges.zip”.

Adding A and C to B (Model A-C) results in a markedly better fit (~67 likelihood units; Table 6). This primarily results from improved fits to the bycatch size compositions from the groundfish fishery and to size compositions for mature males in the survey. The overall improvement was substantially larger than that obtained in Model C relative to Model 0 (~40 units). Adding change D to Model A-C, fitting to male discard mortality in the directed fishery rather than total mortality, incrementally improved fits to retained catch biomass (~22 likelihood units) but reduced fits to size compositions for retained catch (~27 units)

and total male catch (~16 units). Adding change E (estimating parameters related to BBRKC bycatch mortality) to Model A-D resulted in an improvement in model fit by almost 6 likelihood units, but this gain was offset, from a parsimony standpoint, by adding 25 new parameters. Making this addition improved the fit to size compositions for immature female crab (9 units), but degraded the fit to size compositions for mature females (6 units). Adding F (setting an initial value for historic recruitment) to Model A-E changed nothing because the change was ignored in the jittering process; results are not included in Table 6.

Adding G (estimating the probability of size-specific molt-to-maturity using logit-scale parameters) to Model A-F resulted in a slightly degraded overall model fit masking several large changes in individual likelihood components. Substantially better fits (> 10 likelihood units) were obtained for size compositions for bycatch in the groundfish fisheries, mature males in the survey, mature females in the survey, and mature survey biomass. Substantially worse fits (>10 units) were obtained for immature males and females in the survey, particularly for immature males (~47 units). Adding changes H (starting the model in 1930) and I (enforcing logistic selectivity) to Model A-G had extremely small effects (< 1 likelihood unit) on most components, with the largest change being a better fit to immature female size compositions in the survey (1.4 units).

Comparison of time series from these models (Figures 7-26) indicates, particularly since 1980, very similar trajectories for mature survey biomass, retained catch biomass, total (male) catch mortality in the directed fishery, male bycatch mortality in the ground fish, snow crab and BBRKC fisheries, MMB, and recruitment. Fairly large relative differences exist, however, for estimated female bycatch mortality in the non-Tanner fisheries, reflecting an interplay between whether or not offsets to fishing mortality rates for females are estimated and partially-compensating adjustments to fishery selectivity curves for females. (Figures 27-32). Male fishery selectivity and retention curves show few changes between models, except that the total selectivity curve for 1996 in the directed fishery for Model B is right-shifted to smaller sizes (as in the 2015 assessment; Figure 27). Bycatch fishery selectivity curves for females are typically shifted to smaller sizes for Models A-C and above (e.g., Figures 28-30), although not necessarily so for the BBRKC fishery (Figure 28).

Although time series trends in MMB and recruitment (Figures 23-26) were quite similar, final MMB and average (1982+) recruitment estimates decreased slightly as model changes were added from Model B (Table 8: final MMB: 73.9 thousand t; average male recruitment: 87.7 million) to Model A-I (final MMB: 65.8 thousand t; average male recruitment: 80.7 million)

For Change “J”, the GMACS fishing mortality model (FMM; Appendix A) was used in place of the standard TCSAM FMM. One advantage to the GMACS approach is that it estimates the overall capture process, simply and clearly reflecting the on-deck sorting process to decompose the catch into retained and discarded components. The standard TCSAM FMM estimates the overall mortality process, but it does not “get back” to what was captured. As such, the GMACS formulation is consistent with the size compositions obtained from “at-sea” observer sampling in the directed fishery, because these reflect captured crab prior to sorting, whereas the standard TCSAM model is not. Models using the GMACS FMM were considered at the September, 2015 assessment as alternatives to the preferred model, but all of the models exhibited poor convergence behavior and were rejected. Here, the results for Model A-I, using the standard TCSAM FMM, are compared with the Model A-J using the GMACS FMM, are based on converged models obtained by evaluating multiple runs with jittered initial parameters. More graphical comparisons than shown here between Models A-I and A-J are available in the accompanying online material in “ModelComparisons.A-IvsA-J.zip”.

Based on differences in likelihood, Model A-I apparently fits the data much better (~48 likelihood units) than Model A-J, with most of the difference related to the fit to total male size compositions in the

directed fishery (54 units; Table 7). The major difference in model fit appears to be that the size compositions predicted by Model A-J exhibit a distinct “kink” on the upslope of the distributions near 120 mm CW in 2005, 2006 and 2007, as well less-distinct kinks in 2013 and 2014, whereas those predicted by Model A-I do not (Figure 33). However, this difference belies the similarity in parameter estimates and model time series (see the “online” auxiliary material in TCSAM2013.A-IvsA-J.zip). The estimated selectivity curves differ between the two models (Figure 34), but are not directly comparable because the curves for Model A-I reflect selectivity associated with total (retained + discard) mortality, whereas those for Model A-J reflect selectivity associated with *capture*, before discard mortality occurs. The curves associated with retention (Figure 35) are much more similar.

One issue the CPT has raised regarding using the GMACS FMM is whether or not it, applied on a size-specific basis, is equivalent to $\{\text{total estimated discard mortality}\} = \{\text{handling mortality}\} \times \{\text{total estimated discards}\}$ at the fishery level (i.e., integrated over sizes). This is not an issue with the bycatch fisheries, which don’t have retention, but might be for males in the directed fishery, which are subject to both handling mortality and retention. While it should be apparent from the GMACS FMM equations (Appendix B) that this condition indeed holds from a theoretical point-of-view, it never hurts to verify in practice. Thus, Figure 36 presents the ratio of total (size-integrated) estimated discard mortality from Model A-J to total (size integrated) estimated discards. The ratio should be 0.321, the assumed handling mortality for pot gear, which it is (within numerical limits).

Finally, the “L” changes used lognormal, rather than normal, likelihood functions to fit fishery retained and discard mortality (biomass). This required assigning relative errors (CV’s) to data on retention and discards in the directed and bycatch fisheries, because the error rates are unknown. Because these data types originate from different sampling regimes (fish tickets for all retained catch, observers on a fraction of the fleets for discard data), it was assumed that observed retained catch had a smaller cv than observed discards. For L0, the cv for retained biomass was taken to be 0.05 while the cv for discards was 0.20 in all fisheries (the latter in the range of cv’s obtained by the NMFS bottom trawl survey). For L1, the data was assumed to be more accurate and cv’s were set at 0.01 and 0.05, respectively. More graphical comparisons than shown here between the A-I, A-J, and associated L0 models are available in the accompanying online material in “ModelComparisons.A-IvsA-JandL0.zip”.

Because the L models incorporate different error structures than the non-L ones, likelihood comparisons between them are not appropriate and may be misleading. Consequently, only comparisons between L0 models and L1 models are made in Table 7. It is not clear, however, what to make of these comparisons. Comparisons between A-I and A-J and between A-I.L0 and A-J.L0 seem to show the same pattern in the difference between objective function components, such that the I models fit male total catch size comps in the directed fishery better than the J models (as noted previously for the A-I, A-J models) and the J models fit male discard mortality better. The L1 models appear to be unreasonable and are not considered further here.

Examining estimate time series of fits to data from the A-I/J, and A-I/J.L0 models (Figures 37-52), the main effect of the lognormal error structure for fishery catch mortality data is to fit small values (e.g., Figure 39 and 49), mainly for female crab, much more closely at the expense of fitting some of the largest catches (Figures 44 and 48), mainly for male crab in the directed fishery. This has impacts on estimated fishery selectivity curves (Figures 53-62).

Although small values are fit more closely using the lognormal likelihoods, it is questionable whether this represents a better picture of processes affecting the stock, because these values probably have small impact on stock dynamics. Conversely, it may be important to accurately reflect these processes, mainly because the only observations available in the crab bycatch fisheries are for small values, but the ratio between fishing mortality and effort during this time period is used to scale effort to times (pre-1991)

when effort was much larger but bycatch data are unavailable, although presumably larger. Fortunately, estimated trends in MMB and recruitment are similar for all models, particularly since 1990 (Figures 65-68). Final MMB is slightly smaller for the “L” models than the non-“L” models, whether A-I or A-J, as is average recruitment (1982+), while the differences in final MMB and average recruitment between the A-I and A-J models are very small whether L0 or not (Table 8).

Suggested model configurations to evaluate for September

Given the results presented here, I suggest that the following model runs be evaluated for the September 2016 assessment:

1. Model 0, with updated data.
2. Model A-I, with updated data.
3. Model A-I, with updated data but fitting total male mortality in the directed fishery, not discard mortality.
4. Model A-J, with updated data.
5. Model A-J, with updated data but fitting total male mortality in the directed fishery, not discard mortality.
6. Model A-I.L0, with updated data.
7. Model A-J.L0, with update data.

Literature Cited

- Stockhausen, W., L. Rugolo and B. Turnock. 2013. 2013 Stock Assessment and Fishery Evaluation Report for the Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. In: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands: 2013 Final Crab SAFE. North Pacific Fishery Management Council. Anchorage, AK. pp. 342-478.
- Stockhausen, W. 2014. 2014 Stock Assessment and Fishery Evaluation Report for the Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. In: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands: 2014 Final Crab SAFE. North Pacific Fishery Management Council. Anchorage, AK. pp. 324-545.
- Stockhausen, W. 2015. 2015 Stock Assessment and Fishery Evaluation Report for the Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. In: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands: 2015 Final Crab SAFE. North Pacific Fishery Management Council. Anchorage, AK.

Tables

Table 1. Substantive changes to TCSAM2013 code since Sept., 2015. Implementation changes that may affect model results are highlighted. Implementation changes considered in this report are highlighted in yellow. It should be noted that an option to use the GMACS fishing mortality model was already implemented but not adequately evaluated.

Category	Description
recruitment	The beginning of the "historic" and "current" recruitment periods now inputs.
	Initial parameter values and estimation phase set now inputs.
natural mortality	Initial parameter values and estimation phase now inputs. Time period for high natural mortality now an input.
fishing mortality	Phase to estimate fishing mortality in BBRKC fishery now an input.
	Lognormal likelihoods implemented for fishery catch data (assumed cv's are inputs).
	Option to fit male discard (rather than total mortality) in directed fishery implemented.
	Ln-scale offsets to mean fishing mortality/capture for female crab added as parameters.
	Parameters added to estimate scalars to extrapolate fishing mortality using effort.
	Methods to extrapolate fishing mortality using effort are set in control file.
molt to maturity	Implemented alternative methods to normalize size comps from the groundfish fisheries.
	Normalization method for size comps from the groundfish fisheries set in control file.
control file	Added nominal legal size as input. Was hard-wired to 138 mm CW. Survey Q: means, std devs now set in control file.
other	Model start year now an input.
	Revised code to vectorize many calculations. Added z-scores from likelihood calculations to output.

Table 2. Individual changes considered in model scenarios.

Change	Description
O	2015 assessment model
A	start "current" recruitment estimation in 1975, instead of 1974
B	normalize groundfish fishery size comps using original sample sizes, not input sample sizes
C	estimate log-scale fishing mortality/capture rate offsets for female crab
D	fit to male discard mortality in directed fishery
E	turn on fishing mortality/capture rate estimation for BBRKC
F	set initial estimate for historic log-scale recruitment (= 11.4)
G	estimate probability of molt-to-maturity using logit-scale parameterization
H	change model start year to 1930, keep start year for "historic" recruitment deviations = 1949
I	enforce logistic selectivity = 1 in largest size bin
J	use GMACS fishing mortality model
L0	use lognormal NLL's with moderate cv's for fits to fishery catch data
L1	use lognormal NLL's with small cv's for fits to fishery catch data

Table 3. Model scenarios.

Model Scenario	# params	# of jitter runs	Objective Function		invertible hessian?	Model - Base			
			Value	Max Gradient		Base Model	# params	obj function	Comparable ?
0	307	200	2048.68	0.0005142	yes	0	0	0.00	yes
A	307	100	2048.83	0.0038720	yes	0	0	0.15	yes
B	307	100	2483.82	0.0007151	yes	0	0	435.14	no
C	310	100	2008.96	0.0007887	yes	0	3	-39.72	yes
D	307	100	2083.57	0.0012947	yes	0	0	34.89	no
E	332	100	2038.86	0.0014776	yes	0	25	-9.82	yes
G	307	100	2051.84	0.0004363	yes	0	0	3.16	yes
H	307	100	2048.74	0.0001790	yes	0	0	0.06	yes
I	307	100	2052.32	1.6245600	no	0	0	3.64	yes
CE	335	100	2000.32	0.0020877	yes	0	28	-48.36	yes
AB	307	100	2483.84	0.0009730	yes	B	0	0.02	yes
A-C	310	100	2417.18	0.0015367	yes	AB	3	-66.66	yes
A-D	310	100	2451.98	0.0008679	yes	A-C	0	34.80	no
A-E	335	100	2446.25	0.3956490	yes	A-D	25	-5.73	yes
A-F	335	100	2446.25	0.7825310	yes	A-E	0	0.00	yes
A-G	335	100	2449.10	0.0007482	yes	A-F	0	2.85	yes
A-H	335	100	2449.15	0.0006855	yes	A-G	0	0.05	yes
A-I	335	100	2449.42	0.0010910	yes	A-H	0	0.27	yes
A-I.L0	335	150	3119.23	0.0001949	yes	A-I	0	669.81	no
A-I.L1	335	150	6337.45	0.0117883	yes	A-I.L0	0	3218.22	no
A-J	335	100	2496.92	0.0057845	yes	A-I	0	47.50	yes
A-J.L0	335	150	3149.83	0.0001897	yes	A-J	0	652.91	no
A-J.L1	335	150	6519.10	0.0006310	yes	A-J.L1	0	3369.27	no

Table 4. Comparison of objective function components for the 2015 assessment model and Model 0. Green highlighting indicates differences (Model 0 – assessment model) > 2 likelihood units, red indicates differences < -2.

2015 Model	Model 0	0 - 2015	Type	Description
2.30	2.24	-0.06	penalties	recruitment penalty
0.66	0.61	-0.05		immatures natural mortality penalty
4.21	5.65	1.44		mature male natural mortality penalty
51.50	49.35	-2.14		mature female natural mortality penalty
1.99	1.38	-0.60		survey q penalty
16.18	15.91	-0.27		female survey q penalty
1.41	1.41	0.00		smoothing penalty on female maturity curve
0.16	0.17	0.00		smoothing penalty on male maturity curve
49.46	50.79	1.33		penalty on F-devs in directed fishery
7.70	7.53	-0.18		penalty on F-devs in snow crab fishery
11.69	11.68	-0.01		penalty on F-devs in groundfish fishery
0.90	0.90	0.00	priors	prior on female growth parameter a
0.68	0.68	0.00		prior on female growth parameter b
0.58	0.44	-0.15		prior on male growth parameter a
0.04	0.04	0.00		prior on male growth parameter b
194.58	193.94	-0.64	size compositions	likelihood for directed fishery: retained males
115.48	110.57	-4.92		likelihood for directed fishery: total males
14.00	14.18	0.18		likelihood for directed fishery: discarded females
49.27	49.43	0.16		likelihood for snow crab fishery: discarded males
13.84	14.06	0.21		likelihood for snow crab fishery: discarded females
24.22	24.58	0.36		likelihood for BBRKC fishery: discarded males
1.96	2.04	0.08		likelihood for BBRKC fishery: discarded females
135.13	137.58	2.46		likelihood for groundfish fishery
279.96	280.22	0.26		likelihood for survey: immature males
273.26	273.11	-0.15		likelihood for survey: mature males
307.64	301.93	-5.71		likelihood for survey: immature females
99.27	105.18	5.91	likelihood for survey: mature females	
311.58	315.65	4.07	biomass	likelihood for survey: mature survey biomass
31.87	31.01	-0.87		likelihood for directed fishery: male retained catch biomass
18.21	17.39	-0.81		likelihood for directed fishery: male total catch biomass
6.75	6.48	-0.27		likelihood for directed fishery: female catch biomass
10.51	10.45	-0.06		likelihood for snow crab fishery: total catch biomass
9.61	9.61	0.00		likelihood for BBRKC fishery: total catch biomass
2.53	2.52	-0.01		likelihood for groundfish fishery: total catch biomass
2,049.13	2,048.69	-0.44		total

Table 5a. Comparison of objective function components among single-change TCSAM2013 models. Green highlights indicate alternative model fit is better than base model by at least 2 likelihood units, red highlights indicate the alternative model fit is worse than the base mode by at least 2 likelihood units. Refer to Table 3 for information on number of estimated parameters and model comparability.

Model:	0	A	delta	B	delta	C	delta	D	delta	Category	Description
weight	ObjFun	ObjFun	A - 0	ObjFun	B - 0	ObjFun	C - 0	ObjFun	D - 0		
1	2.24	2.37	0.13	2.44	0.20	2.22	-0.02	2.24	0.00		recruitment penalty
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		sex ratio penalty
1	0.61	0.61	0.00	0.15	-0.46	0.84	0.23	0.56	-0.05		immatures natural mortality penalty
1	5.65	5.67	0.01	4.61	-1.05	6.47	0.82	5.85	0.20		mature male natural mortality penalty
1	49.35	49.33	-0.03	53.25	3.89	49.52	0.17	48.73	-0.62		mature female natural mortality penalty
1	1.38	1.40	0.02	2.78	1.40	0.95	-0.43	1.13	-0.25		survey q penalty
1	15.91	15.96	0.04	14.36	-1.55	19.97	4.06	15.47	-0.44		female survey q penalty
1	0.90	0.90	0.00	0.90	0.00	0.90	0.00	0.90	0.00	Penalties & Priors	prior on female growth parameter a
1	0.68	0.68	0.00	0.66	-0.02	0.60	-0.08	0.68	0.00		prior on female growth parameter b
1	0.44	0.44	0.00	0.77	0.34	0.35	-0.09	0.51	0.07		prior on male growth parameter a
1	0.04	0.04	0.00	0.04	0.01	0.04	0.00	0.04	0.00		prior on male growth parameter b
1	1.41	1.41	0.00	1.29	-0.11	1.43	0.02	1.41	0.00		smoothing penalty on female maturity curve
0.5	0.17	0.17	0.00	0.17	0.00	0.17	0.00	0.17	0.01		smoothing penalty on male maturity curve
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		1st difference penalty on male size at 50% selectivity in TCF
1	50.79	50.95	0.16	51.13	0.33	50.92	0.13	48.00	-2.79		penalty on F-devs in directed fishery
0.5	7.53	7.53	0.00	8.03	0.50	7.35	-0.17	7.42	-0.10		penalty on F-devs in snow crab fishery
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		penalty on F-devs in BBRKC fishery
0.5	11.68	11.68	0.00	11.86	0.17	11.75	0.07	11.67	-0.01	penalty on F-devs in groundfish fishery	
1	193.94	194.05	0.10	195.89	1.95	193.48	-0.46	220.67	26.73	Size Comps	likelihood for directed fishery: retained males
1	110.57	110.46	-0.11	115.02	4.46	111.16	0.60	126.56	15.99		likelihood for directed fishery: total males
1	14.18	14.18	0.00	15.44	1.26	8.74	-5.44	14.24	0.06		likelihood for directed fishery: discarded females
1	49.43	49.43	0.00	50.28	0.85	49.30	-0.13	49.50	0.07		likelihood for snow crab fishery: discarded males
1	14.06	14.05	0.00	14.07	0.01	11.98	-2.08	14.11	0.05		likelihood for snow crab fishery: discarded females
1	24.58	24.58	0.00	24.36	-0.21	24.52	-0.05	24.78	0.21		likelihood for BBRKC fishery: discarded males
1	2.04	2.04	0.00	2.73	0.68	2.46	0.41	2.05	0.01		likelihood for BBRKC fishery: discarded females
1	137.58	137.33	-0.26	523.96	386.38	113.98	-23.61	137.99	0.41		likelihood for groundfish fishery
1	280.22	280.46	0.24	276.52	-3.70	279.13	-1.09	281.87	1.65		likelihood for survey: immature males
1	273.11	273.05	-0.06	284.02	10.91	264.94	-8.18	272.37	-0.74		likelihood for survey: mature males
1	301.93	302.07	0.14	309.10	7.17	312.21	10.28	300.72	-1.21		likelihood for survey: immature females
1	105.18	105.18	0.00	110.85	5.67	95.55	-9.63	105.36	0.18		likelihood for survey: mature females
1	315.65	315.33	-0.32	327.84	12.19	314.89	-0.76	314.86	-0.79		likelihood for survey: mature survey biomass
10	31.01	31.04	0.03	32.31	1.31	30.78	-0.23	8.42	-22.58	Biomass	likelihood for directed fishery: male retained catch biomass
10	17.39	17.41	0.02	18.55	1.16	17.43	0.03	36.25	18.86		likelihood for directed fishery: male total catch biomass
10	6.48	6.48	0.00	7.31	0.83	5.79	-0.69	6.43	-0.05		likelihood for directed fishery: female catch biomass
10	10.45	10.45	0.00	10.74	0.29	6.95	-3.50	10.50	0.05		likelihood for snow crab fishery: total catch biomass
10	9.61	9.61	0.00	9.63	0.02	9.62	0.01	9.61	0.00		likelihood for BBRKC fishery: total catch biomass
10	2.52	2.51	0.00	2.76	0.24	2.59	0.07	2.50	-0.02		likelihood for groundfish fishery: total catch biomass
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	penalty	penalty on sel50 devs for TCF
Totals:	2,048.69	2,048.83	0.14	2,483.82	435.14	2,008.96	-39.73	2,083.57	34.89	Totals	

Table 6b. Comparison of objective function components among single-change TCSAM2013 models. Green highlights indicate alternative model fit is better than base model by at least 2 likelihood units, red highlights indicate the alternative model fit is worse than the base mode by at least 2 likelihood units. Refer to Table 3 for information on number of estimated parameters and model comparability.

Model:	0	E	delt	CE	delt	G	delta	H	delta	I	delta	Category	Description
weight	ObjFun	ObjFun	E - 0	ObjFun	CE - 0	ObjFun	G - 0	ObjFun	H - 0	ObjFun	I - 0		
1	2.24	2.22	-0.02	2.21	-0.02	2.23	0.00	2.26	0.03	2.24	0.00		recruitment penalty
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		sex ratio penalty
1	0.61	0.43	-0.18	0.64	0.03	0.61	0.00	0.61	0.00	0.73	0.12		immatures natural mortality penalty
1	5.65	5.33	-0.32	6.20	0.55	5.68	0.03	5.67	0.02	5.53	-0.12		mature male natural mortality penalty
1	49.35	37.82	-11.54	39.05	-10.31	49.24	-0.11	49.37	0.01	50.20	0.85		mature female natural mortality penalty
1	1.38	0.61	-0.77	0.53	-0.86	1.36	-0.03	1.38	0.00	1.39	0.00		survey q penalty
1	15.91	15.34	-0.57	20.64	4.73	15.94	0.02	15.91	0.00	15.54	-0.38		female survey q penalty
1	0.90	0.90	0.00	0.90	0.00	0.90	0.00	0.90	0.00	0.90	0.00		prior on female growth parameter a
1	0.68	0.57	-0.10	0.51	-0.17	0.67	-0.01	0.68	0.00	0.68	0.00		prior on female growth parameter b
1	0.44	0.35	-0.09	0.30	-0.14	0.46	0.02	0.44	0.00	0.43	-0.01		prior on male growth parameter a
1	0.04	0.04	0.00	0.04	0.00	0.04	0.00	0.04	0.00	0.04	0.00		prior on male growth parameter b
1	1.41	1.30	-0.11	1.33	-0.08	2.51	1.10	1.41	0.00	1.40	0.00		smoothing penalty on female maturity curve
0.5	0.17	0.16	-0.01	0.16	0.00	0.76	0.59	0.17	0.00	0.17	0.00		smoothing penalty on male maturity curve
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		1st difference penalty on male size at 50% selectivity in TCF
1	50.79	46.93	-3.86	47.30	-3.49	50.66	-0.14	50.81	0.02	50.78	-0.02		penalty on F-devs in directed fishery
0.5	7.53	7.45	-0.07	7.37	-0.15	7.53	0.00	7.53	0.00	7.51	-0.01		penalty on F-devs in snow crab fishery
0	0.00	0.23	0.23	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00		penalty on F-devs in BBRKC fishery
0.5	11.68	11.63	-0.05	11.72	0.04	11.68	0.00	11.68	0.00	11.64	-0.04		penalty on F-devs in groundfish fishery
1	193.94	194.04	0.09	193.69	-0.26	193.77	-0.17	193.94	0.00	193.96	0.02		likelihood for directed fishery: retained males
1	110.57	115.36	4.79	115.97	5.40	110.93	0.36	110.57	0.00	110.53	-0.04		likelihood for directed fishery: total males
1	14.18	15.46	1.28	8.88	-5.31	14.30	0.12	14.18	0.00	14.10	-0.08		likelihood for directed fishery: discarded females
1	49.43	49.18	-0.25	49.08	-0.35	49.47	0.04	49.43	0.00	49.42	0.00		likelihood for snow crab fishery: discarded males
1	14.06	15.03	0.98	12.34	-1.71	13.99	-0.06	14.06	0.00	13.99	-0.07		likelihood for snow crab fishery: discarded females
1	24.58	24.06	-0.52	24.04	-0.53	24.60	0.03	24.58	0.00	24.58	0.00		likelihood for BBRKC fishery: discarded males
1	2.04	8.00	5.95	6.23	4.18	2.34	0.30	2.04	0.00	2.04	-0.01		likelihood for BBRKC fishery: discarded females
1	137.58	138.14	0.55	116.21	-21.38	137.69	0.11	137.58	0.00	139.75	2.16		likelihood for groundfish fishery
1	280.22	290.10	9.88	286.10	5.88	281.50	1.28	280.19	-0.03	280.71	0.49		likelihood for survey: immature males
1	273.11	258.72	-14.40	250.17	-22.94	272.44	-0.67	273.12	0.01	273.91	0.80		likelihood for survey: mature males
1	301.93	285.97	-15.96	296.16	-5.77	302.18	0.26	301.95	0.02	298.41	-3.52		likelihood for survey: immature females
1	105.18	125.83	20.65	118.04	12.86	105.69	0.51	105.17	0.00	109.70	4.52		likelihood for survey: mature females
1	315.65	305.94	-9.71	306.44	-9.21	315.19	-0.45	315.63	-0.02	314.48	-1.17		likelihood for survey: mature survey biomass
10	31.01	32.03	1.02	31.85	0.84	31.00	0.00	31.00	0.00	31.02	0.02		likelihood for directed fishery: male retained catch biomass
10	17.39	18.31	0.92	18.30	0.91	17.40	0.01	17.39	0.00	17.40	0.00		likelihood for directed fishery: male total catch biomass
10	6.48	5.33	-1.15	4.92	-1.56	6.52	0.04	6.48	0.00	6.54	0.06		likelihood for directed fishery: female catch biomass
10	10.45	10.19	-0.26	6.55	-3.90	10.44	0.00	10.45	0.00	10.51	0.06		likelihood for snow crab fishery: total catch biomass
10	9.61	13.40	3.79	13.69	4.08	9.59	-0.02	9.61	0.00	9.61	0.00		likelihood for BBRKC fishery: total catch biomass
10	2.52	2.47	-0.05	2.54	0.03	2.51	0.00	2.52	0.00	2.51	-0.01		likelihood for groundfish fishery: total catch biomass
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	penalty	penalty on sel50 devs for TCF
Totals:	2,048.69	2,038.86	-9.83	2,000.33	-48.36	2,051.84	3.15	2,048.74	0.05	2,052.32	3.64	Totals	

Table 7. Comparison of objective function components among incremental TCSAM2013 models. Green highlights indicate alternative model fit better than base model by at least 2 likelihood units, red highlights indicate the alternative model fit is worse than the base mode by at least 2 likelihood units. Refer to Table 3 for information on number of estimated parameters and model comparability.

Model:	0	B	delta	A-C	delta	A-D	delta	A-E	delta	A-G	delta	A-H	delta	A-I	delta	Category	Description
weight	ObjFun	ObjFun	B - 0	ObjFun	A-C - B	ObjFun	A-D - A-C	ObjFun	A-E - A-D	ObjFun	A-G - A-E	ObjFun	A-H - A-G	ObjFun	A-I - A-G		
1	2.24	2.44	0.20	2.44	0.00	2.46	0.03	2.47	0.00	2.88	0.41	2.90	0.03	2.90	0.03		recruitment penalty
0	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	0.00		sex ratio penalty
1	0.61	0.15	-0.46	0.58	0.43	0.55	-0.03	0.47	-0.08	0.87	0.40	0.87	0.00	0.81	-0.06		immatures natural mortality penalty
1	5.65	4.61	-1.05	6.66	2.06	6.91	0.25	7.03	0.12	6.89	-0.15	6.90	0.02	6.90	0.01		mature male natural mortality penalty
1	49.35	53.25	3.89	50.75	-2.49	50.24	-0.52	46.00	-4.24	46.98	0.98	46.99	0.01	46.89	-0.09		mature female natural mortality penalty
1	1.38	2.78	1.40	1.48	-1.30	1.22	-0.26	0.78	-0.44	0.39	-0.39	0.39	0.00	0.38	-0.02		survey q penalty
1	15.91	14.36	-1.55	19.00	4.64	18.50	-0.49	17.63	-0.88	14.84	-2.79	14.85	0.00	15.22	0.38		female survey q penalty
1	0.90	0.90	0.00	0.90	0.00	0.90	0.00	0.90	0.00	0.90	0.00	0.90	0.00	0.90	0.00		prior on female growth parameter a
1	0.68	0.66	-0.02	0.55	-0.11	0.55	0.00	0.51	-0.03	0.46	-0.05	0.46	0.00	0.46	0.00		prior on female growth parameter b
1	0.44	0.77	0.34	0.36	-0.41	0.43	0.07	0.37	-0.06	0.17	-0.19	0.17	0.00	0.17	0.00		prior on male growth parameter a
1	0.04	0.04	0.01	0.04	-0.01	0.04	0.00	0.04	0.00	0.04	0.00	0.04	0.00	0.04	0.00		prior on male growth parameter b
1	1.41	1.29	-0.11	1.34	0.04	1.34	0.00	1.34	0.01	2.28	0.94	2.28	0.00	2.29	0.00		smoothing penalty on female maturity curve
0.5	0.17	0.17	0.00	0.17	0.01	0.18	0.01	0.18	0.00	0.70	0.52	0.70	0.00	0.70	0.00		smoothing penalty on male maturity curve
0	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	0.00		1st difference penalty on male size at 50% selectivity in TCF
1	50.79	51.13	0.33	53.30	2.17	50.53	-2.77	49.82	-0.70	60.76	10.94	60.78	0.02	60.76	0.00		penalty on F-devs in directed fishery
0.5	7.53	8.03	0.50	7.75	-0.28	7.65	-0.10	7.63	-0.02	7.55	-0.09	7.55	0.00	7.54	0.00		penalty on F-devs in snow crab fishery
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.26	0.28	0.02	0.28	0.00	0.28	0.00		penalty on F-devs in BBRKC fishery
0.5	11.68	11.86	0.17	11.86	0.00	11.85	-0.01	11.84	0.00	11.94	0.10	11.94	0.00	11.93	-0.01		penalty on F-devs in groundfish fishery
1	193.94	195.89	1.95	194.99	-0.91	222.09	27.10	222.30	0.21	216.15	-6.14	216.15	0.00	216.16	0.01		likelihood for directed fishery: retained males
1	110.57	115.02	4.46	110.03	-4.99	125.81	15.78	125.77	-0.04	127.32	1.55	127.33	0.00	127.31	-0.01		likelihood for directed fishery: total males
1	14.18	15.44	1.26	8.71	-6.73	8.70	-0.01	8.81	0.11	8.15	-0.65	8.15	0.00	8.15	0.00		likelihood for directed fishery: discarded females
1	49.43	50.28	0.85	50.31	0.03	50.40	0.09	50.40	0.00	51.51	1.11	51.51	0.00	51.50	-0.01		likelihood for snow crab fishery: discarded males
1	14.06	14.07	0.01	12.27	-1.79	12.27	-0.01	12.35	0.08	12.32	-0.03	12.32	0.00	12.32	0.00		likelihood for snow crab fishery: discarded females
1	24.58	24.36	-0.21	24.66	0.30	24.88	0.22	24.83	-0.05	25.31	0.48	25.31	0.00	25.32	0.00		likelihood for BBRKC fishery: discarded males
1	2.04	2.73	0.68	2.55	-0.18	2.53	-0.01	2.44	-0.09	2.49	0.05	2.49	0.00	2.48	0.00		likelihood for BBRKC fishery: discarded females
1	137.58	523.96	386.38	483.05	-40.91	483.40	0.35	483.53	0.12	471.87	-11.66	471.87	0.00	471.92	0.05		likelihood for groundfish fishery
1	280.22	276.52	-3.70	277.88	1.36	279.55	1.67	281.71	2.16	328.54	46.83	328.52	-0.02	328.92	0.38		likelihood for survey: immature males
1	273.11	284.02	10.91	272.22	-11.80	271.17	-1.05	269.70	-1.47	251.61	-18.10	251.61	0.00	252.00	0.39		likelihood for survey: mature males
1	301.93	309.10	7.17	309.17	0.07	308.32	-0.85	299.34	-8.98	309.58	10.24	309.59	0.01	308.20	-1.37		likelihood for survey: immature females
1	105.18	110.85	5.67	113.75	2.90	113.82	0.07	120.26	6.45	106.62	-13.65	106.61	-0.01	107.30	0.68		likelihood for survey: mature females
1	315.65	327.84	12.19	325.61	-2.23	324.59	-1.02	322.54	-2.05	304.05	-18.50	304.04	-0.01	303.96	-0.09		likelihood for survey: mature survey biomass
10	31.01	32.31	1.31	31.21	-1.10	8.73	-22.48	8.61	-0.12	9.13	0.52	9.12	0.00	9.12	0.00		likelihood for directed fishery: male retained catch biomass
10	17.39	18.55	1.16	17.73	-0.82	36.56	18.83	36.71	0.16	35.49	-1.23	35.49	0.00	35.48	0.00		likelihood for directed fishery: male total catch biomass
10	6.48	7.31	0.83	6.35	-0.96	6.32	-0.03	5.57	-0.74	5.85	0.27	5.85	0.00	5.85	0.00		likelihood for directed fishery: female catch biomass
10	10.45	10.74	0.29	7.13	-3.61	7.13	0.00	7.06	-0.07	7.71	0.65	7.71	0.00	7.70	-0.01		likelihood for snow crab fishery: total catch biomass
10	9.61	9.63	0.02	9.66	0.03	9.65	0.00	14.32	4.67	14.69	0.36	14.69	0.00	14.76	0.08		likelihood for BBRKC fishery: total catch biomass
10	2.52	2.76	0.24	2.74	-0.02	2.72	-0.02	2.71	-0.01	2.78	0.08	2.78	0.00	2.78	0.00		likelihood for groundfish fishery: total catch biomass
0	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	0.00	penalty	penalty on sel50 devs for TCF
Totals:	2,048.69	2,483.82	435.14	2,417.18	-66.64	2,451.98	34.79	2,446.25	-5.73	2,449.10	2.86	2,449.15	0.05	2,449.42	0.31	Totals	

Table 8. Comparison of objective function components among incremental TCSAM2013 models. Green highlights indicate alternative model fit is better than base model by at least 2 likelihood units, red highlights indicate the alternative model fit is worse than the base mode by at least 2 likelihood units.

Model:	A-I	A-J	delta A-I - A-J	A-I.L0	A-J.L0	delta I.L0 - J.L0	A-I.L1	A-J.L1	delta A-I.L1 - A-J.L1	Category	Description	
weight	ObjFun	ObjFun	J	ObjFun	ObjFun	J.L0	ObjFun	ObjFun	A-J.L1			
1	2.90	2.94	0.04	2.82	2.84	0.02	4.62	4.09	-0.53	Penalties & Priors	recruitment penalty	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		sex ratio penalty	
1	0.81	0.89	0.08	1.05	1.22	0.17	7.46	12.50	5.04		immatures natural mortality penalty	
1	6.90	8.31	1.41	4.63	5.62	0.99	2.10	0.07	-2.03		mature male natural mortality penalty	
1	46.89	46.43	-0.46	53.77	53.20	-0.57	54.16	162.00	107.84		mature female natural mortality penalty	
1	0.38	0.39	0.01	0.00	0.00	0.00	30.36	24.65	-5.72		survey q penalty	
1	15.22	15.92	0.69	12.38	12.92	0.54	0.75	0.25	-0.51		female survey q penalty	
1	0.90	0.90	0.00	0.90	0.90	0.00	0.90	0.90	0.00		prior on female growth parameter a	
1	0.46	0.47	0.01	0.45	0.47	0.02	0.05	0.40	0.35		prior on female growth parameter b	
1	0.17	0.12	-0.05	0.36	0.18	-0.18	0.73	0.37	-0.37		prior on male growth parameter a	
1	0.04	0.04	0.00	0.05	0.04	-0.01	0.11	0.06	-0.05		prior on male growth parameter b	
1	2.29	2.28	-0.01	2.35	2.34	-0.02	21.52	11.55	-9.97		smoothing penalty on female maturity curve	
0.5	0.70	0.65	-0.05	0.67	0.65	-0.02	0.59	0.67	0.09		smoothing penalty on male maturity curve	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		1st difference penalty on male size at 50% selectivity in TCF	
1	60.76	60.24	-0.52	74.15	69.93	-4.22	170.77	139.81	-30.96		penalty on F-devs in directed fishery	
0.5	7.54	7.52	-0.02	14.73	14.76	0.02	32.82	26.76	-6.06		penalty on F-devs in snow crab fishery	
0	0.28	0.29	0.02	144.07	143.10	-0.97	238.62	226.10	-12.52		penalty on F-devs in BBRKC fishery	
0.5	11.93	11.91	-0.01	16.51	16.57	0.05	19.18	23.27	4.09		penalty on F-devs in groundfish fishery	
1	216.16	226.74	10.58	202.64	210.25	7.61	308.08	318.51	10.43		Size Comps	likelihood for directed fishery: retained males
1	127.31	181.53	54.22	114.63	176.59	61.96	238.95	279.63	40.67			likelihood for directed fishery: total males
1	8.15	8.11	-0.04	7.94	7.89	-0.04	255.61	63.37	-192.24	likelihood for directed fishery: discarded females		
1	51.50	52.27	0.77	51.15	52.09	0.94	108.32	124.98	16.66	likelihood for snow crab fishery: discarded males		
1	12.32	12.23	-0.08	17.89	17.64	-0.25	199.53	29.94	-169.59	likelihood for snow crab fishery: discarded females		
1	25.32	24.99	-0.32	26.31	26.54	0.23	60.40	48.63	-11.77	likelihood for BBRKC fishery: discarded males		
1	2.48	2.48	-0.01	4.93	5.07	0.14	26.92	20.93	-5.98	likelihood for BBRKC fishery: discarded females		
1	471.92	468.29	-3.63	478.07	476.24	-1.83	633.03	761.81	128.78	likelihood for groundfish fishery		
1	328.92	324.64	-4.28	333.75	328.59	-5.16	773.53	420.96	-352.57	likelihood for survey: immature males		
1	252.00	246.48	-5.52	243.54	240.80	-2.74	223.76	214.81	-8.94	likelihood for survey: mature males		
1	308.20	309.33	1.13	317.08	316.40	-0.68	907.56	1,275.53	367.98	likelihood for survey: immature females		
1	107.30	113.31	6.01	104.93	111.82	6.90	31.19	60.95	29.75	likelihood for survey: mature females		
1	303.96	302.21	-1.75	294.69	293.64	-1.05	418.71	714.51	295.81	Biomass	likelihood for survey: mature survey biomass	
10	9.12	9.61	0.48	44.61	43.80	-0.81	15.20	31.79	16.59		likelihood for directed fishery: male retained catch biomass	
10	35.48	25.10	-10.39	88.47	60.63	-27.84	34.89	32.08	-2.81		likelihood for directed fishery: male discard mortality biomass	
10	5.85	5.58	-0.28	240.49	238.39	-2.10	615.77	584.27	-31.50		likelihood for directed fishery: female catch biomass	
10	7.70	7.59	-0.11	83.31	83.05	-0.26	504.58	558.97	54.39		likelihood for snow crab fishery: total catch biomass	
10	14.76	14.32	-0.44	134.64	134.39	-0.26	396.20	343.13	-53.07		likelihood for BBRKC fishery: total catch biomass	
10	2.78	2.82	0.04	1.29	1.28	-0.01	0.49	0.87	0.38		likelihood for groundfish fishery: total catch biomass	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	penalty	penalty on sel50 devs for TCF	
Totals:	2,449.42	2,496.92	47.50	3,119.23	3,149.83	30.60	6,337.45	6,519.09	181.64	Totals		

Table 9. Summary results for selected TCSAM2013 model scenarios.

Model	final MMB (1000's t)	Avg Male Recruitment (millions)
0	69.3	88.4
A	69.4	88.5
B	73.9	87.7
C	68.0	88.1
D	68.2	87.4
E	66.1	85.6
G	69.2	88.2
H	69.3	88.4
I	69.2	88.7
A-C	69.9	86.5
A-D	68.7	85.6
A-E	66.9	83.9
A-G	65.9	80.9
A-I	65.8	80.7
A-J	65.6	81.8
A-I.L0	63.2	75.9
A-J.L0	63.6	77.2

Figures

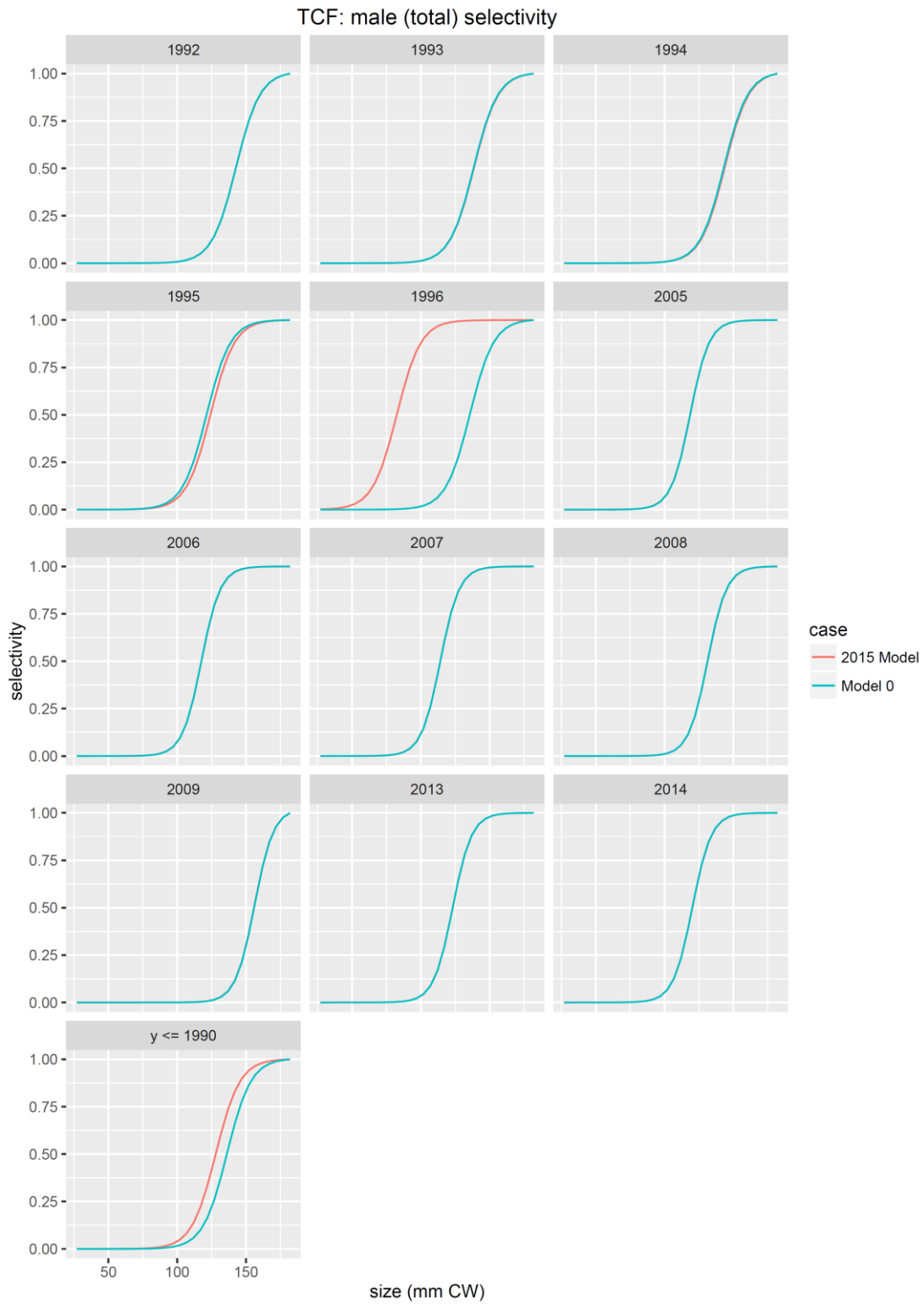


Figure 1. Comparison of estimated male total mortality selectivity curves from the 2015 assessment model and Model 0.

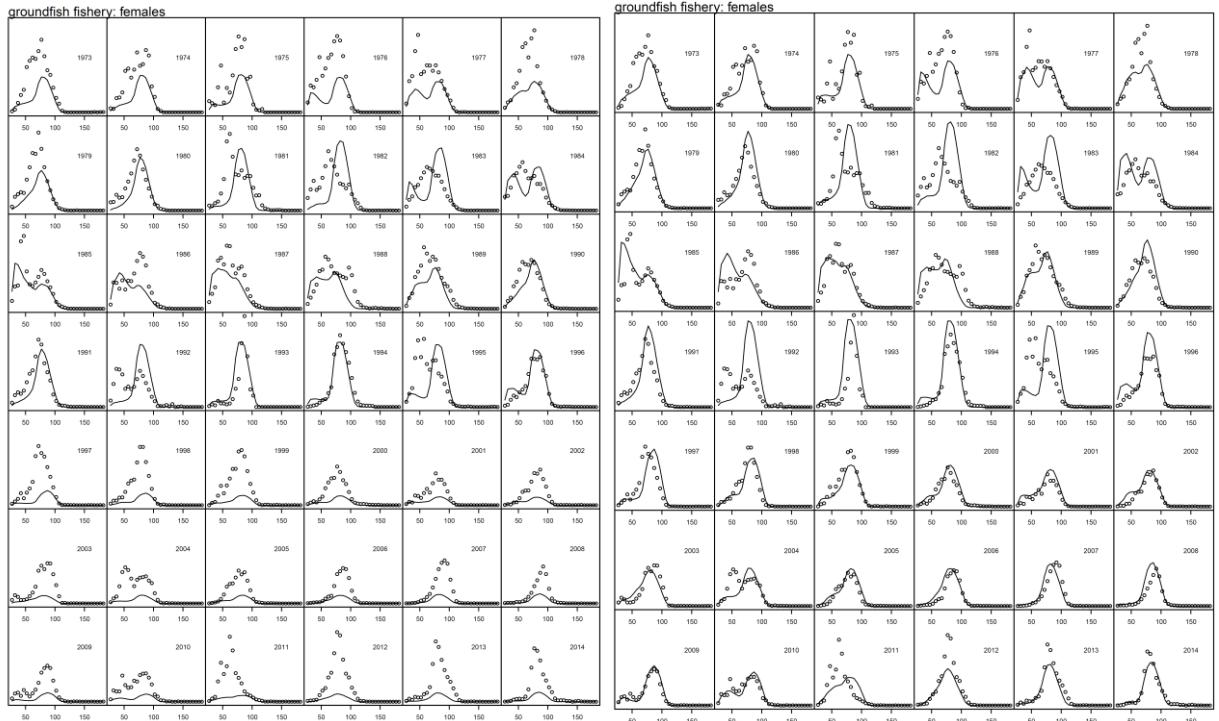


Figure 2. Comparison of model (line) and observed (circles) size compositions for female bycatch in the groundfish fisheries from the 2015 assessment, Model 0 (left) and Model B (right).

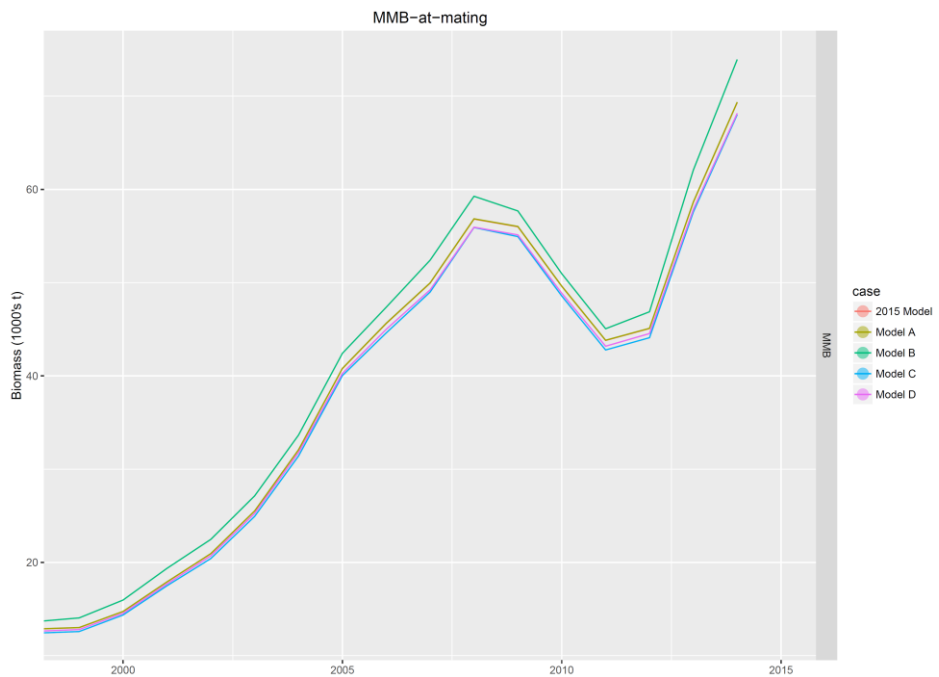


Figure 3. Comparison of estimated recent MMB-at-Mating for Models 0, A, B, C, and D.

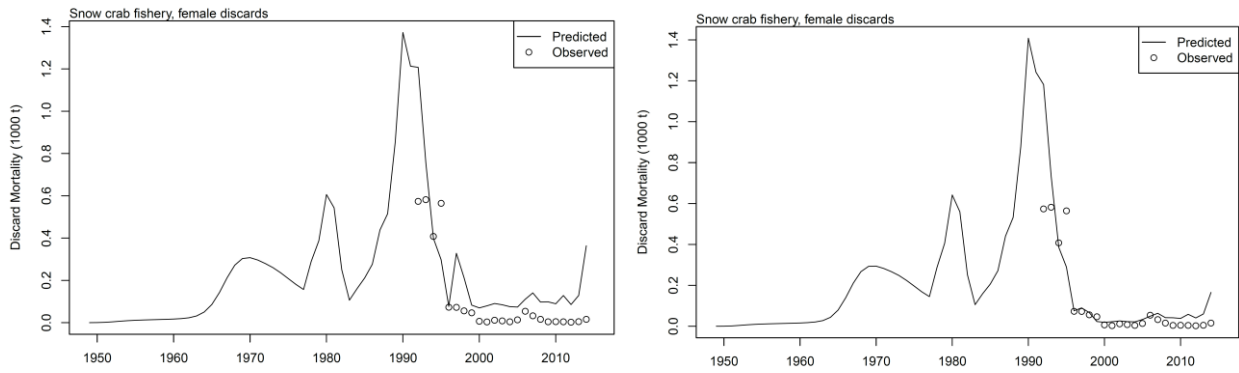


Figure 4. Comparison of model (line) and observed (circles) female bycatch in the snow crab fishery from Model 0 (left) and Model C (right).

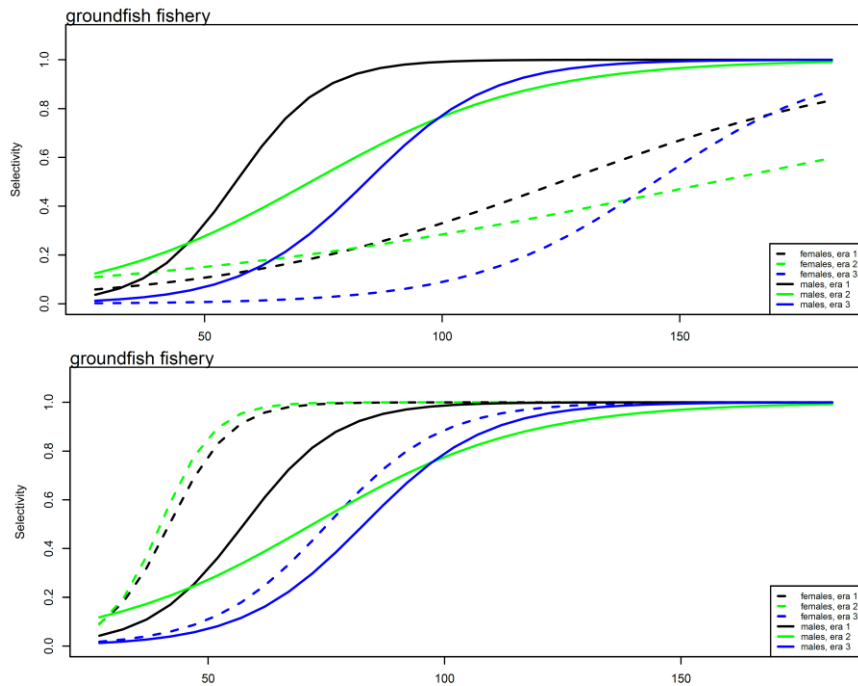


Figure 5. Comparison of bycatch selectivity curves in the groundfish fishery from Model 0 (left) and Model C (right). Curves for females are dashed lines, colors indicate different time periods.

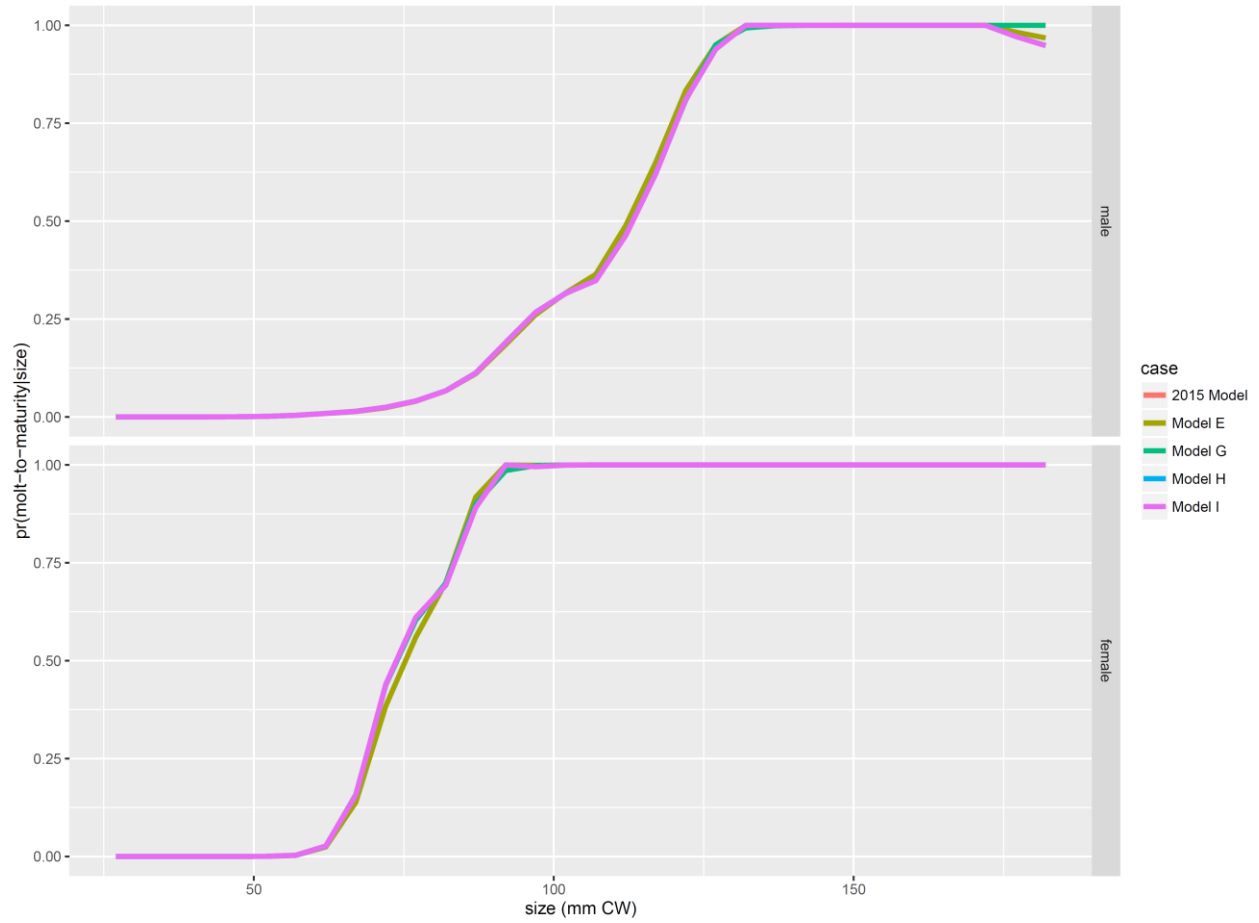


Figure 6. Comparison of the size-specific molt-to-maturity for the models indicated in the legend. Symbols represent data, lines represent model estimates

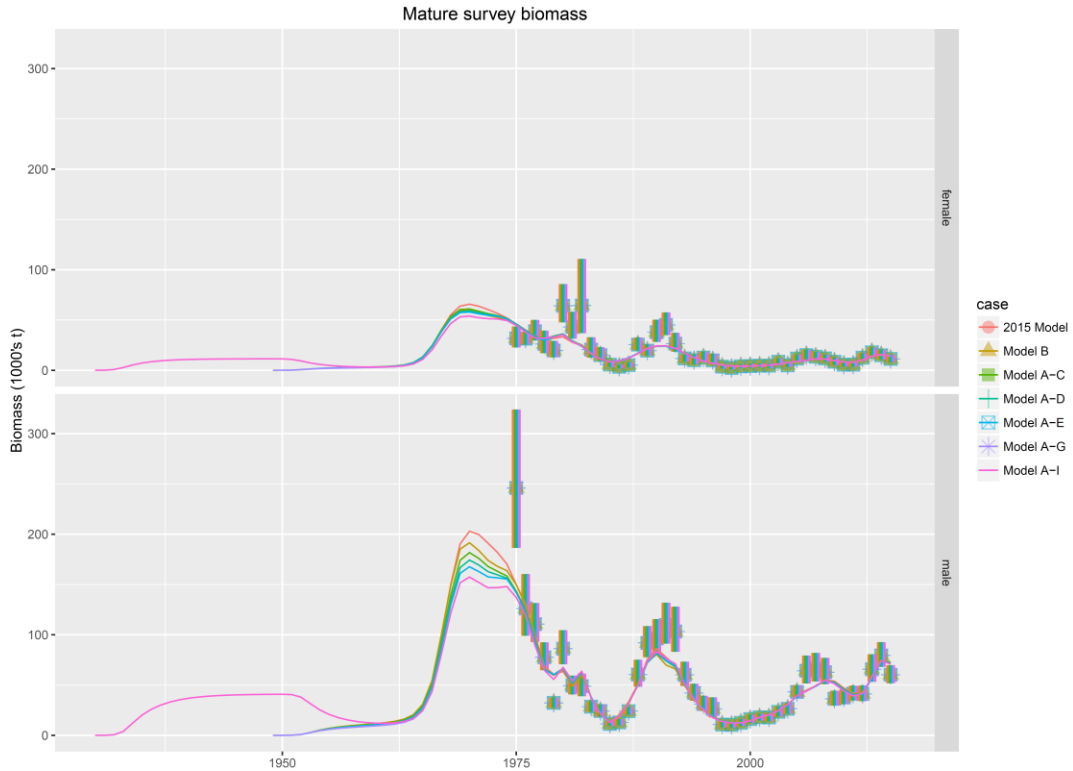


Figure 7. Comparison of fits to mature survey biomass for the models indicated in the legend. Symbols represent data, lines represent model estimates.

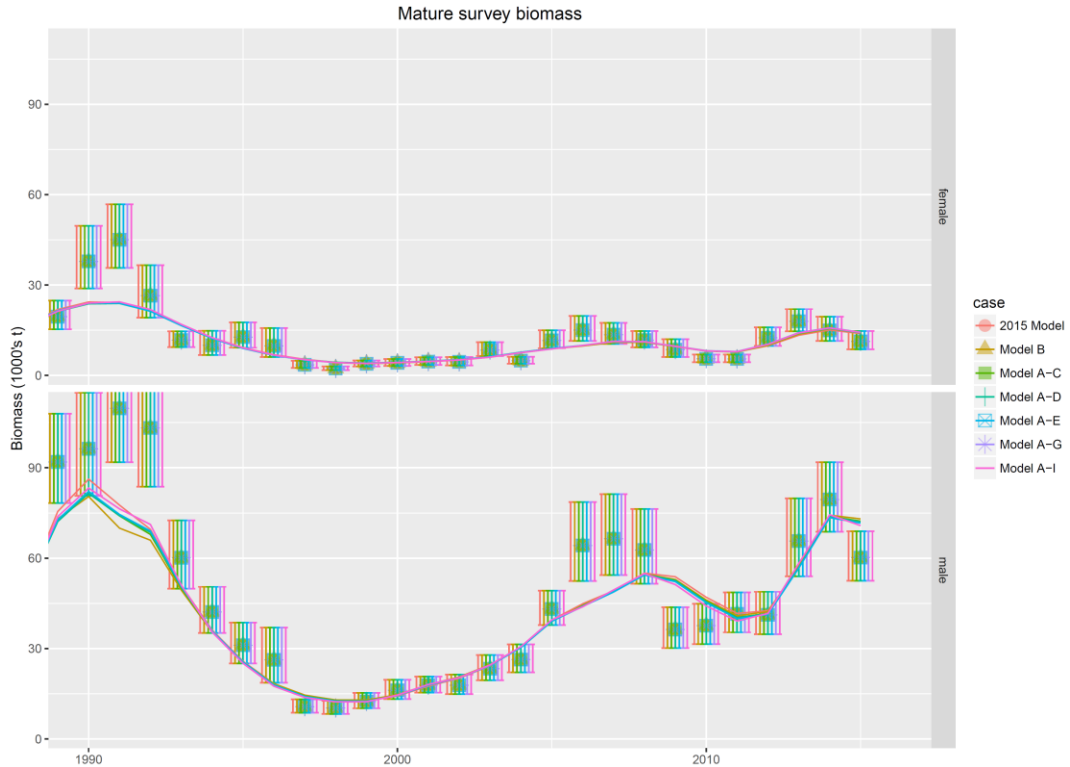


Figure 8. Comparison of fits to mature survey biomass, 1989-2015, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

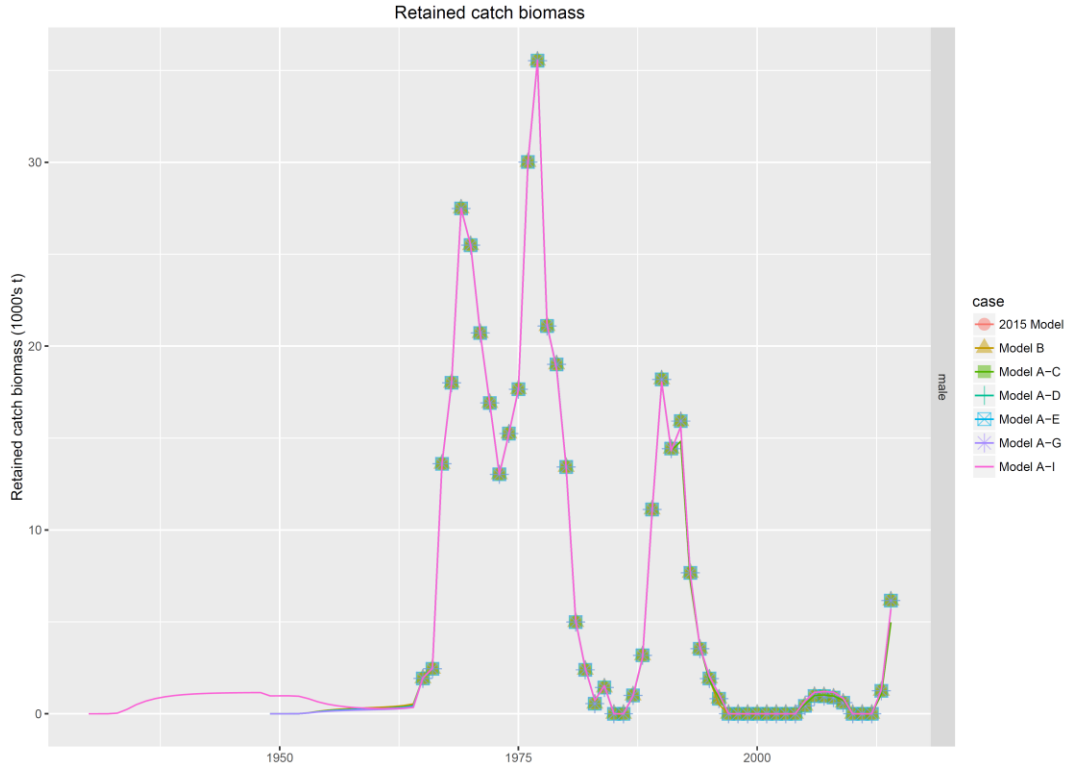


Figure 9. Comparison of fits to retained catch biomass for the models indicated in the legend. Symbols represent data, lines represent model estimates.

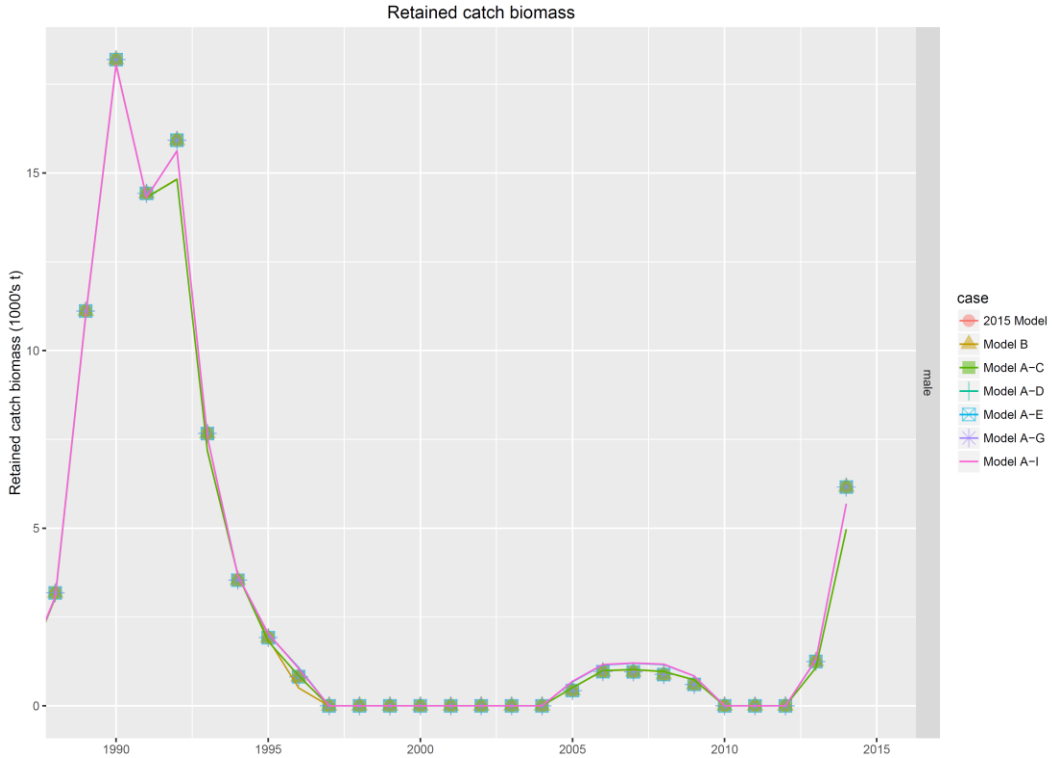


Figure 10. Comparison of fits to retained catch biomass, 1988-2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

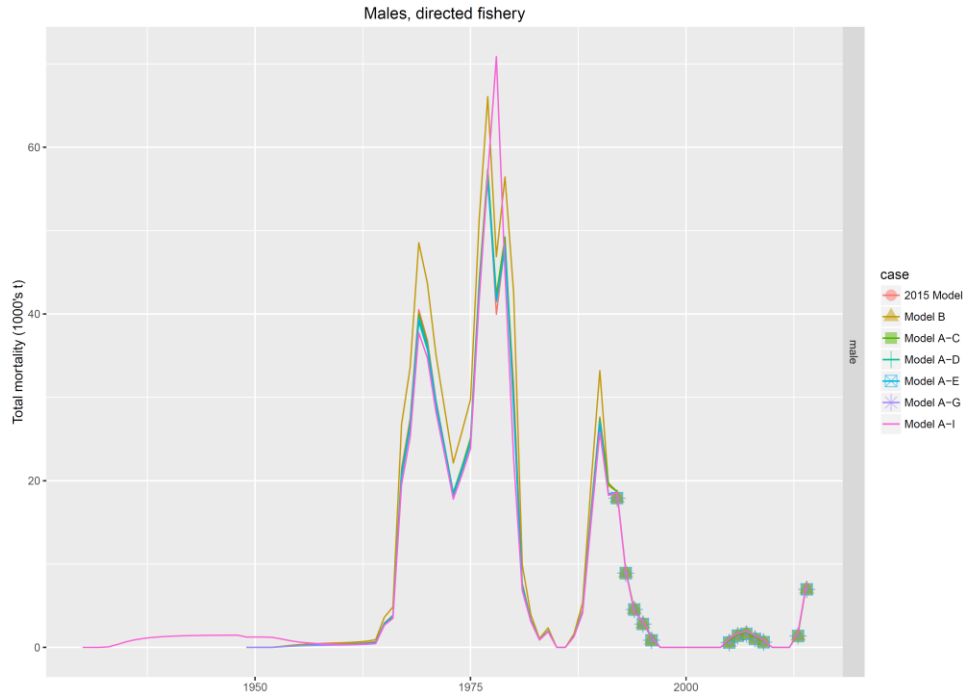


Figure 11. Comparison of fits to total catch biomass for the models indicated in the legend. Models including “D” are fit to discard biomass, but fits to total biomass are shown. Symbols represent data, lines represent model estimates.

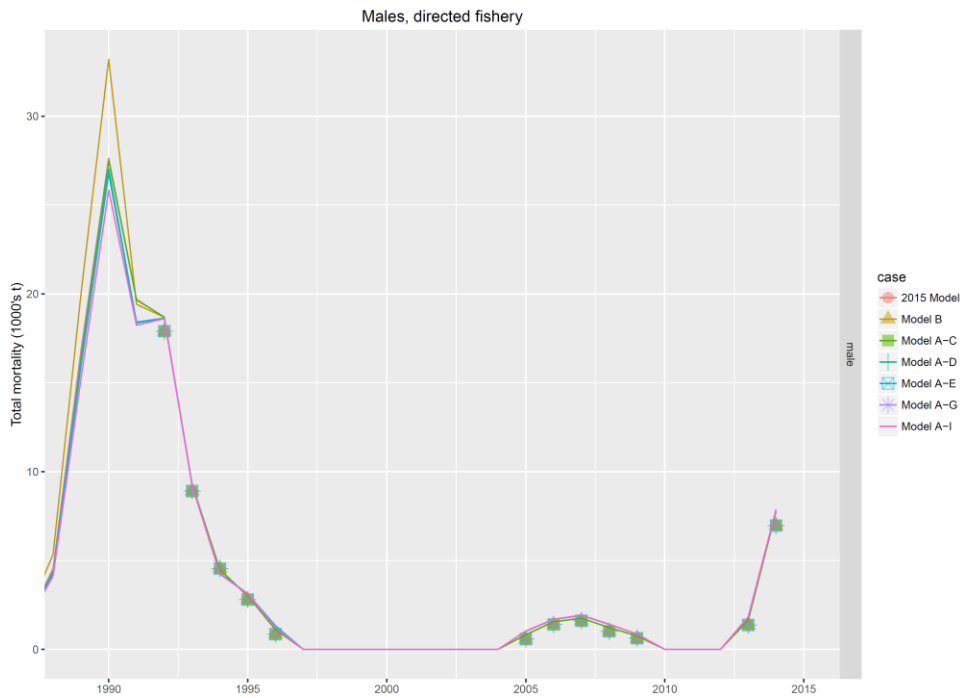


Figure 12. Comparison of fits to total catch biomass, from 1989 to 2014, for the models indicated in the legend. Models including “D” are fit to discard biomass, but fits to total biomass are shown. Symbols represent data, lines represent model estimates.

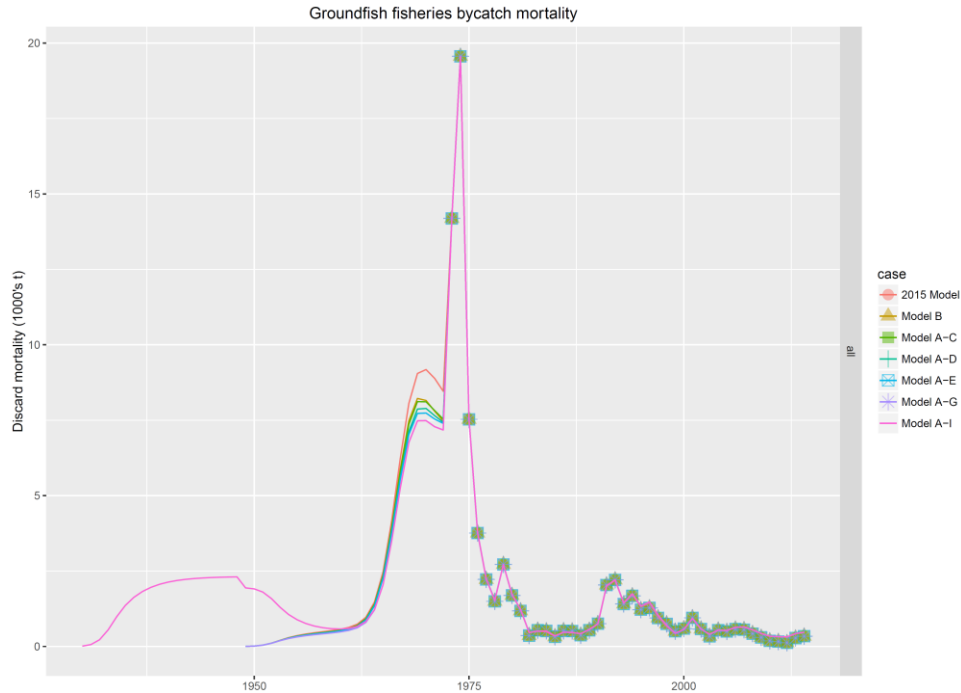


Figure 13. Comparison of fits to bycatch in the groundfish fisheries for the models indicated in the legend. Symbols represent data, lines represent model estimates.

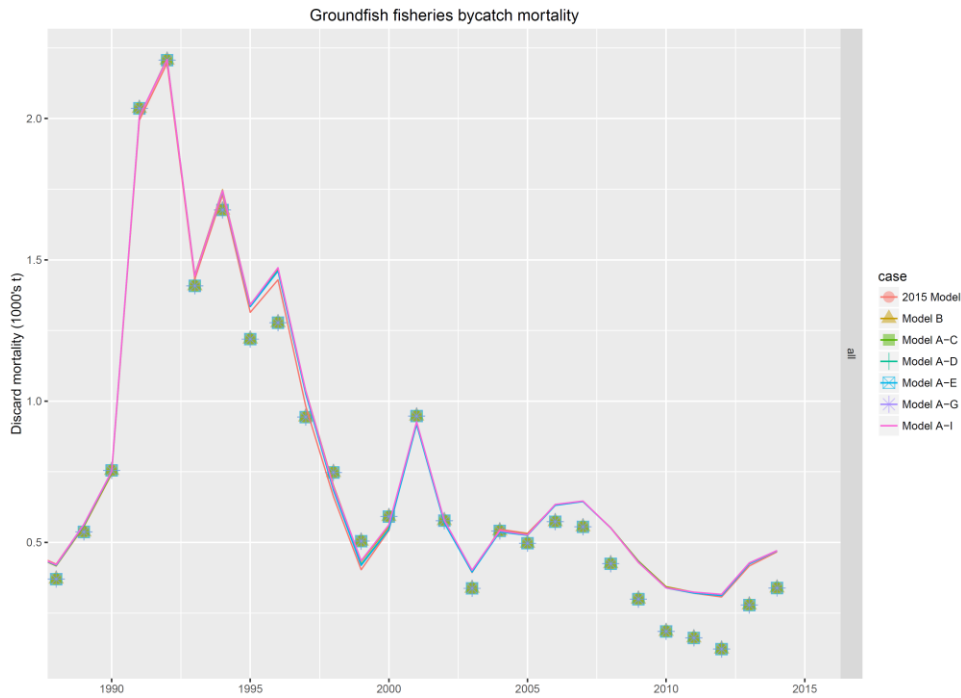


Figure 14. Comparison of fits to bycatch in the groundfish fisheries, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

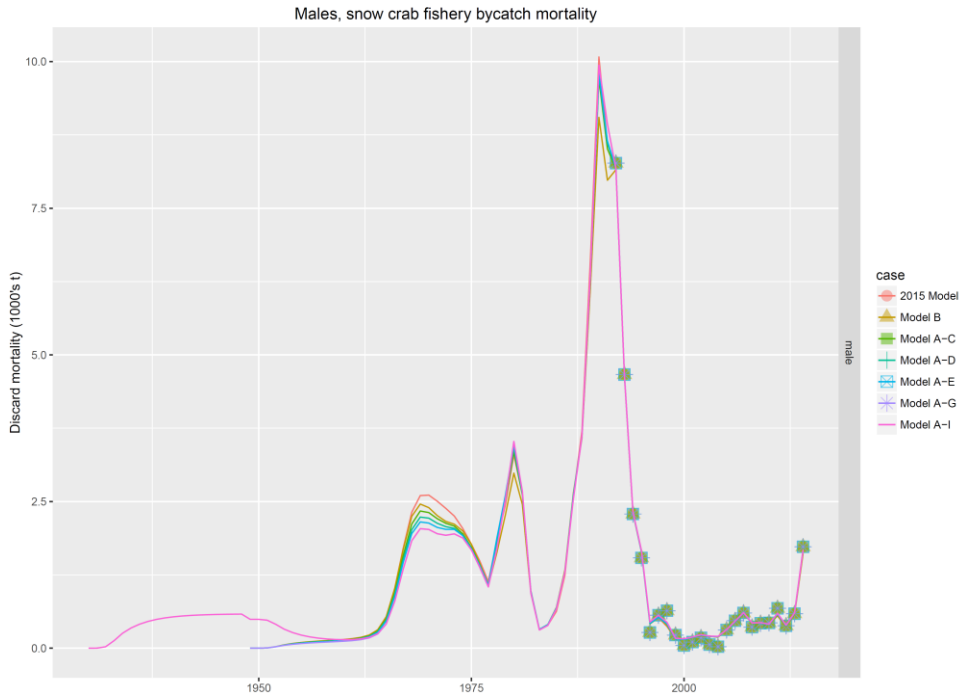


Figure 15. Comparison of fits to male bycatch in the snow crab fishery for the models indicated in the legend. Symbols represent data, lines represent model estimates.

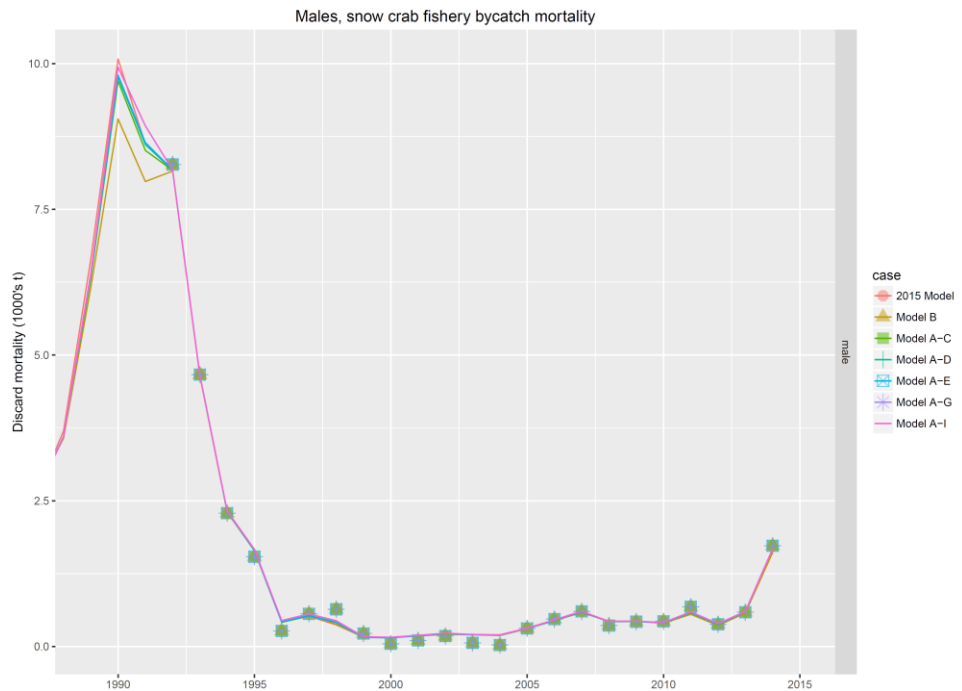


Figure 16. Comparison of fits to male bycatch in the snow crab fishery, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

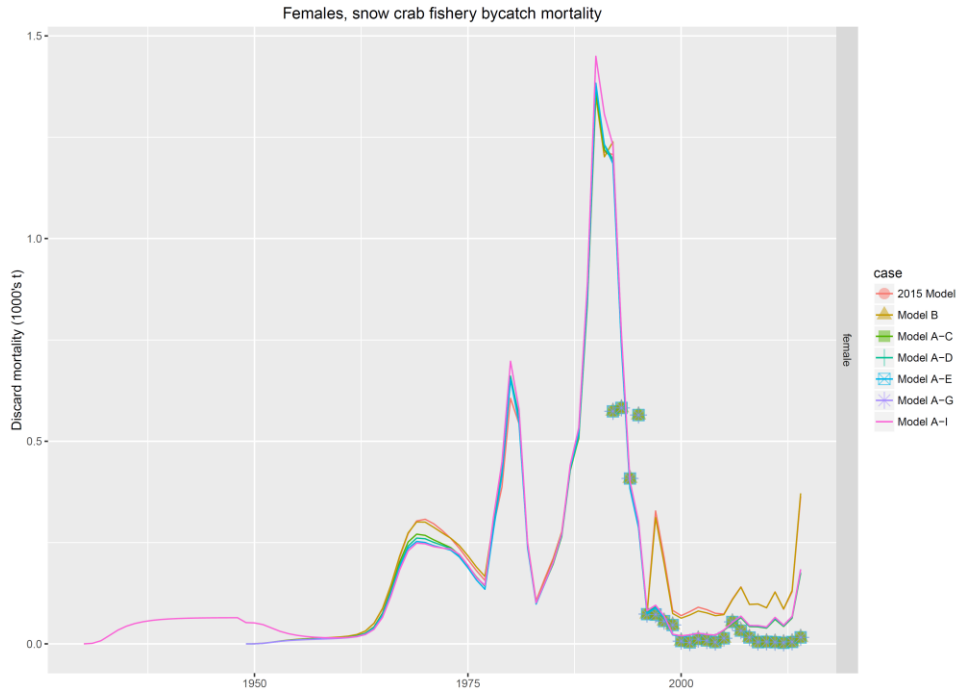


Figure 17. Comparison of fits to female bycatch in the snow crab fishery for the models indicated in the legend. Symbols represent data, lines represent model estimates.

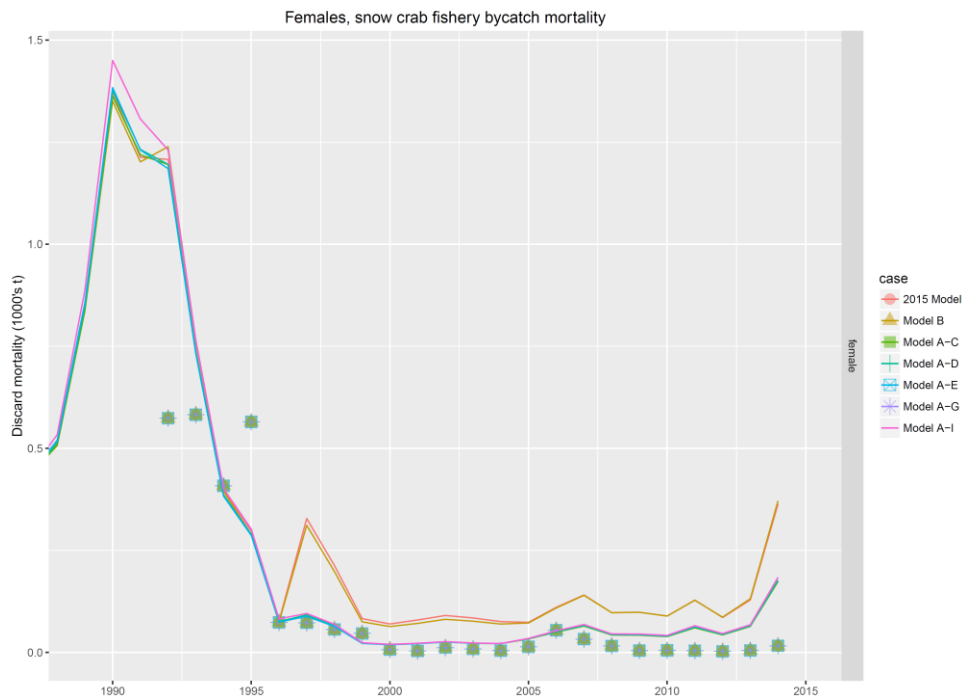


Figure 18. Comparison of fits to female bycatch in the snow crab fishery, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

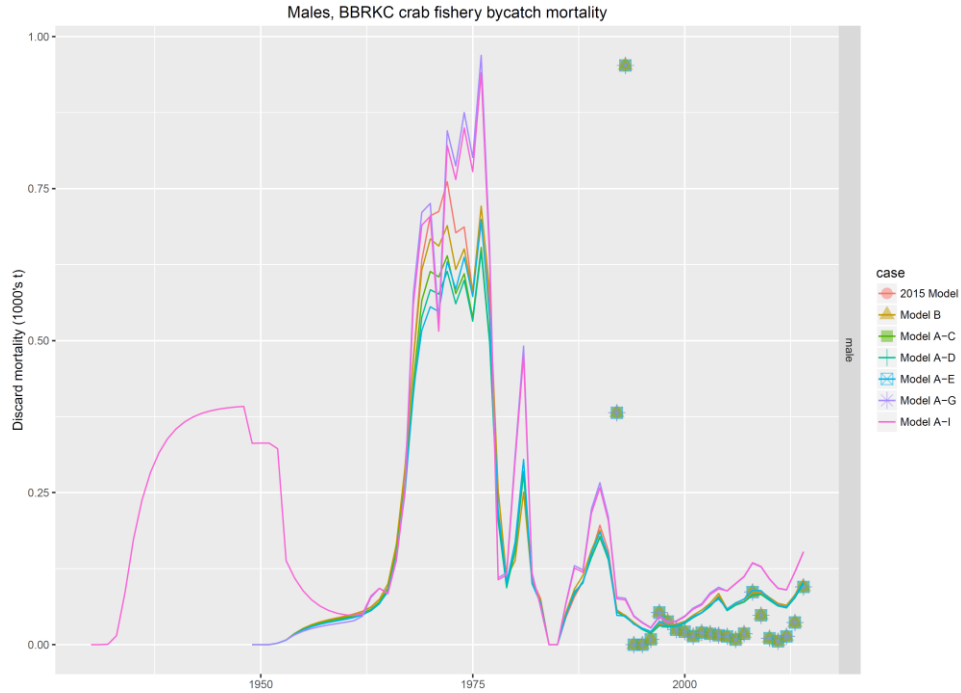


Figure 19. Comparison of fits to male bycatch in the BBRKC fishery for the models indicated in the legend. Symbols represent data, lines represent model estimates.

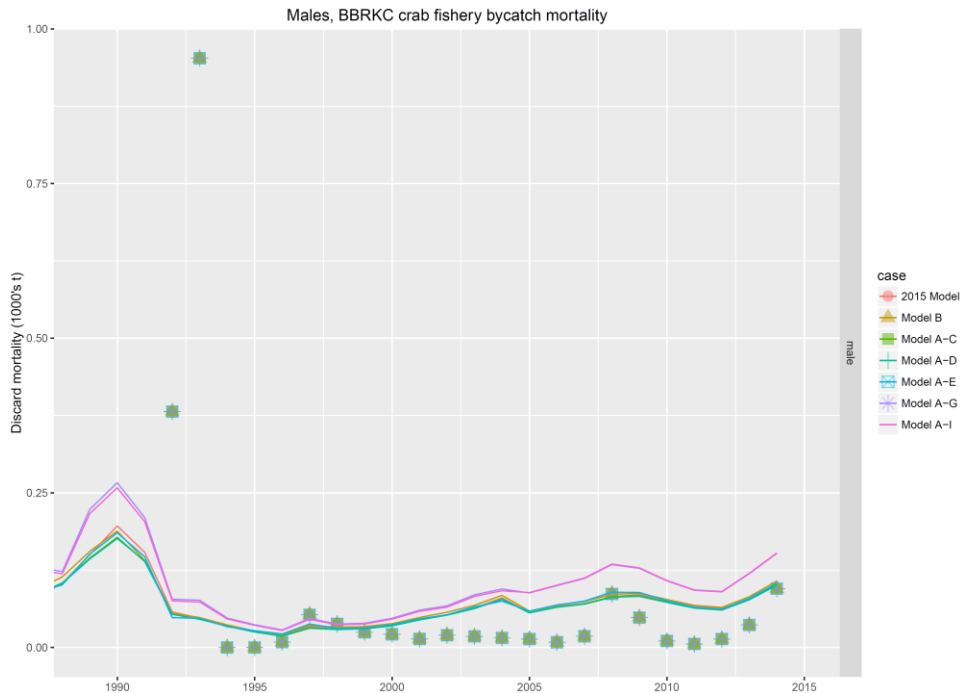


Figure 20. Comparison of fits to male bycatch in the BBRKC fishery, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

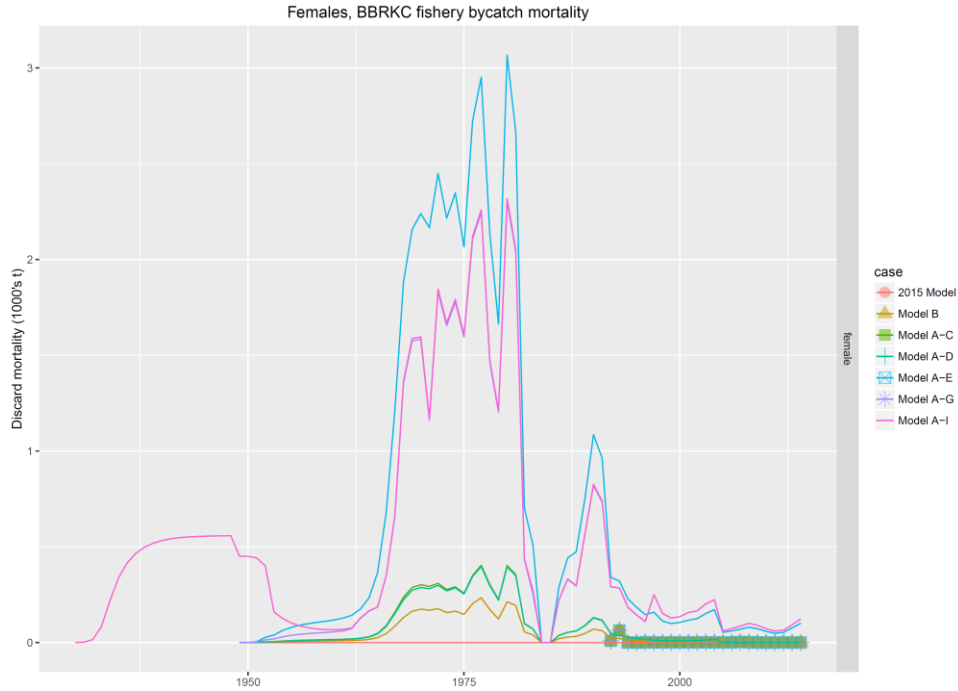


Figure 21. Comparison of fits to female bycatch in the BBRKC fishery for the models indicated in the legend. Symbols represent data, lines represent model estimates.

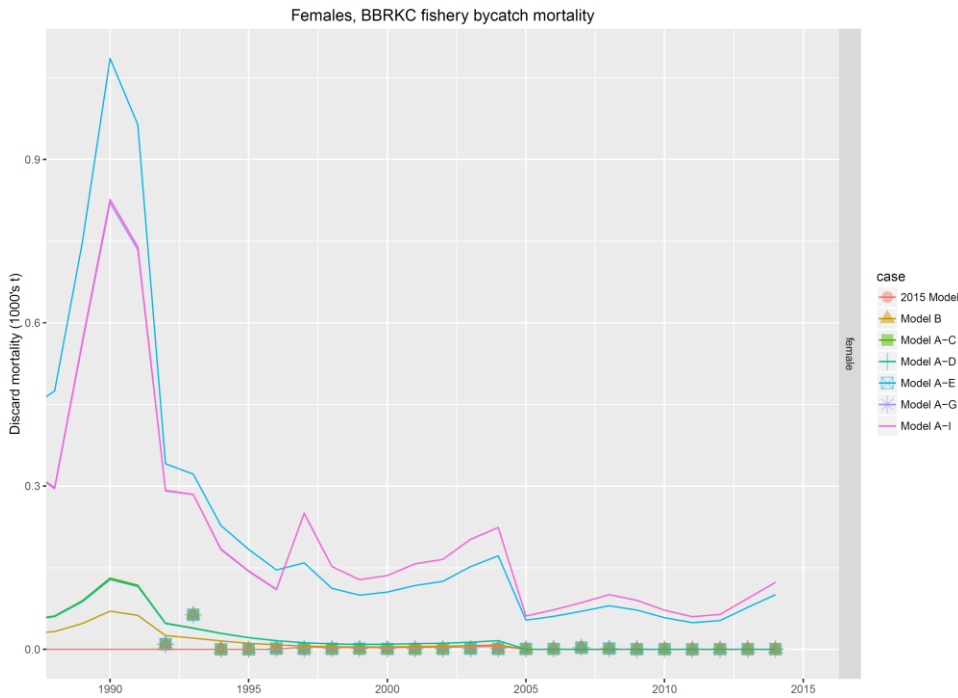


Figure 22. Comparison of fits to female bycatch in the BBRKC fishery, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

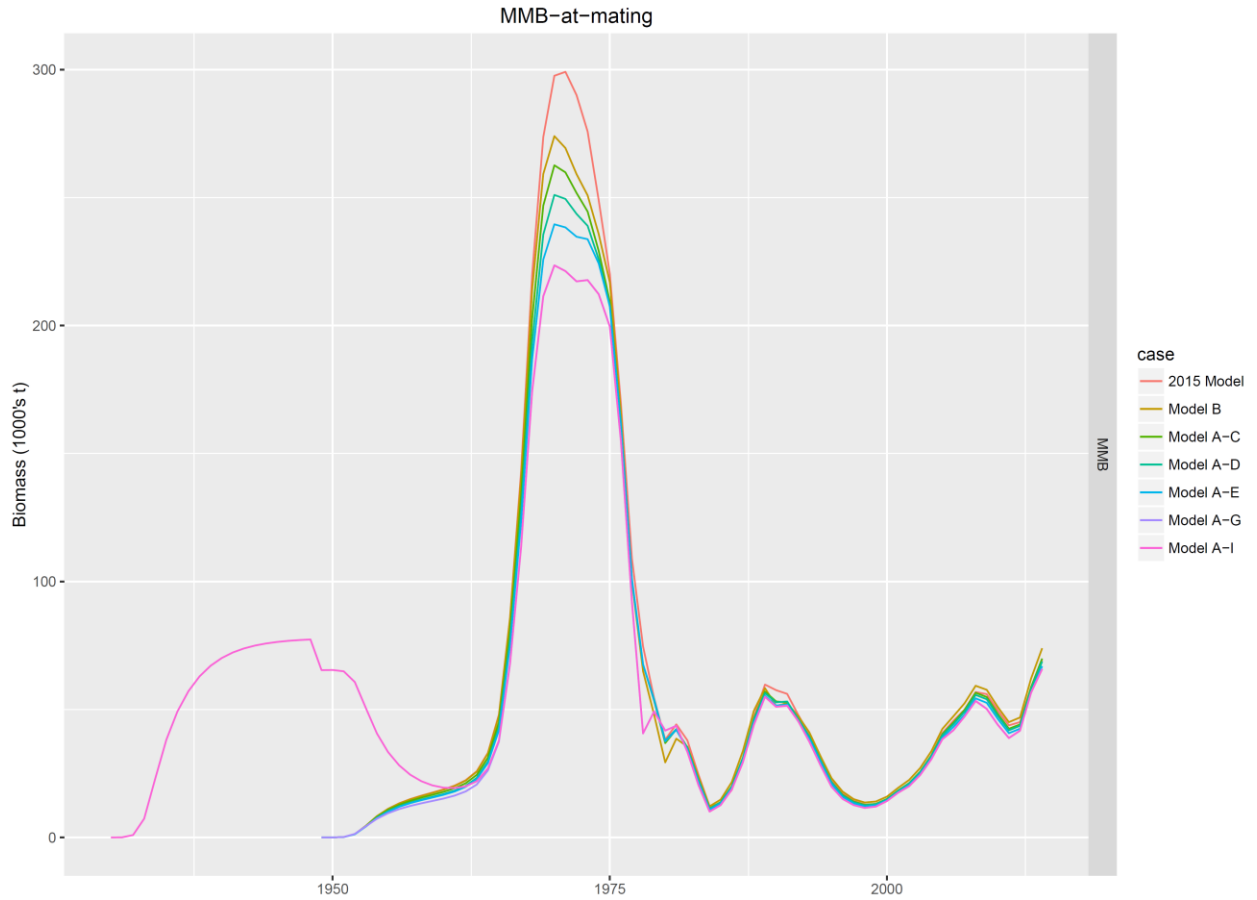


Figure 23. Comparison of model estimates for mature male biomass for the models indicated in the legend.

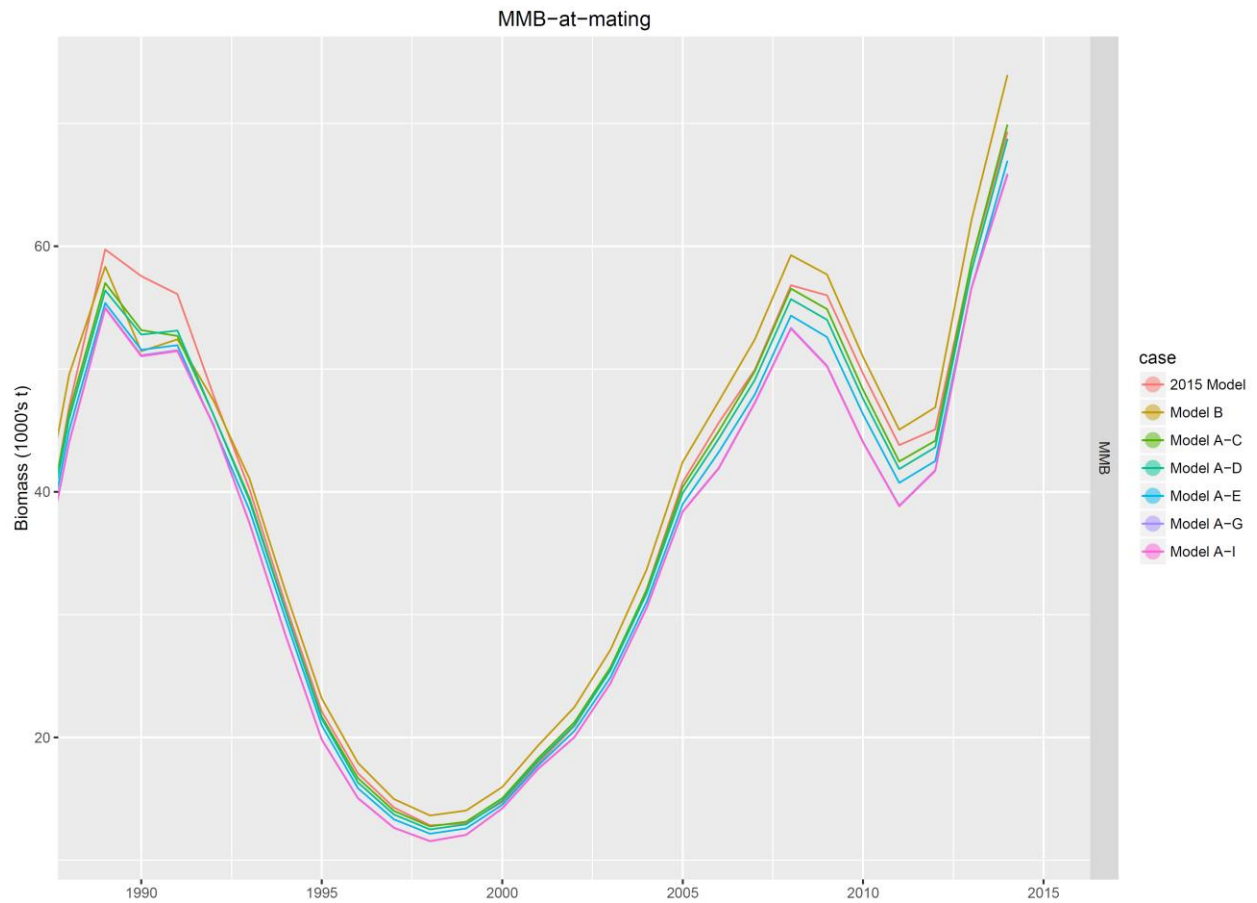


Figure 24. Comparison of model estimates of mature survey biomass, 1989-2015, for the models indicated in the legend.

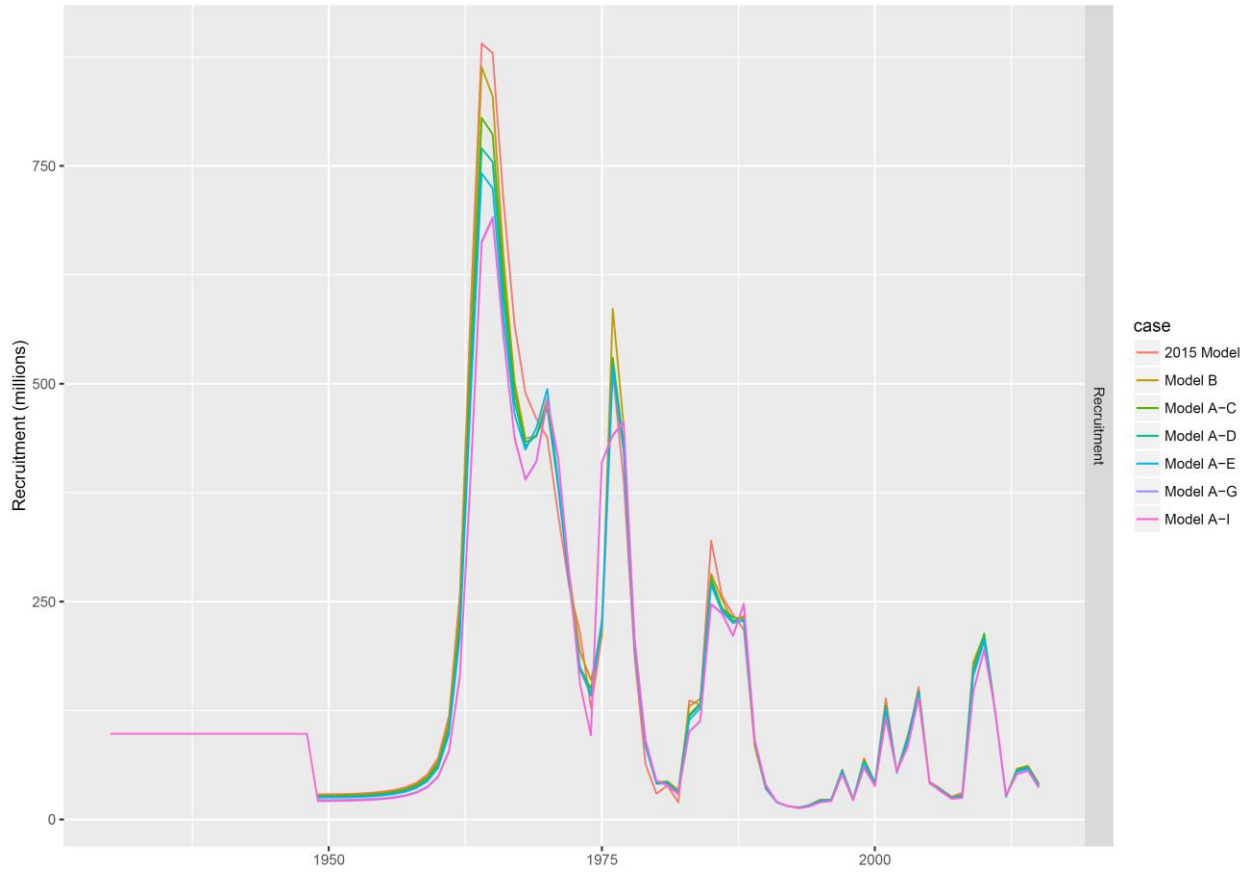


Figure 25. Comparison of model estimates for (male) recruitment for the models indicated in the legend.

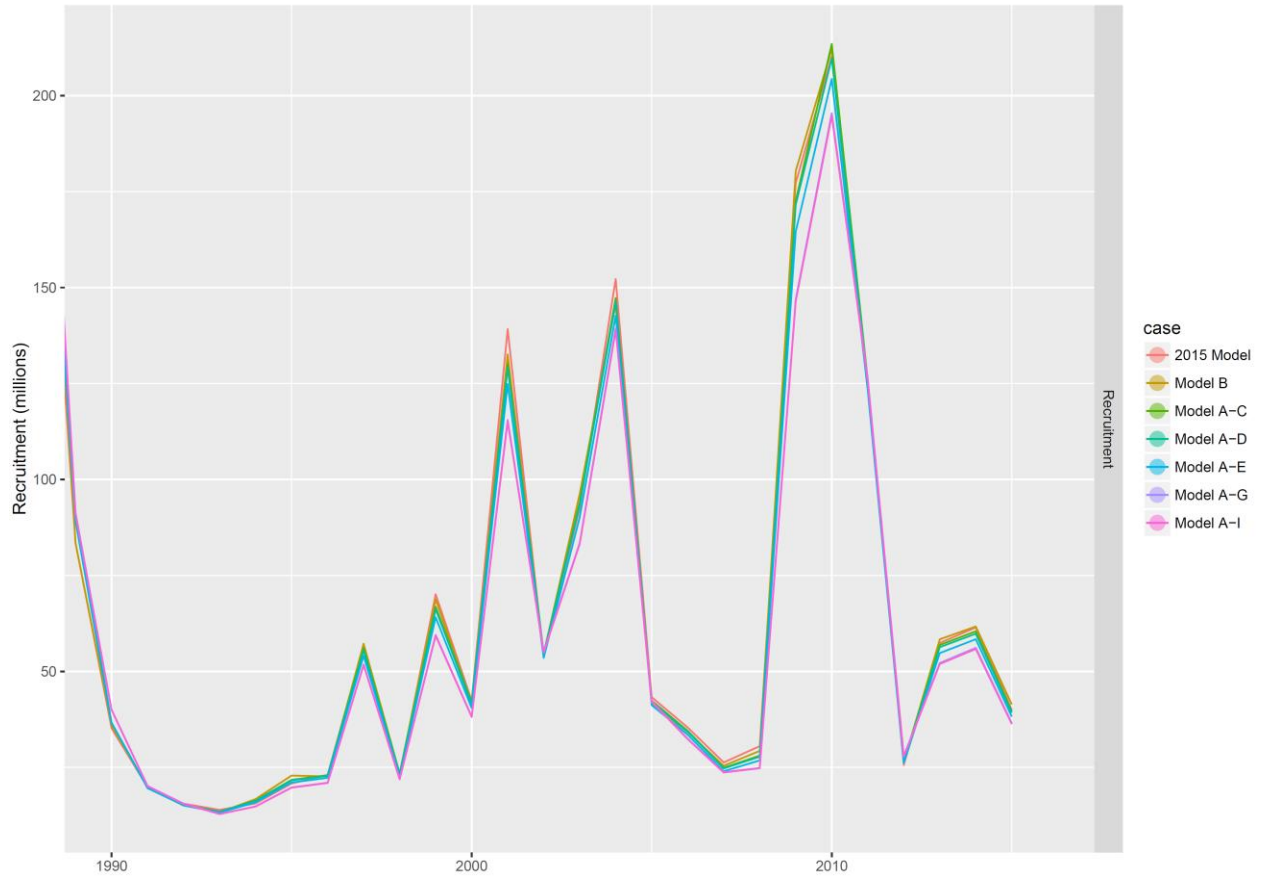


Figure 26. Comparison of model estimates of (male) recruitment, 1989-2015, for the models indicated in the legend.

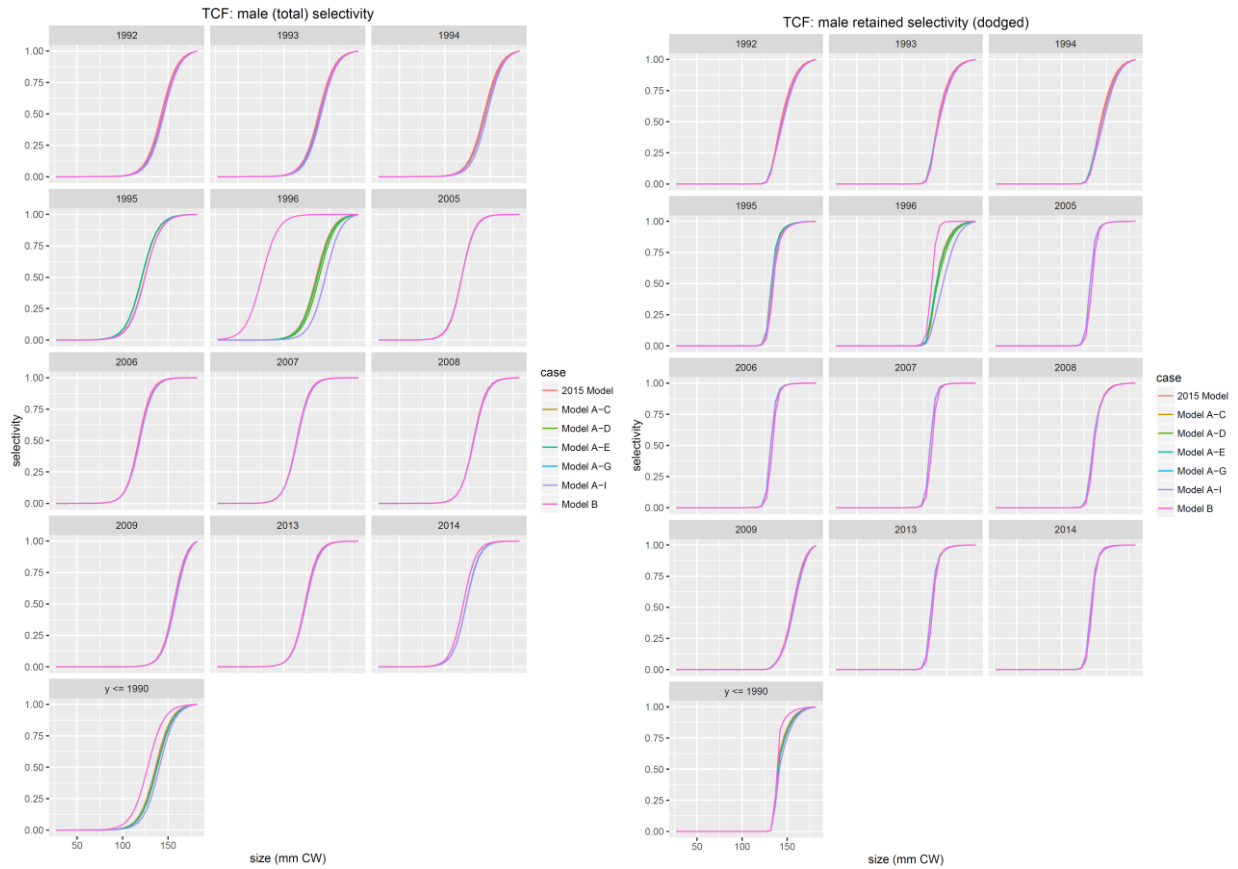


Figure 27. Comparison of model estimates for total (left) and retained (right) selectivity for males in the directed fishery during the time periods indicated.

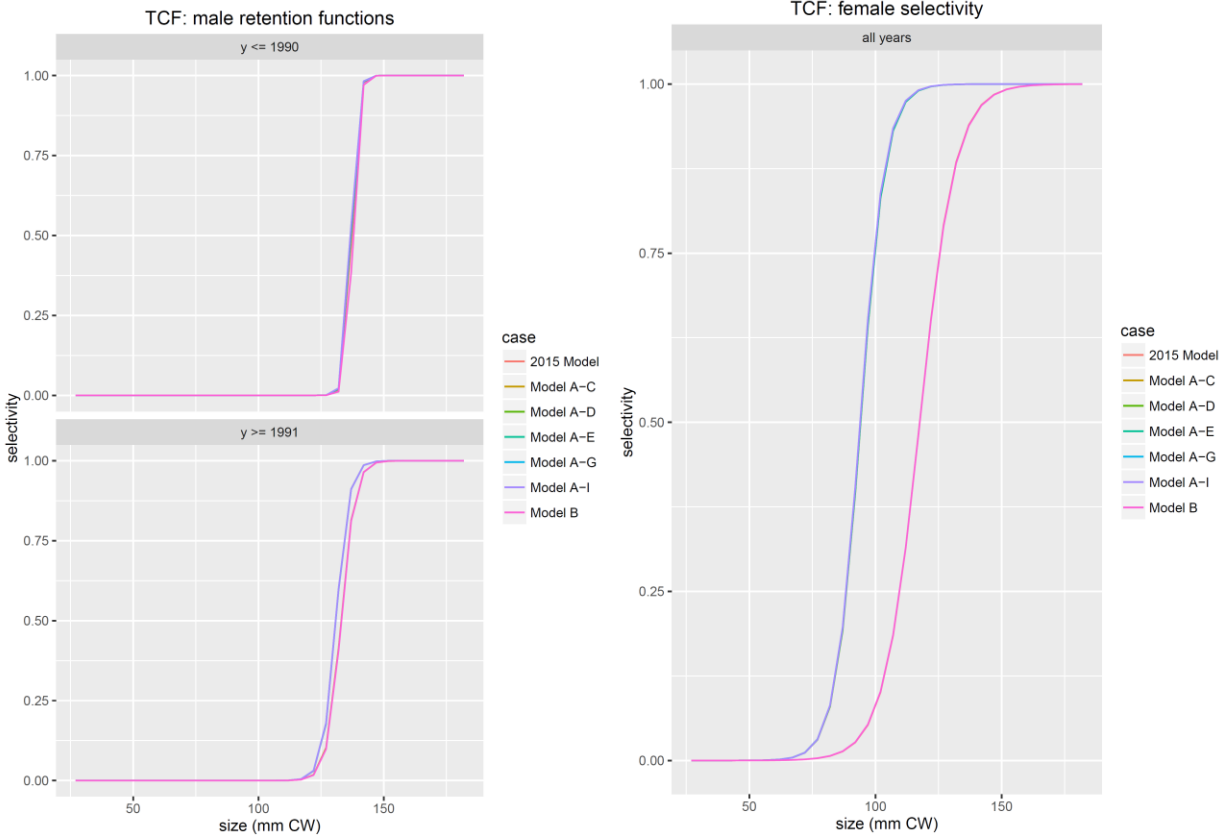


Figure 28. Comparison of model estimates of the retention function (left) and female selectivity (right) in the directed fishery during the time periods indicated.

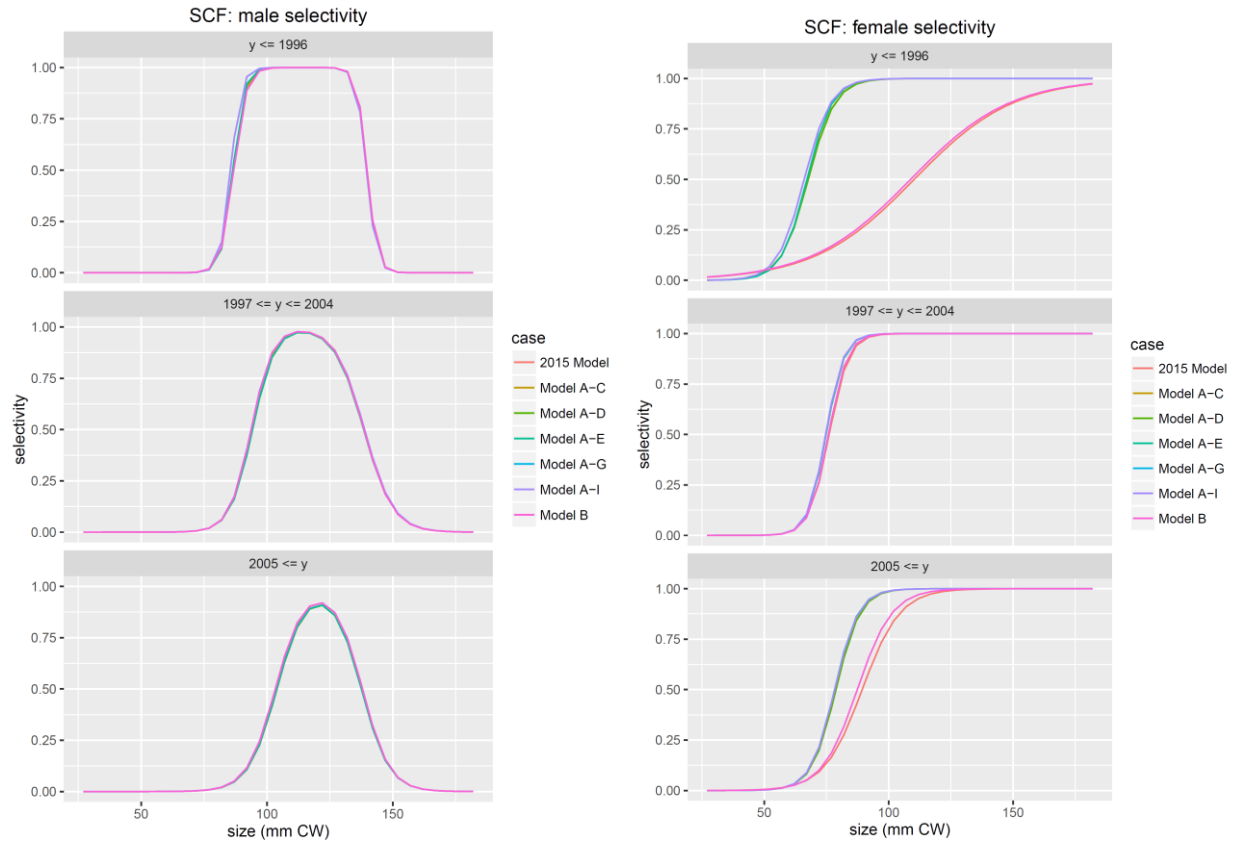


Figure 29. Comparison of model estimates for male (left) and female (right) bycatch selectivity in the snow crab fishery during the time periods indicated.

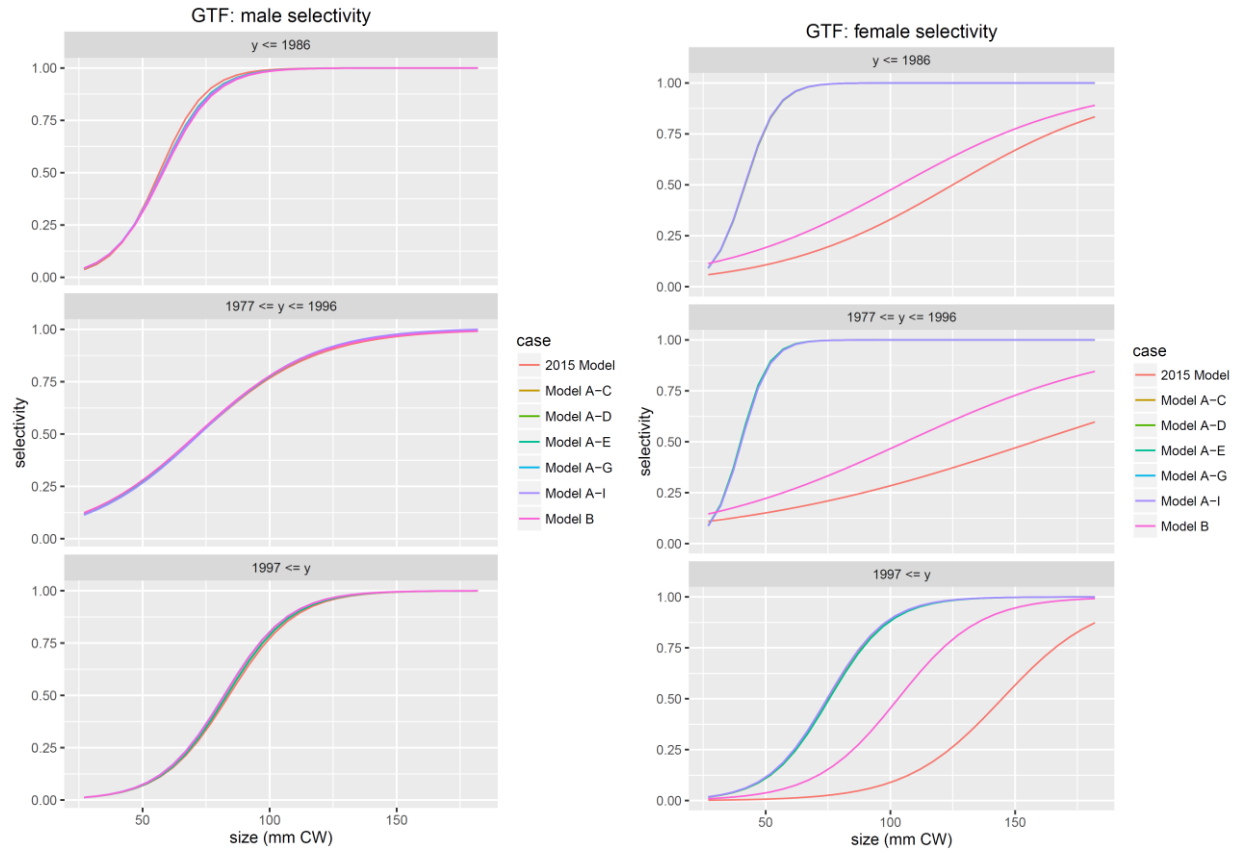


Figure 30. Comparison of model estimates for male (left) and female (right) bycatch selectivity in the groundfish fisheries during the time periods indicated.

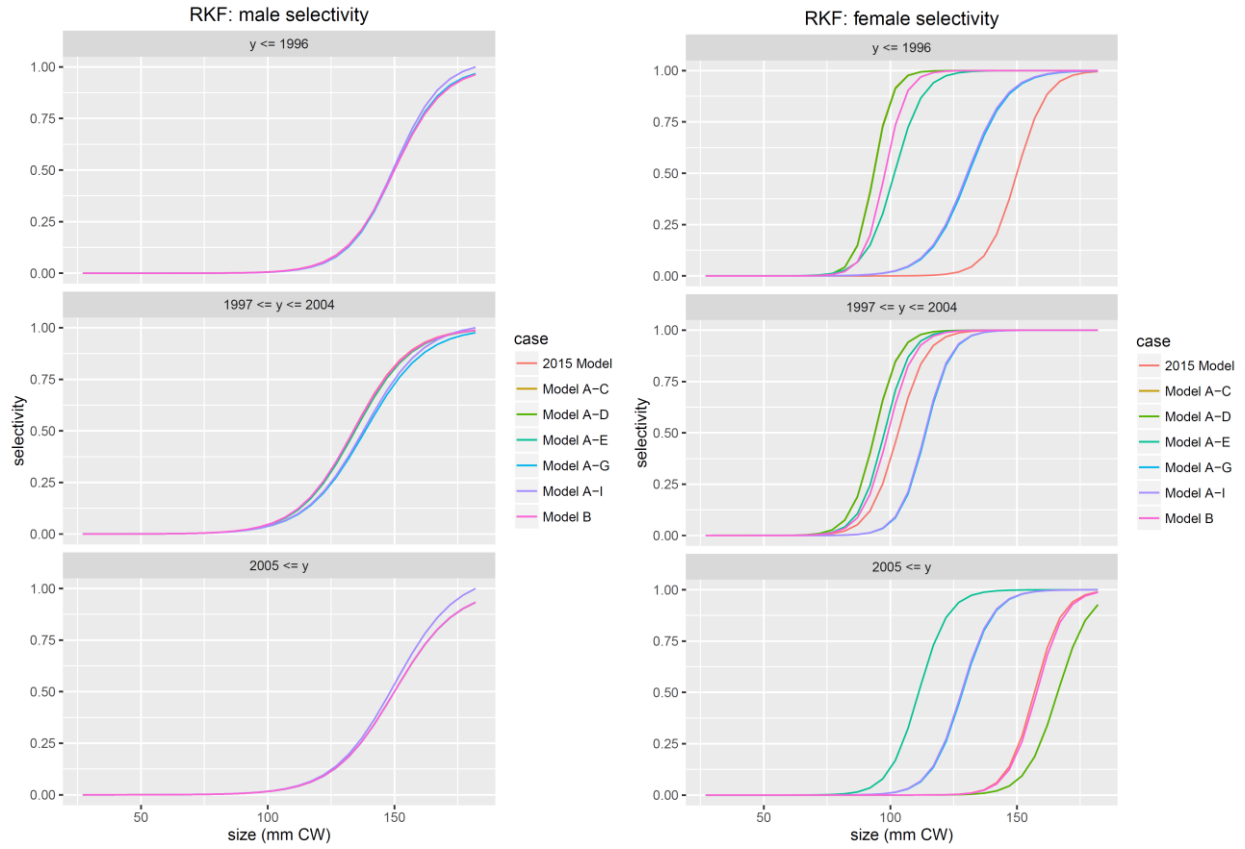


Figure 31. Comparison of model estimates for male (left) and female (right) bycatch selectivity in the BBRKC fishery during the time periods indicated.

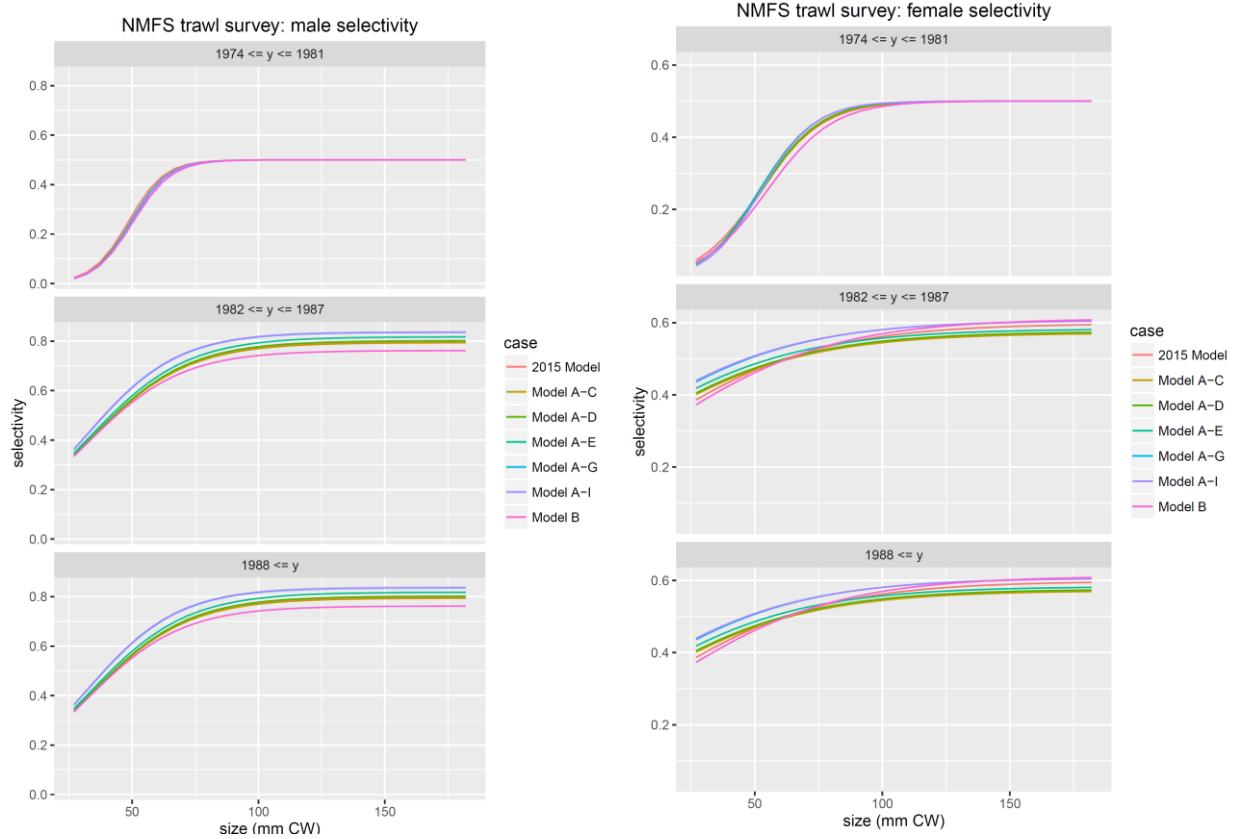


Figure 32. Comparison of model estimates for male (left) and female (right) selectivity in the NMFS bottom trawl survey during the time periods indicated.

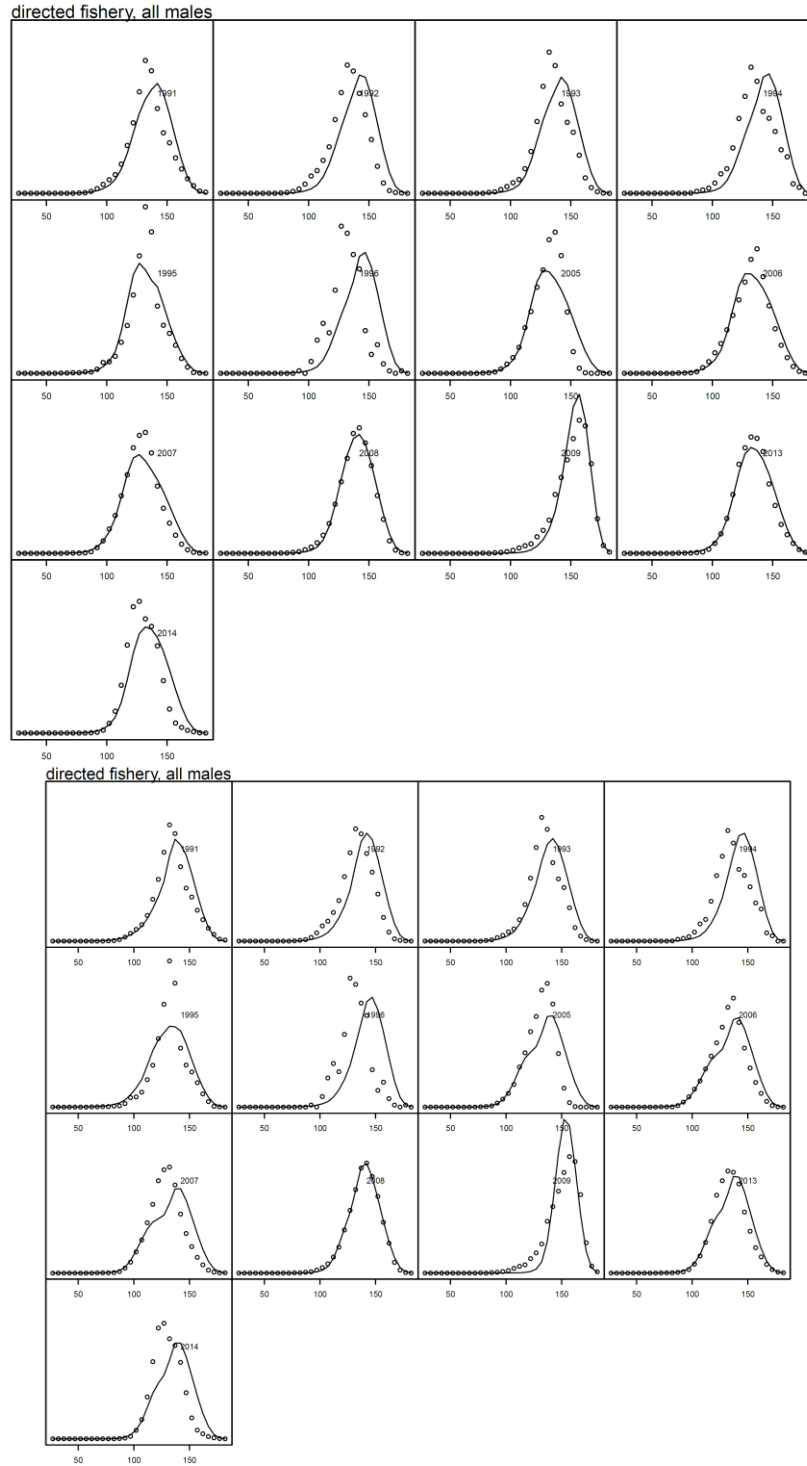


Figure 33. Comparison of model estimates and data for total catch size comps for males in the directed fishery for: Model A-I (upper panel), Model A-J (lower panel).

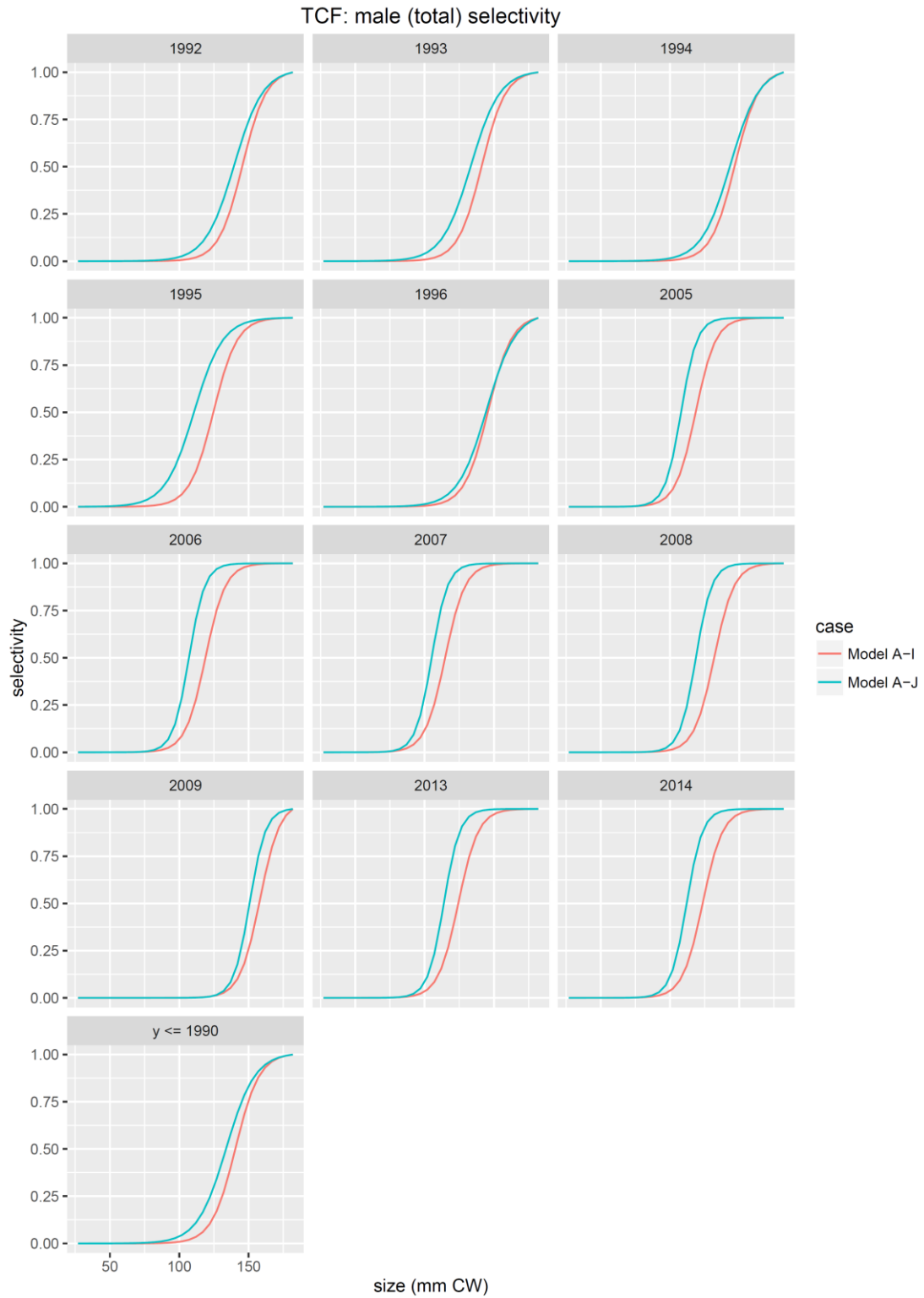


Figure 34. Comparison of estimated total mortality selectivity (Model A-I) and capture selectivity (Model A-J) for males in the directed fishery.

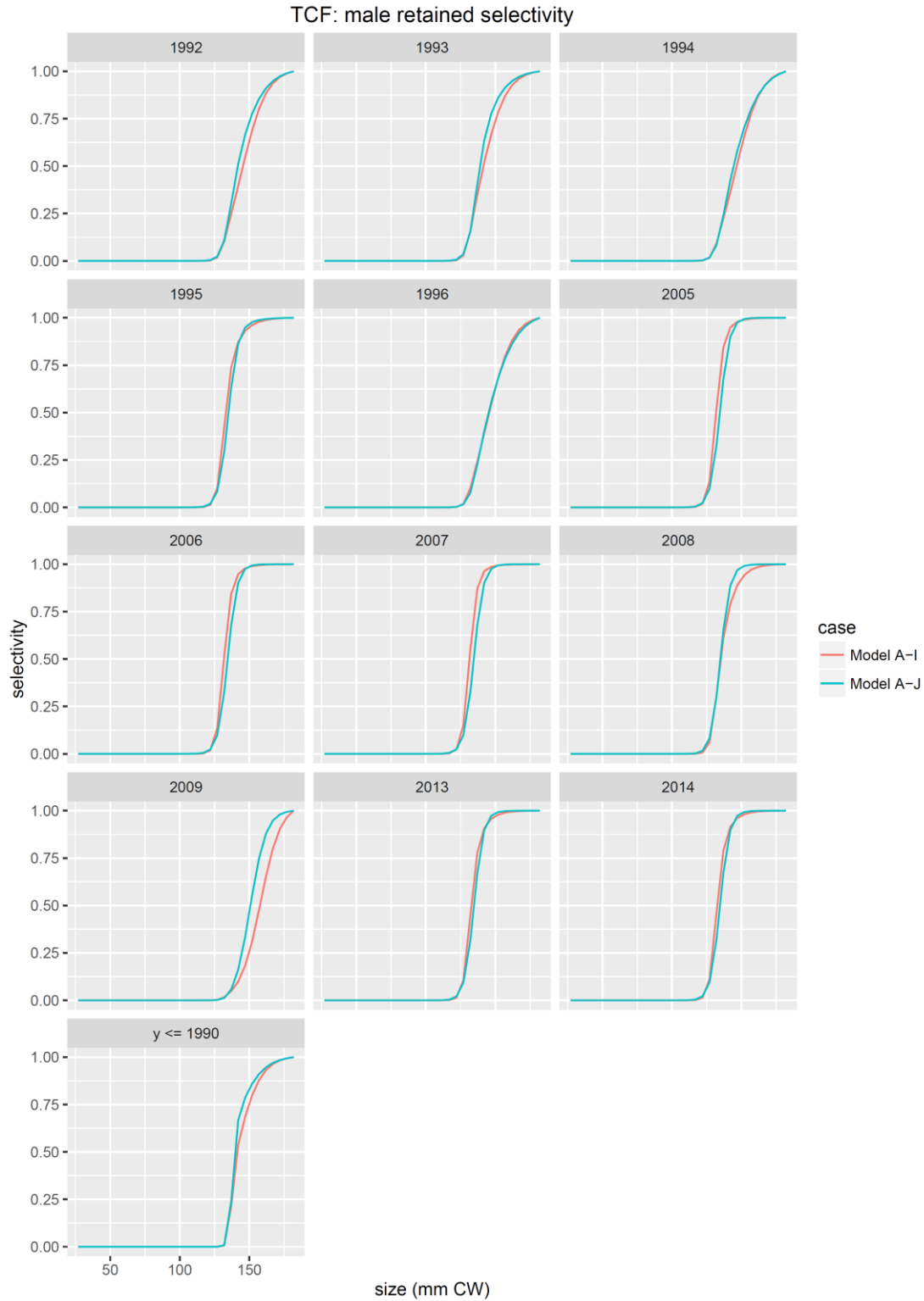


Figure 35. Comparison of retained selectivity for model A-I and the retention ogive for A-J in the directed fishery.

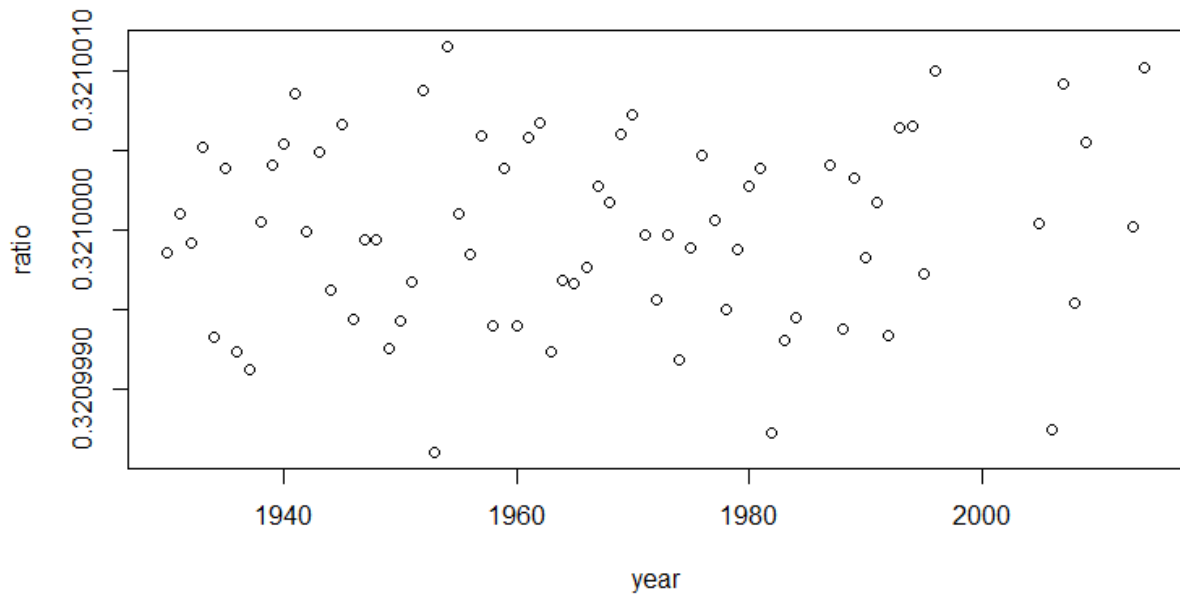


Figure 36. Ratio of estimated male discard mortality (biomass; integrated over size bins) to estimated total male discards (biomass; integrated over size bins) in the directed fishery. This is a test of the GMACS fishing mortality model. The ratio should be 0.321 (handling mortality in the pot fisheries), which it is (within numerical limits).

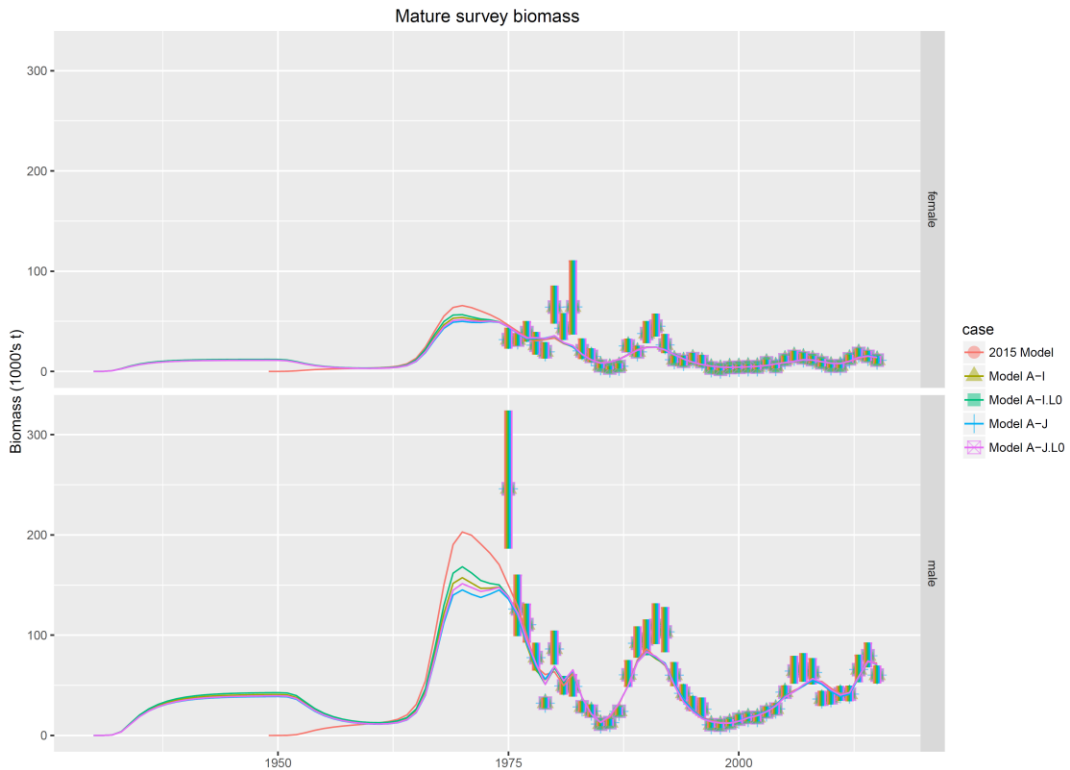


Figure 37. Comparison of fits to mature survey biomass for the models indicated in the legend. Symbols represent data, lines represent model estimates.

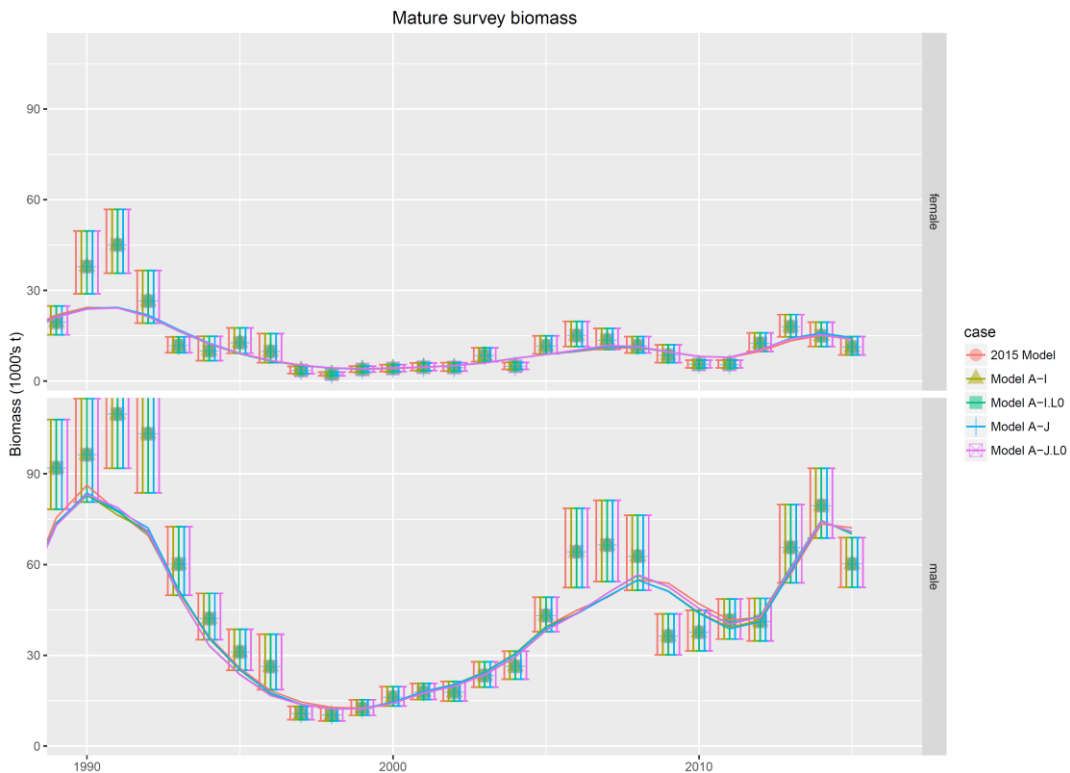


Figure 38. Comparison of fits to mature survey biomass, 1989-2015, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

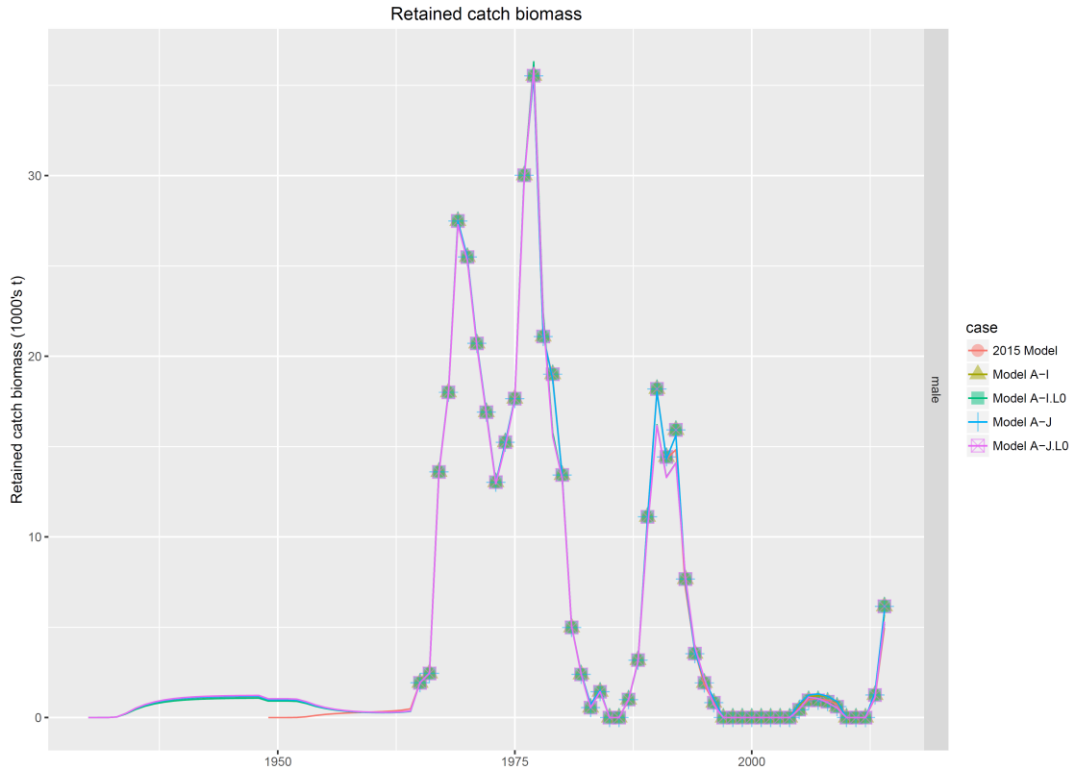


Figure 39. Comparison of fits to retained catch biomass for the models indicated in the legend. Symbols represent data, lines represent model estimates.

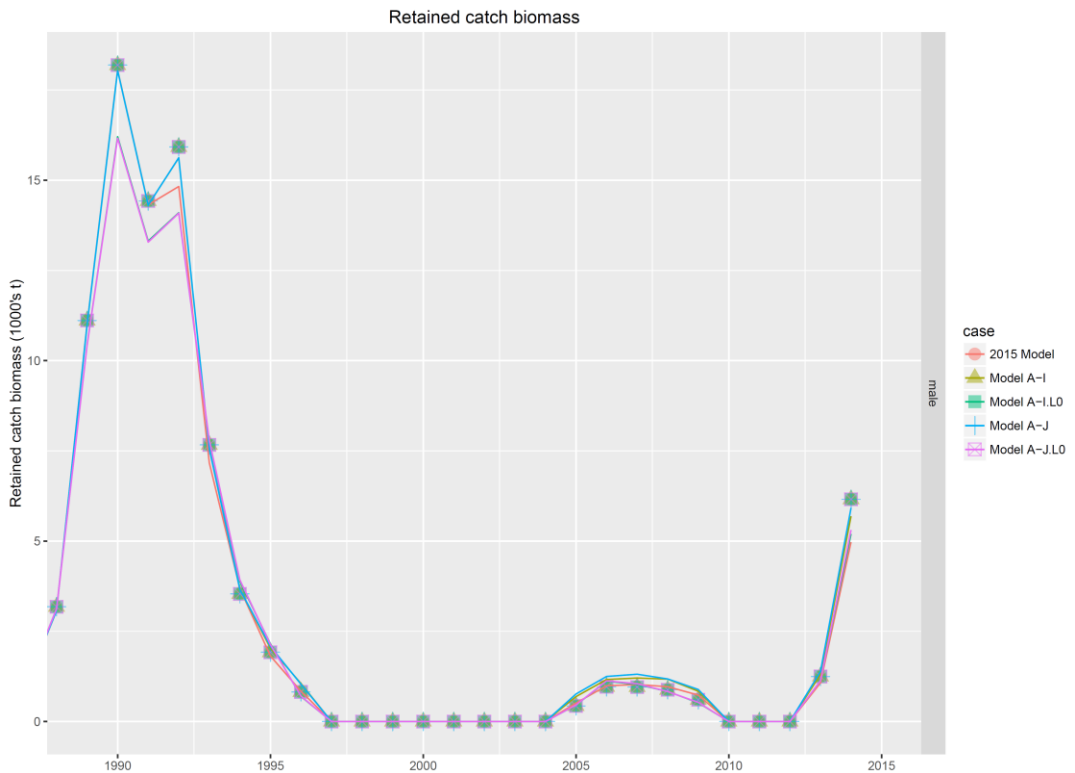


Figure 40. Comparison of fits to retained catch biomass, 1988-2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

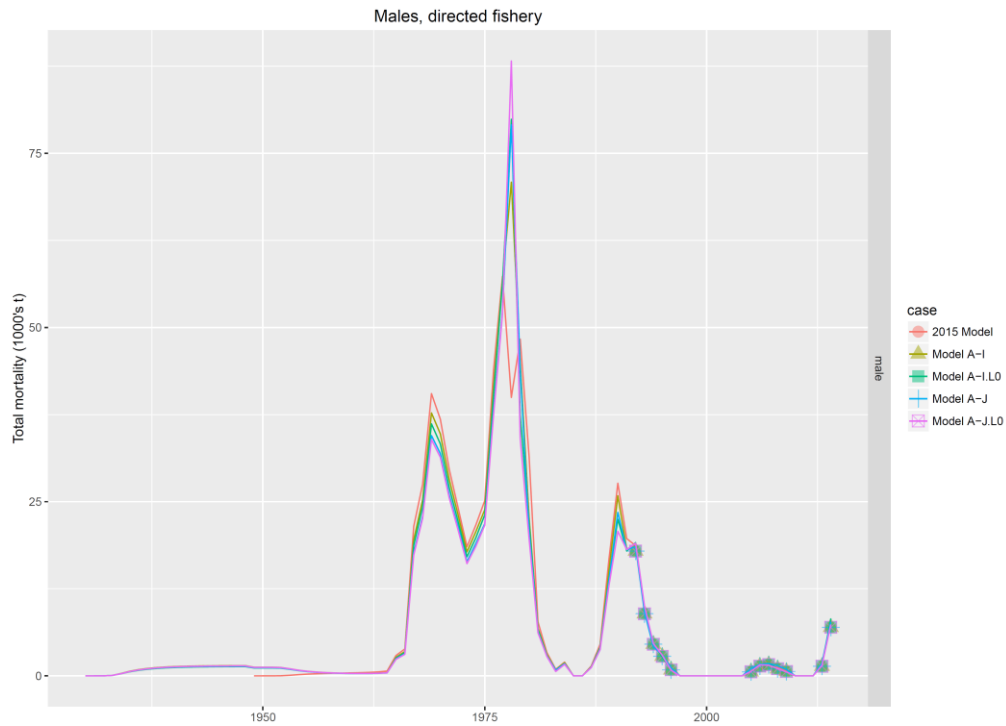


Figure 41. Comparison of fits to total catch biomass for the models indicated in the legend. Models including “D” are fit to discard biomass, but fits to total biomass are shown. Symbols represent data, lines represent model estimates.

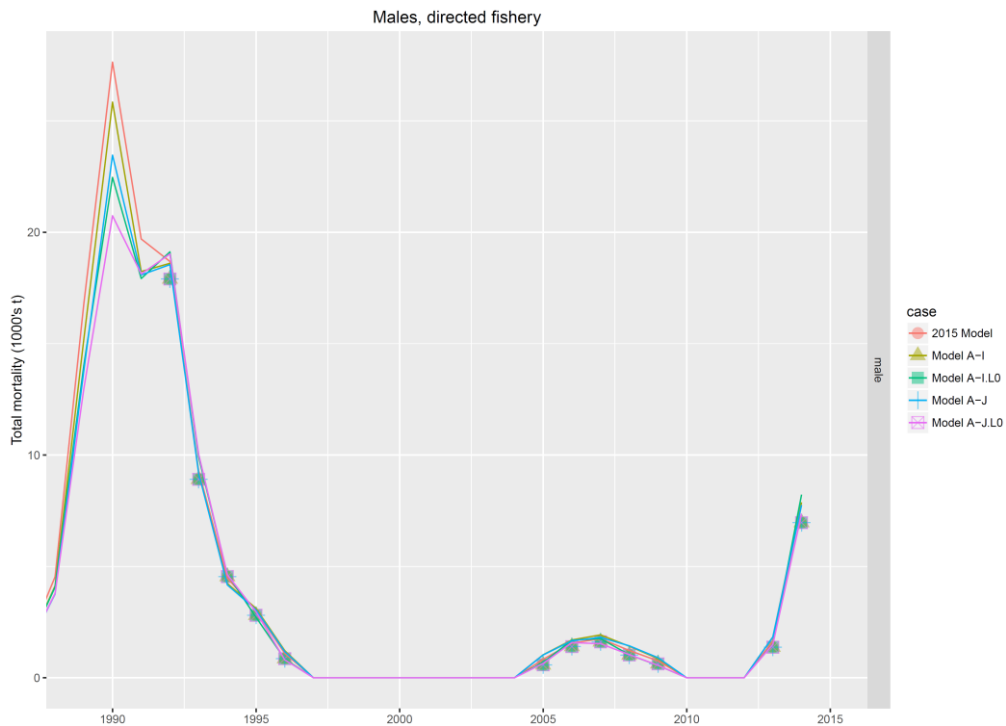


Figure 42. Comparison of fits to total catch biomass, from 1989 to 2014, for the models indicated in the legend. Models including “D” are fit to discard biomass, but fits to total biomass are shown. Symbols represent data, lines represent model estimates.

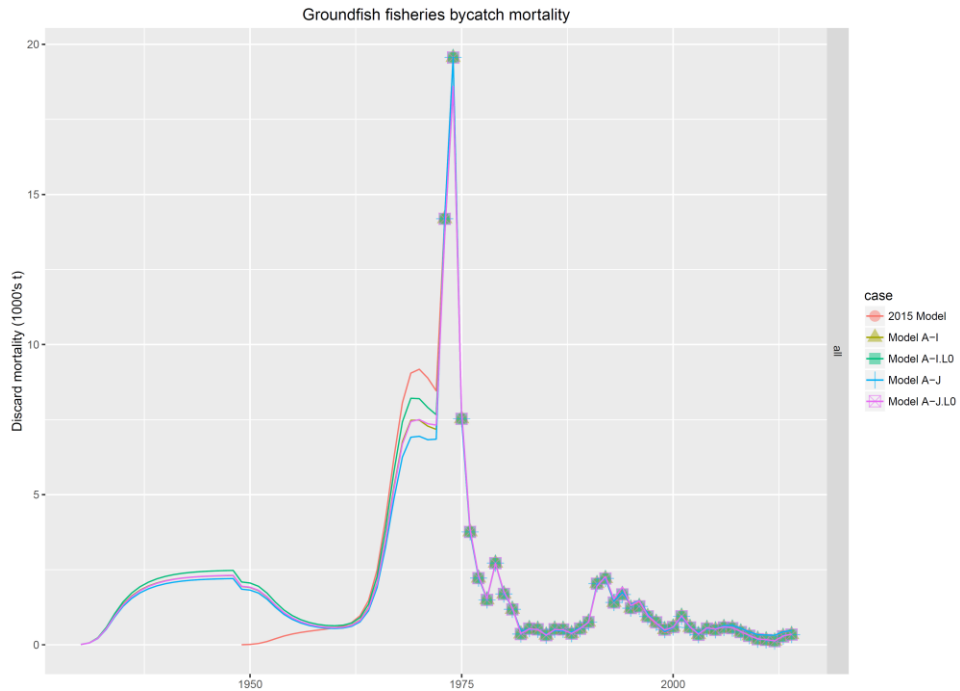


Figure 43. Comparison of fits to bycatch in the groundfish fisheries for the models indicated in the legend. Symbols represent data, lines represent model estimates.

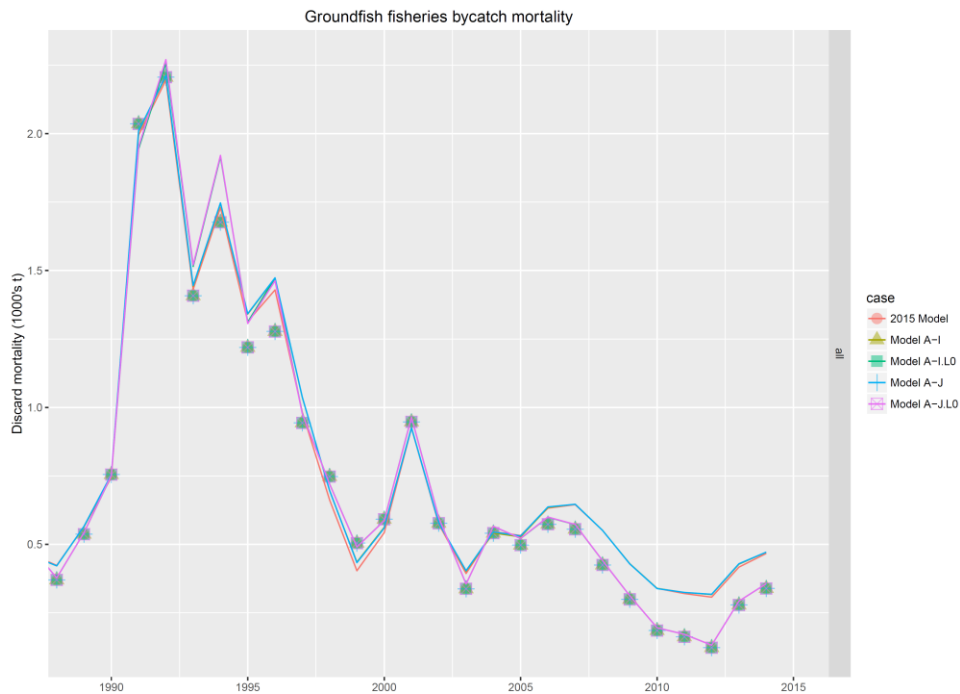


Figure 44. Comparison of fits to bycatch in the groundfish fisheries, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

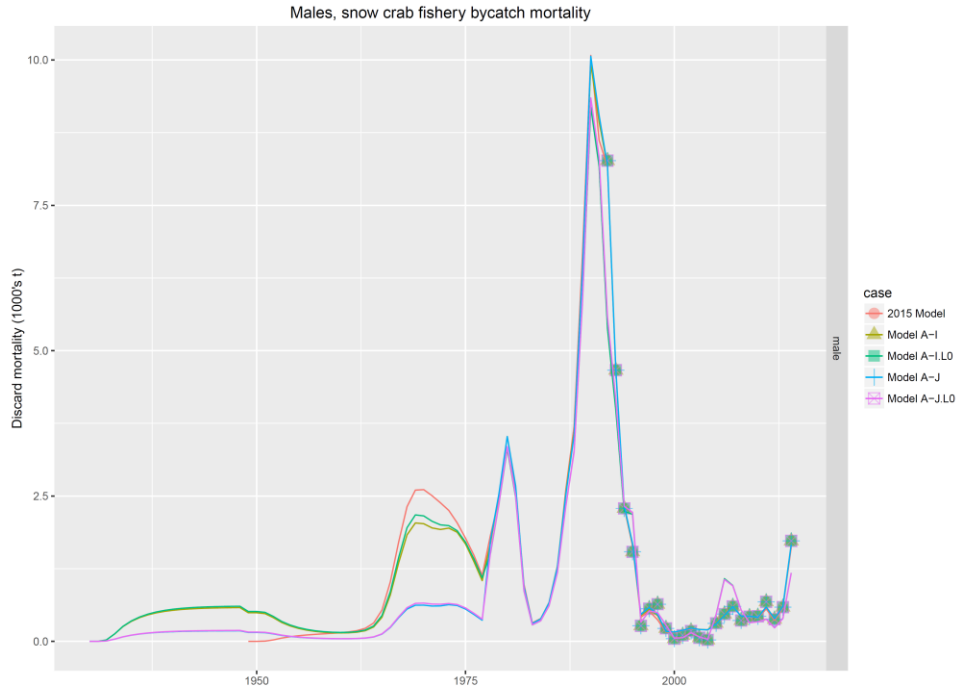


Figure 45. Comparison of fits to male bycatch in the snow crab fishery for the models indicated in the legend. Symbols represent data, lines represent model estimates.

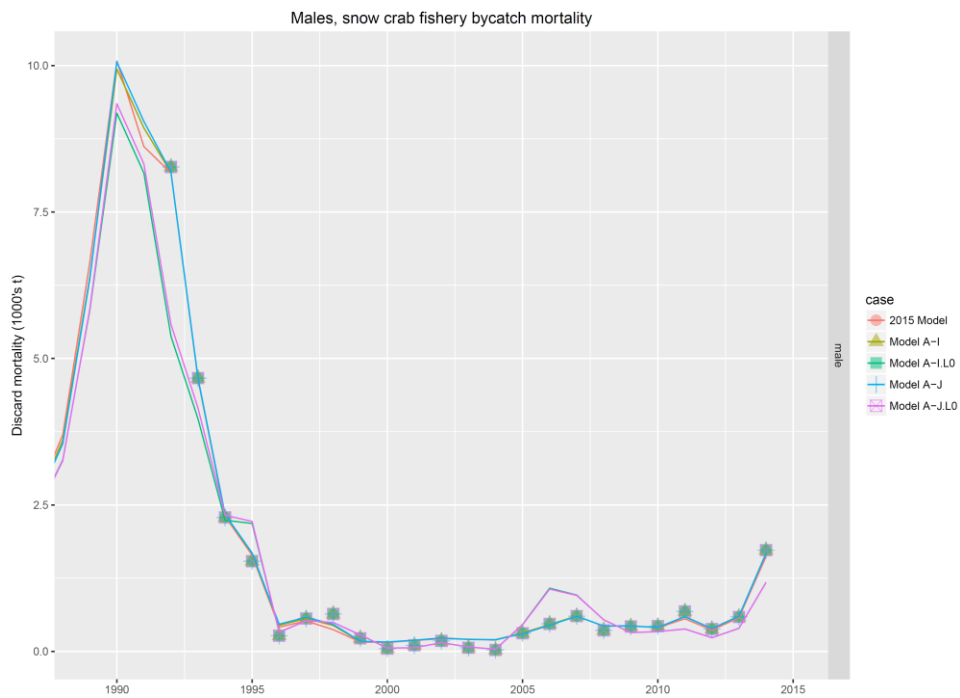


Figure 46. Comparison of fits to male bycatch in the snow crab fishery, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

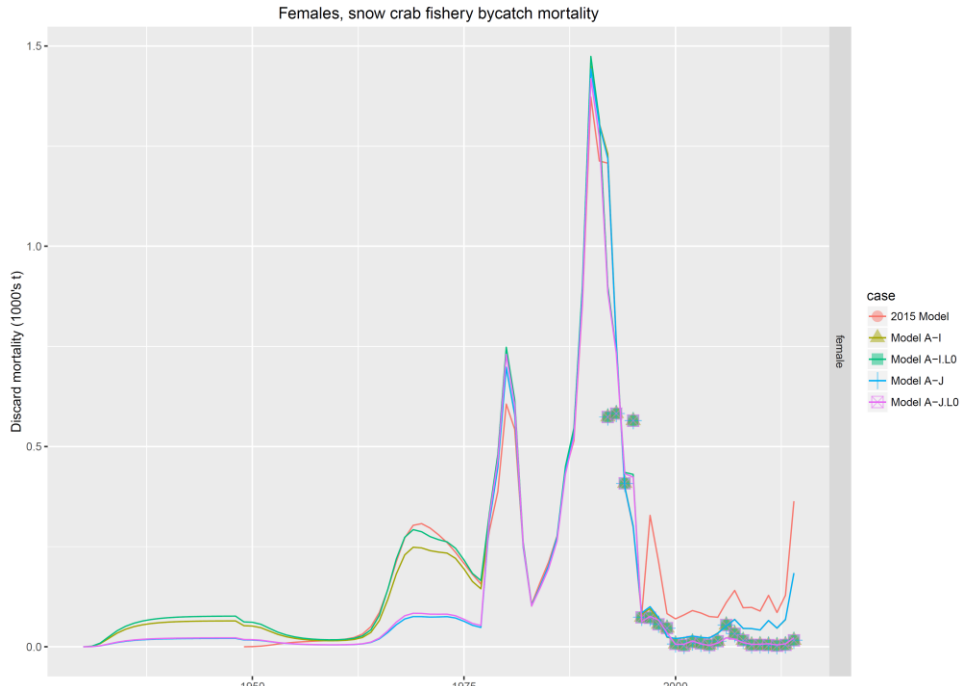


Figure 47. Comparison of fits to female bycatch in the snow crab fishery for the models indicated in the legend. Symbols represent data, lines represent model estimates.

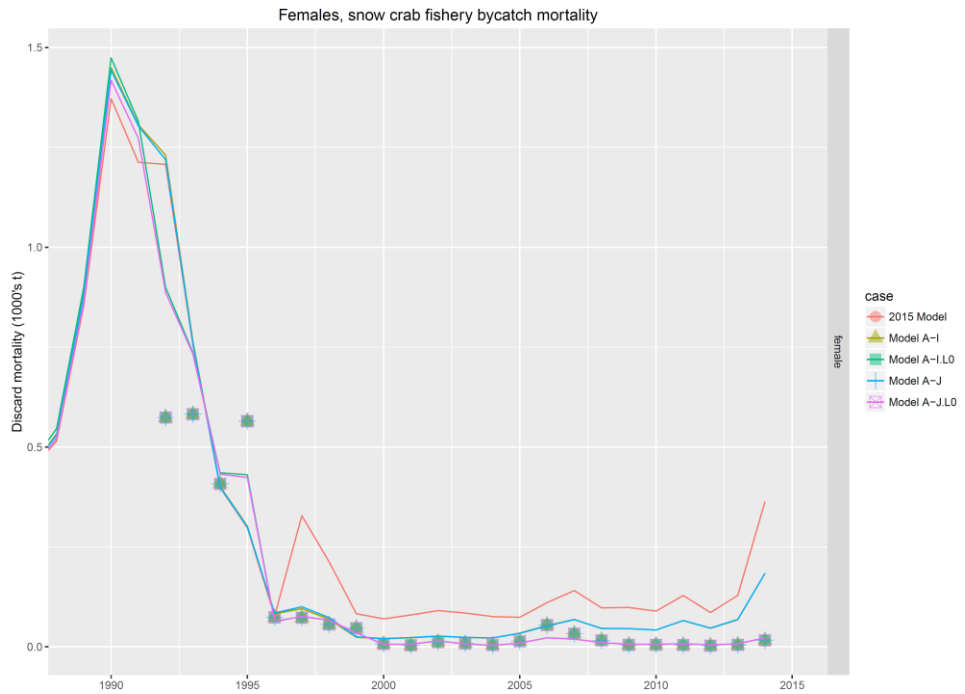


Figure 48. Comparison of fits to female bycatch in the snow crab fishery, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

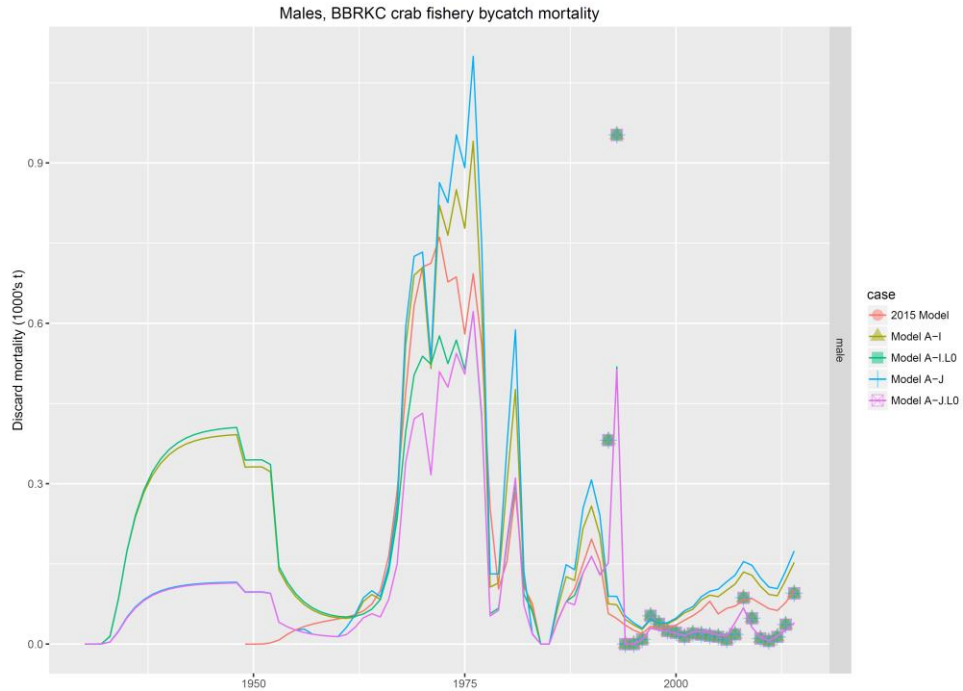


Figure 49. Comparison of fits to male bycatch in the BBRKC fishery for the models indicated in the legend. Symbols represent data, lines represent model estimates.

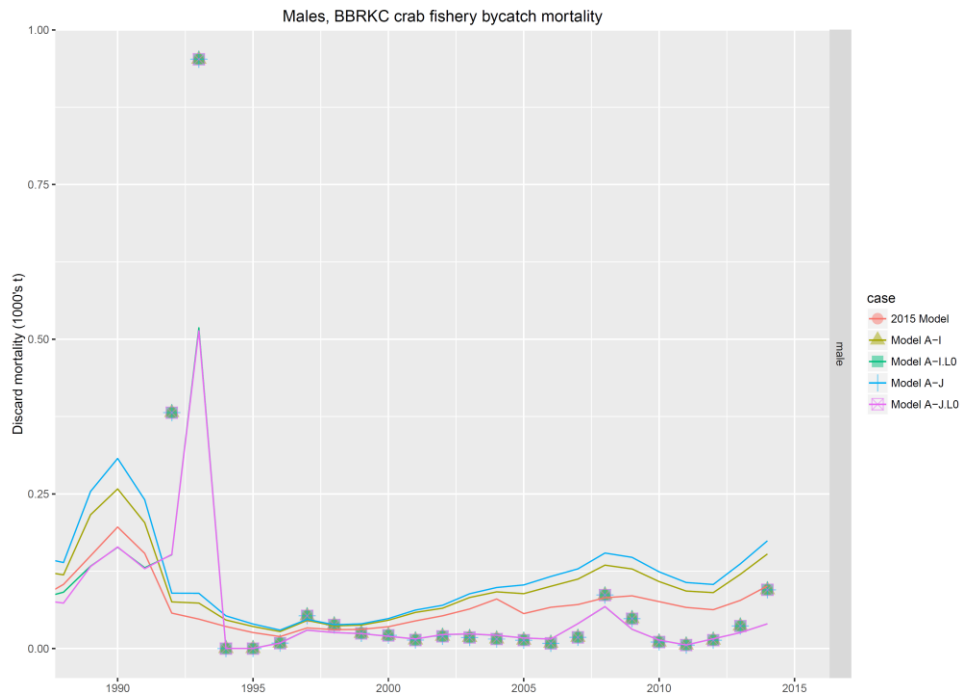


Figure 50. Comparison of fits to male bycatch in the BBRKC fishery, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

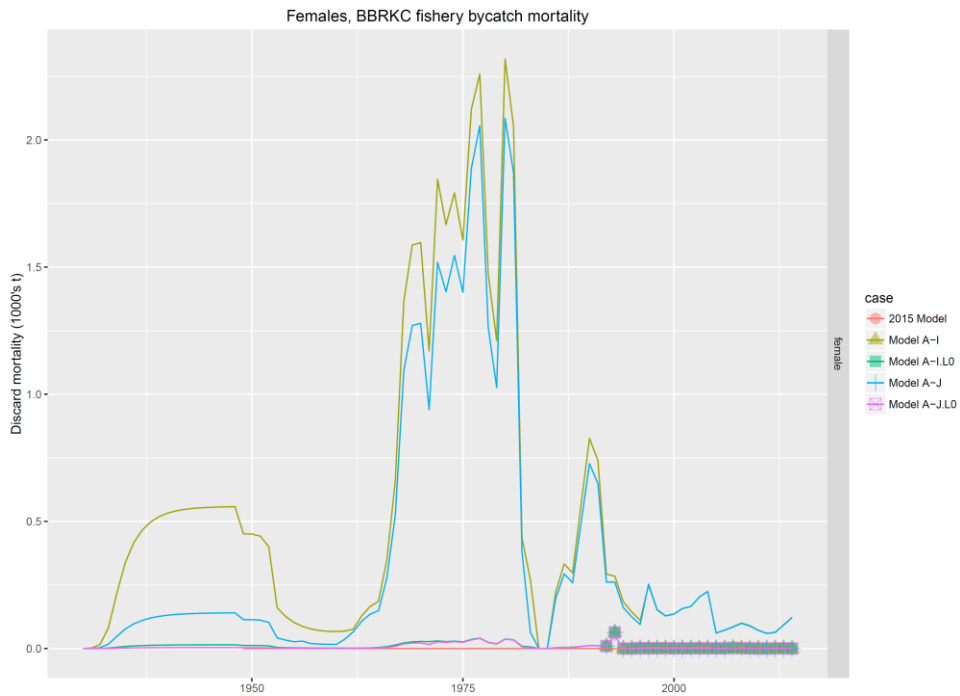


Figure 51. Comparison of fits to female bycatch in the BBRKC fishery for the models indicated in the legend. Symbols represent data, lines represent model estimates.

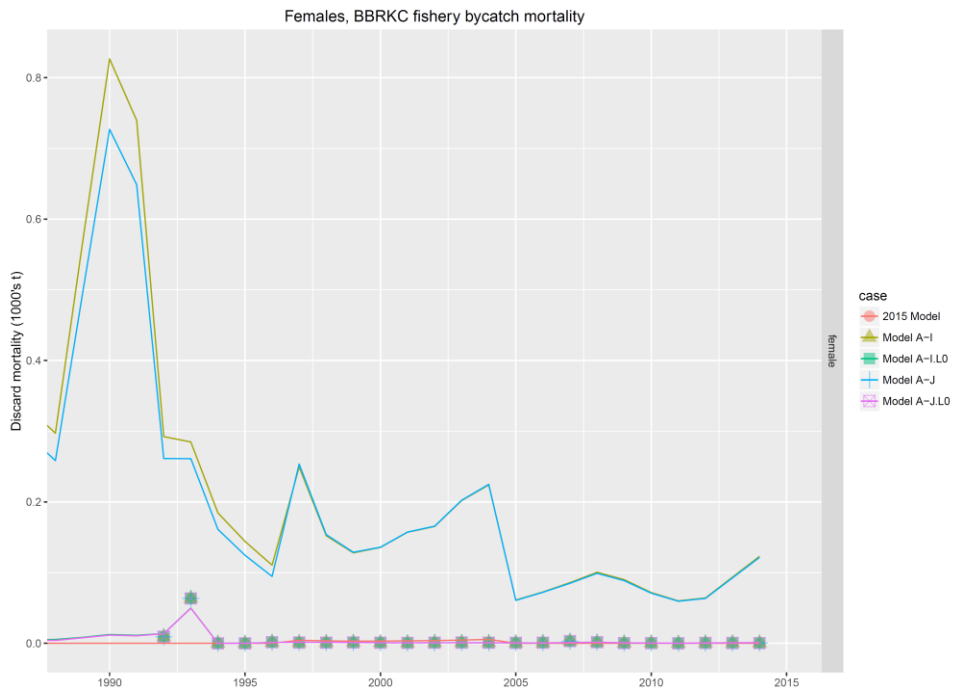


Figure 52. Comparison of fits to female bycatch in the BBRKC fishery, from 1989 to 2014, for the models indicated in the legend. Symbols represent data, lines represent model estimates.

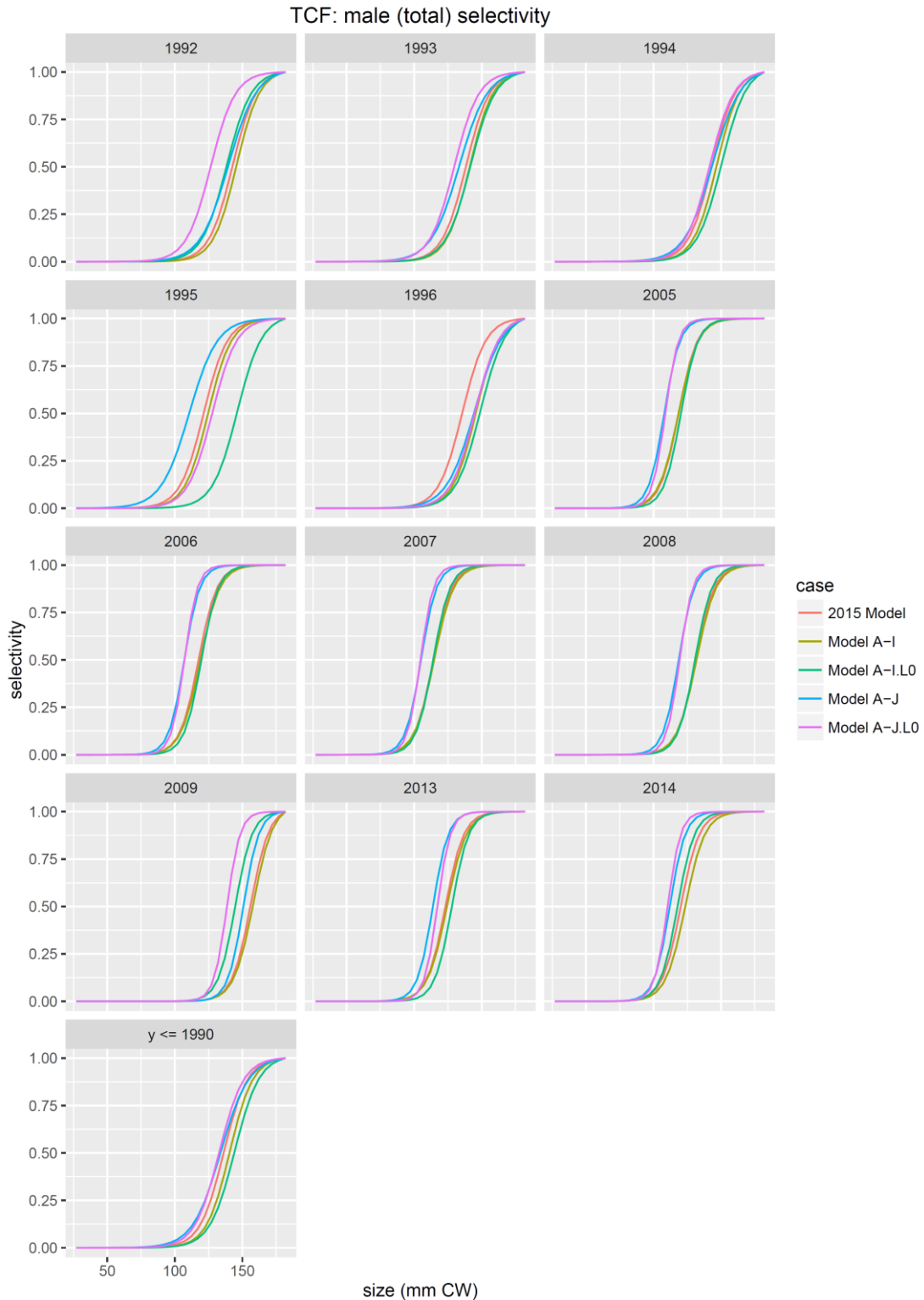


Figure 53. Comparison of model estimates for selectivity for males in the directed fishery during the time periods indicated. Selectivity for the 2015 model (Model 0) and “I” models is total mortality selectivity, while it is capture selectivity for “J” models.

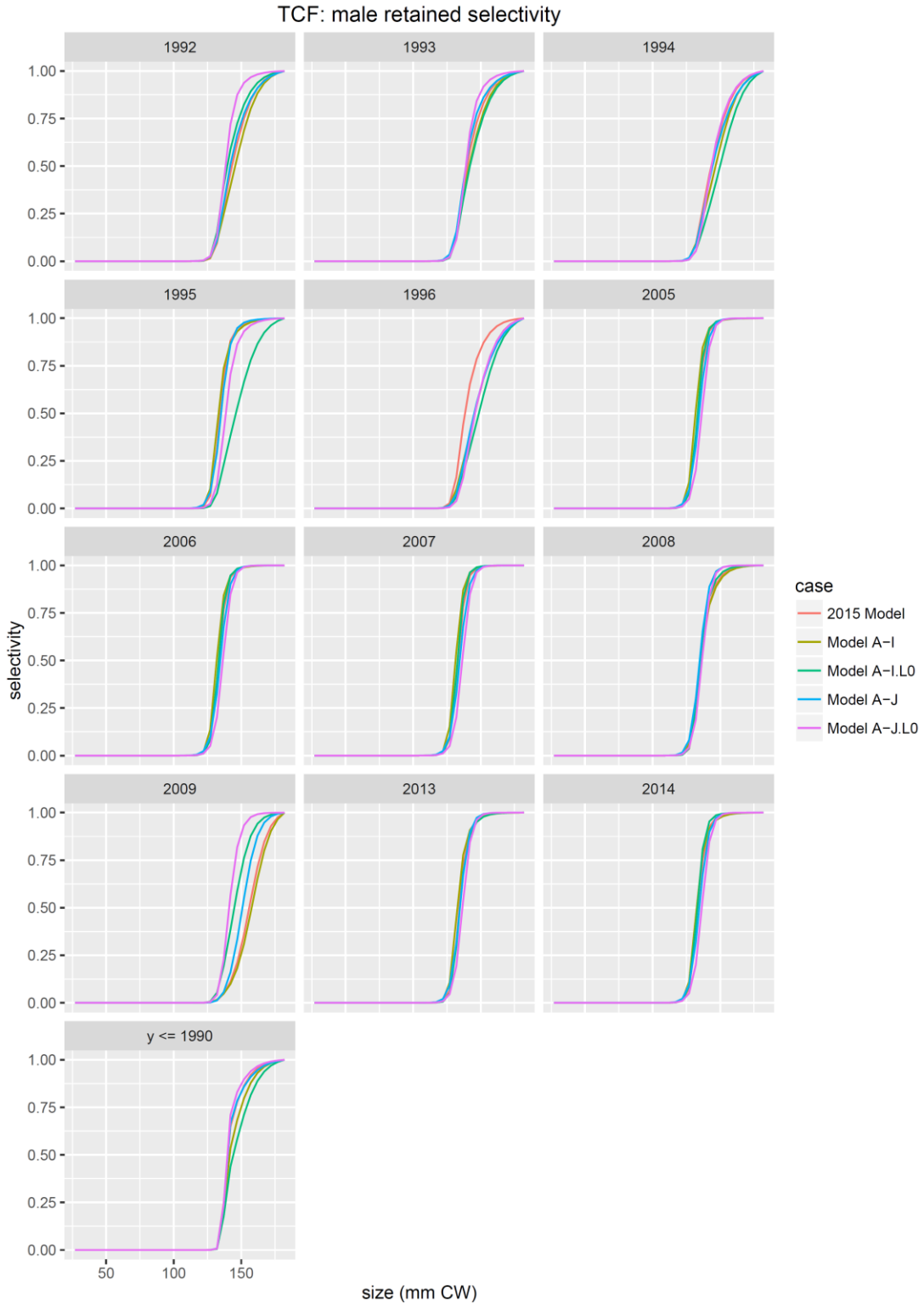


Figure 54. Comparison of model estimates for retained selectivity for males in the directed fishery during the time periods indicated.

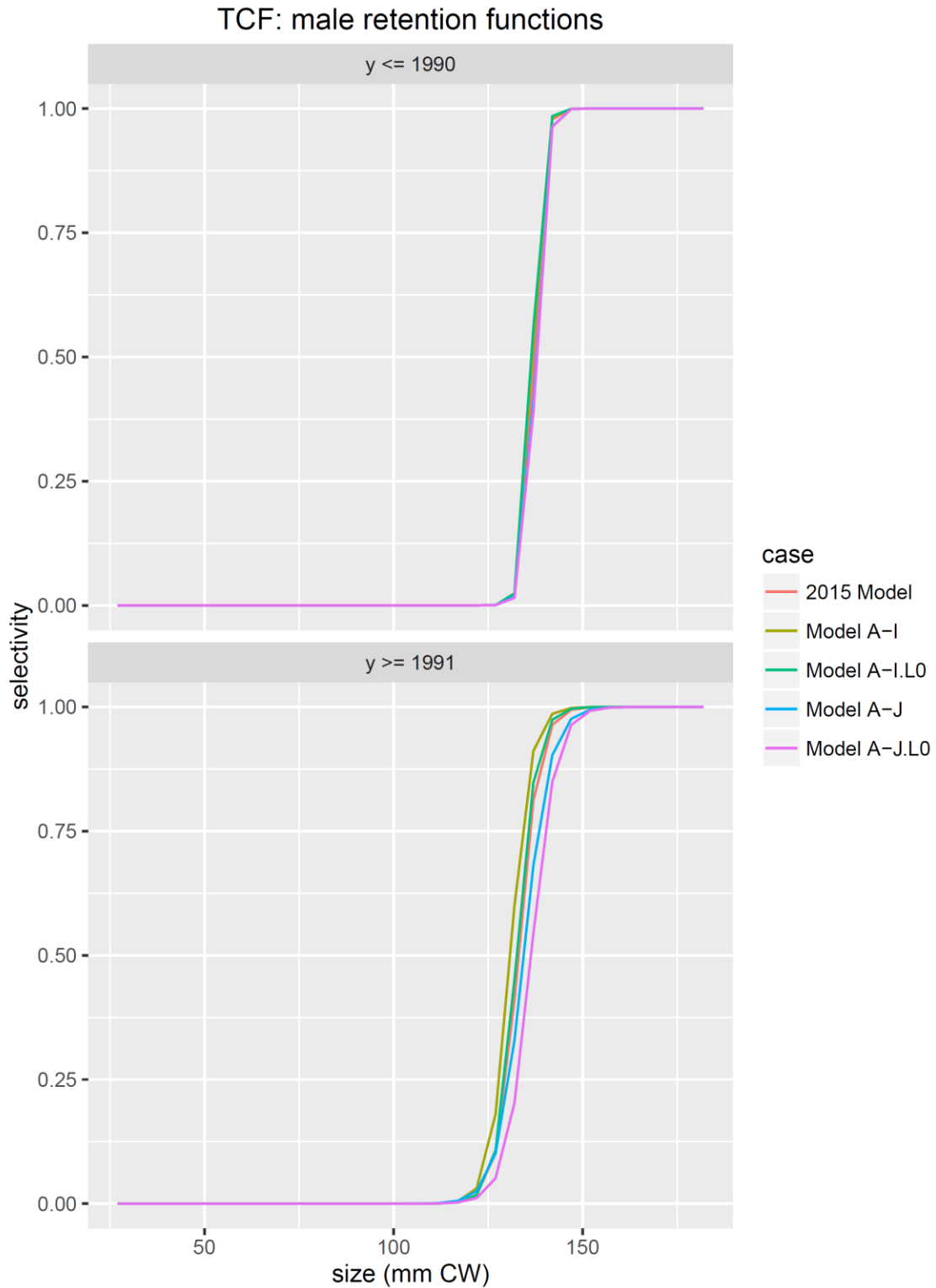


Figure 55. Comparison of model estimates of retention functions in the directed fishery during the time periods indicated.

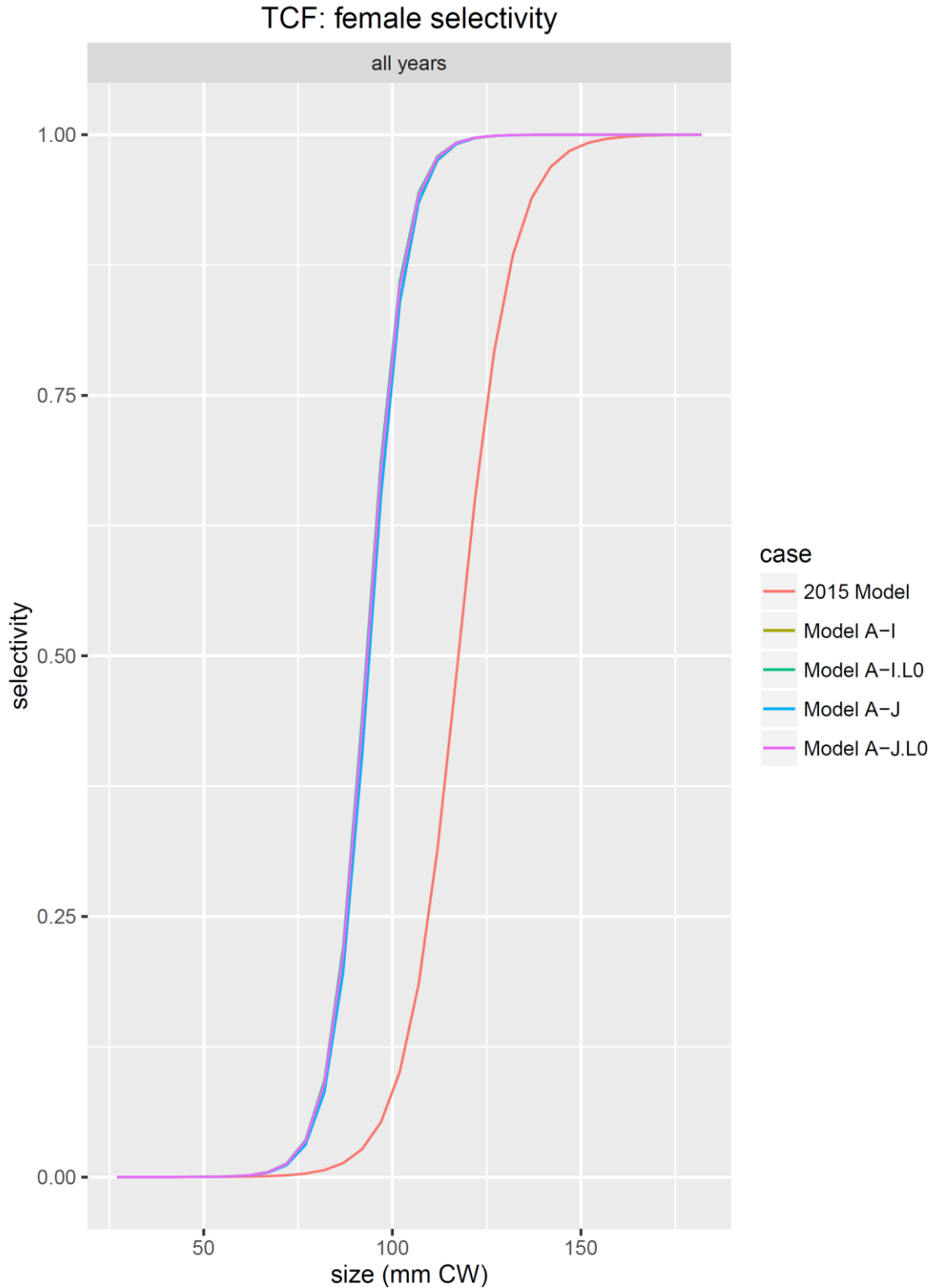


Figure 56. Comparison of model estimates of female selectivity (right) in the directed fishery during the time periods indicated.

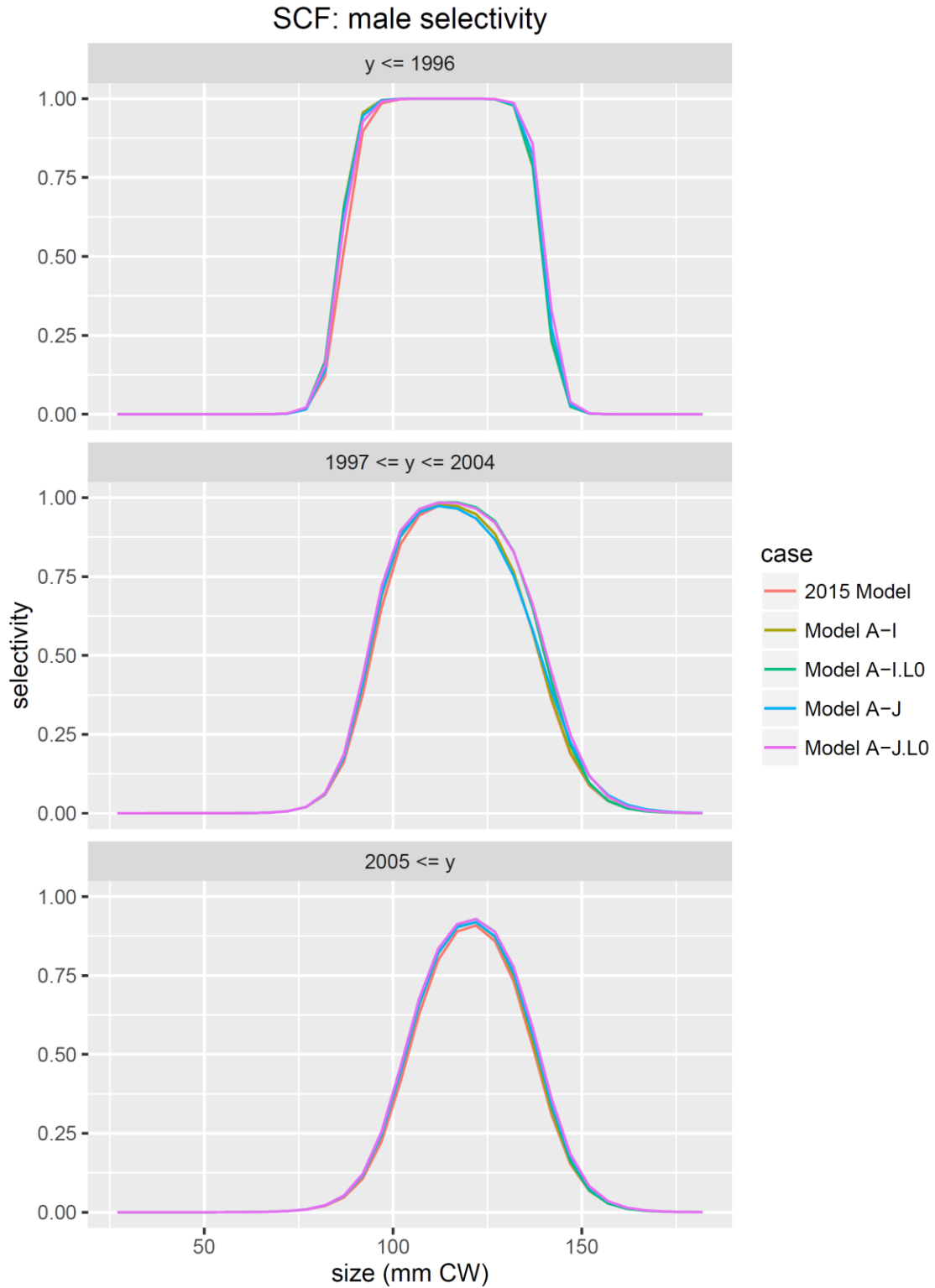


Figure 57. Comparison of model estimates for female bycatch selectivity in the snow crab fishery during the time periods indicated.

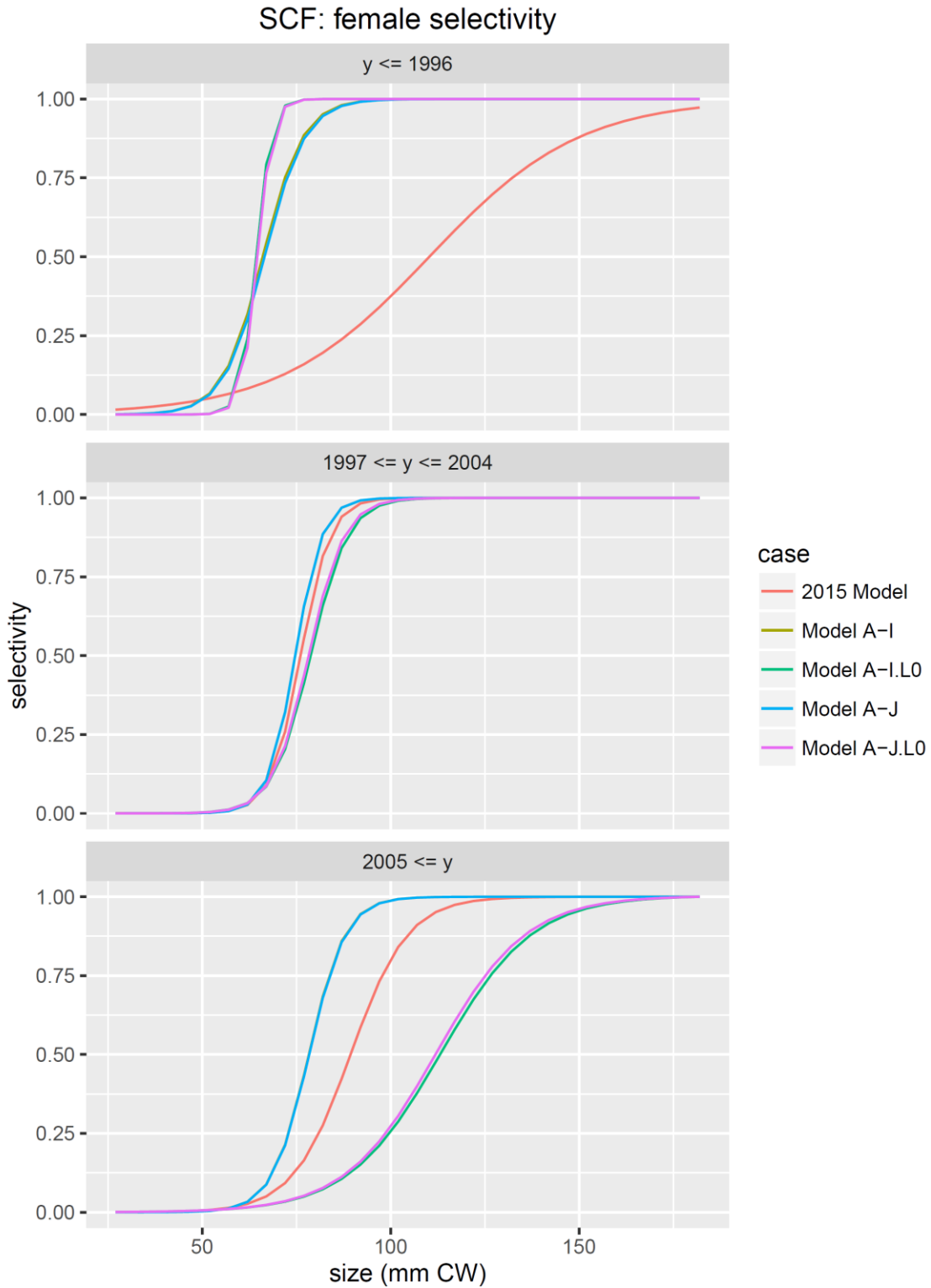


Figure 58. Comparison of model estimates for female bycatch selectivity in the snow crab fishery during the time periods indicated.

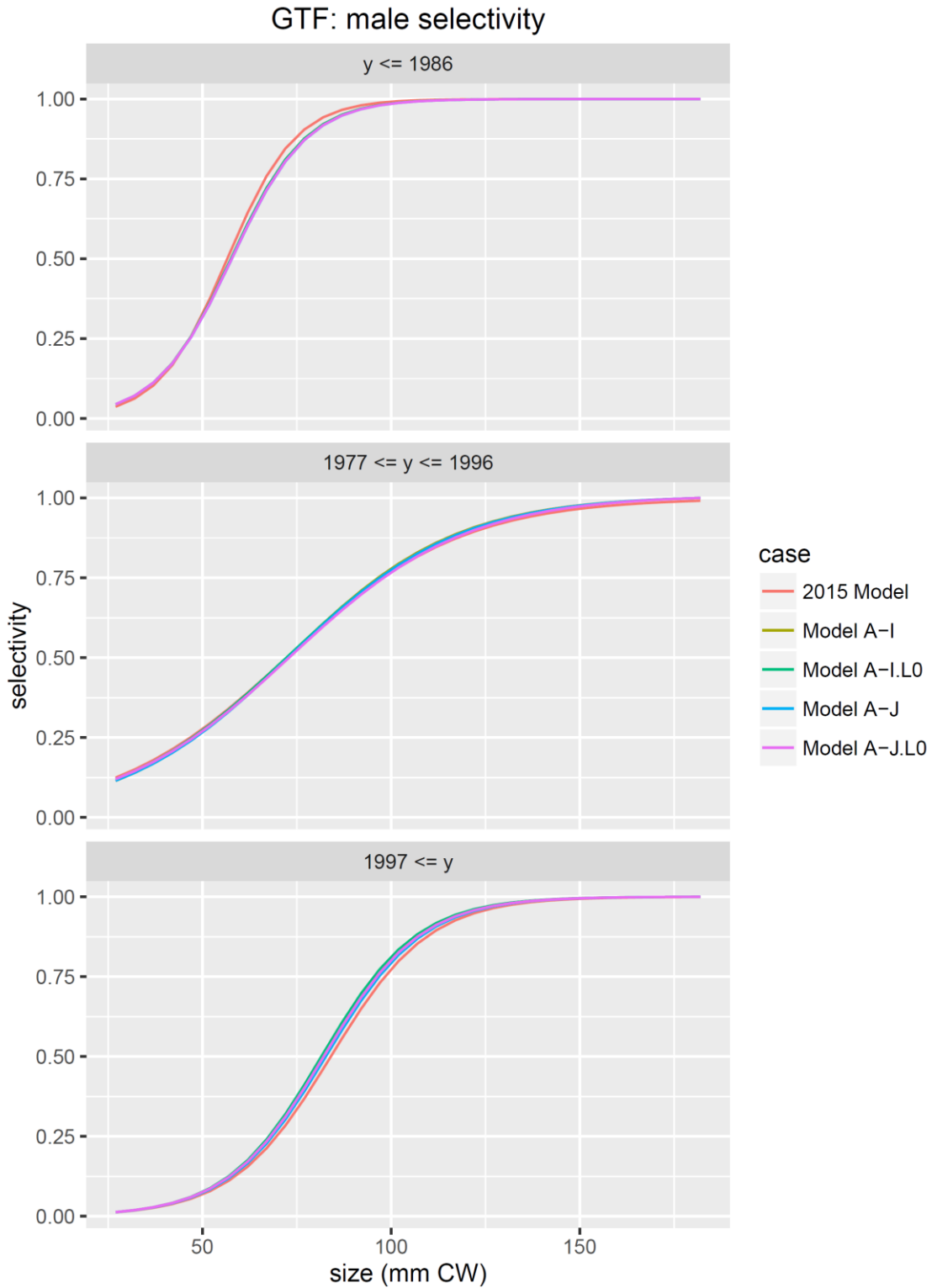


Figure 59. Comparison of model estimates for male bycatch selectivity in the groundfish fisheries during the time periods indicated.

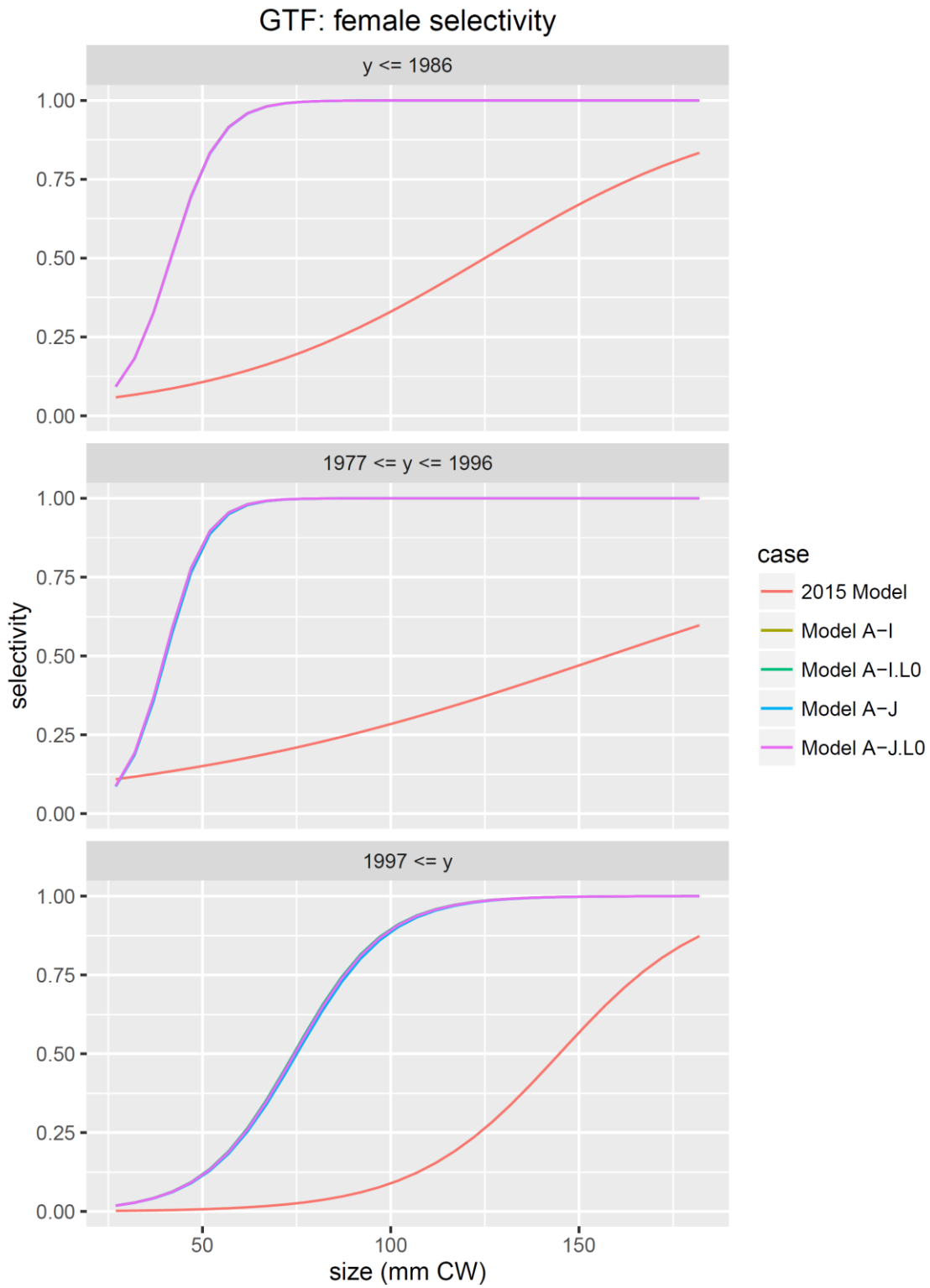


Figure 60. Comparison of model estimates for female bycatch selectivity in the groundfish fisheries during the time periods indicated.

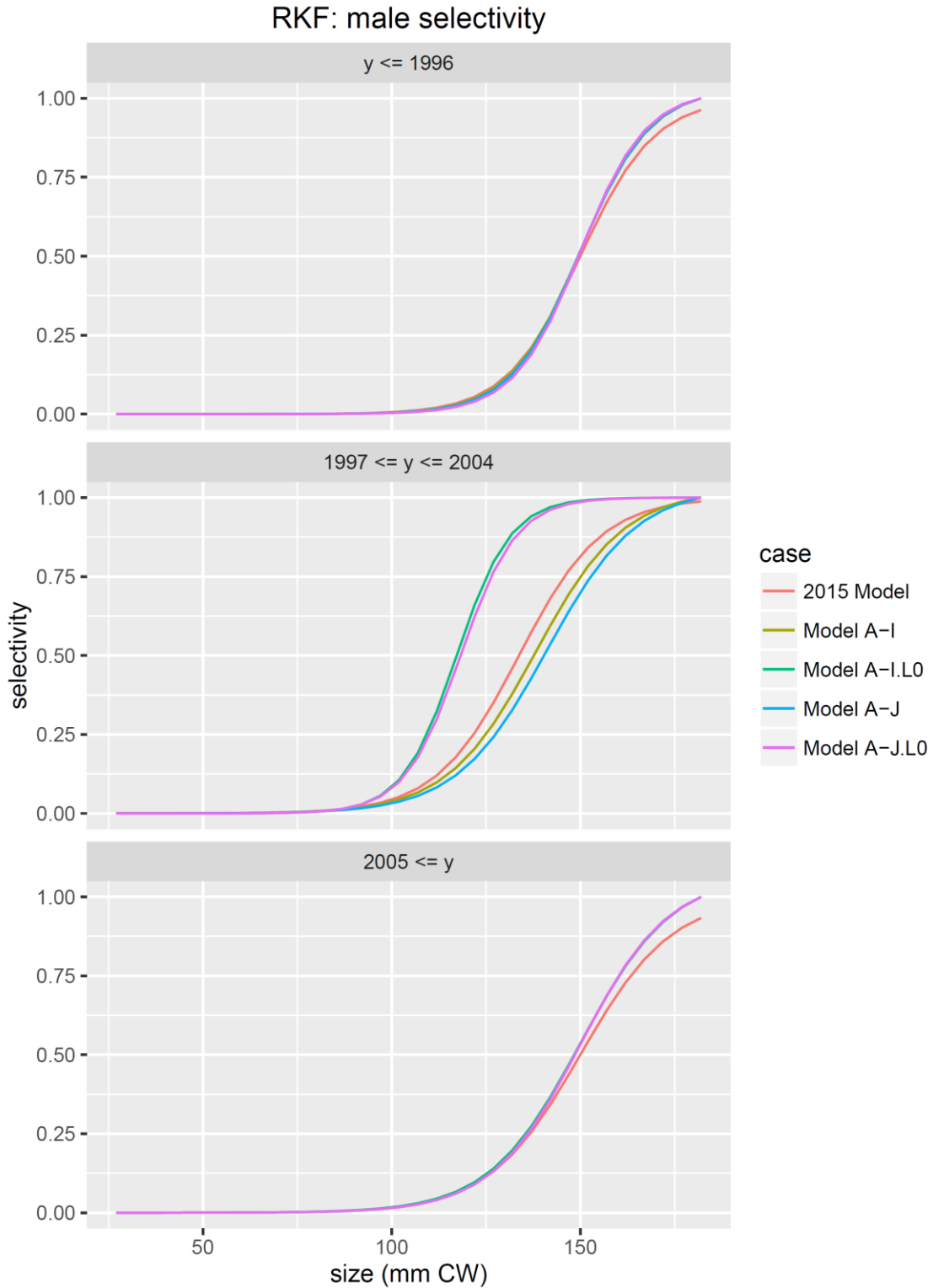


Figure 61. Comparison of model estimates for male bycatch selectivity in the BBRKC fishery during the time periods indicated.

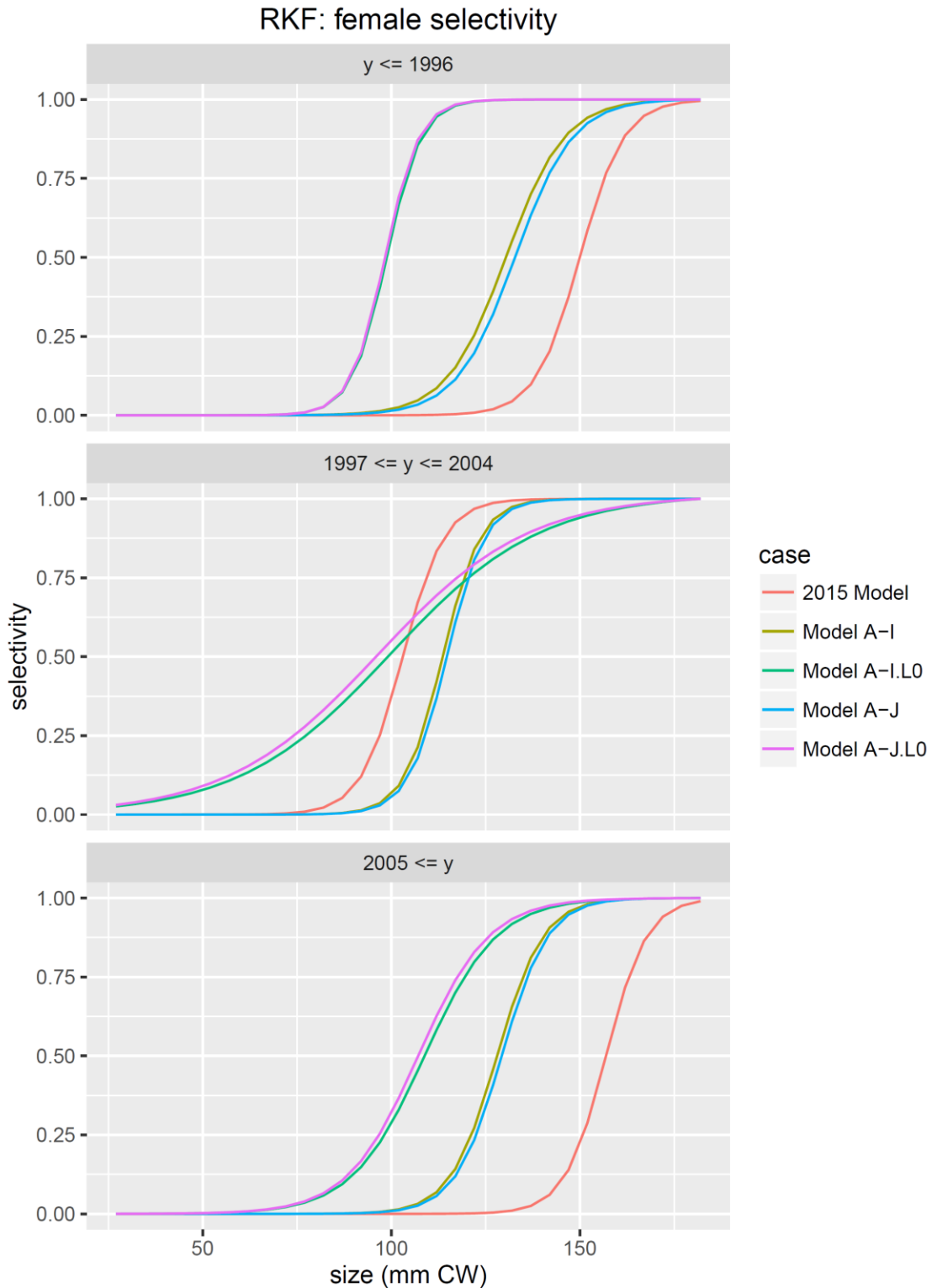


Figure 62. Comparison of model estimates for female bycatch selectivity in the BBRKC fishery during the time periods indicated.

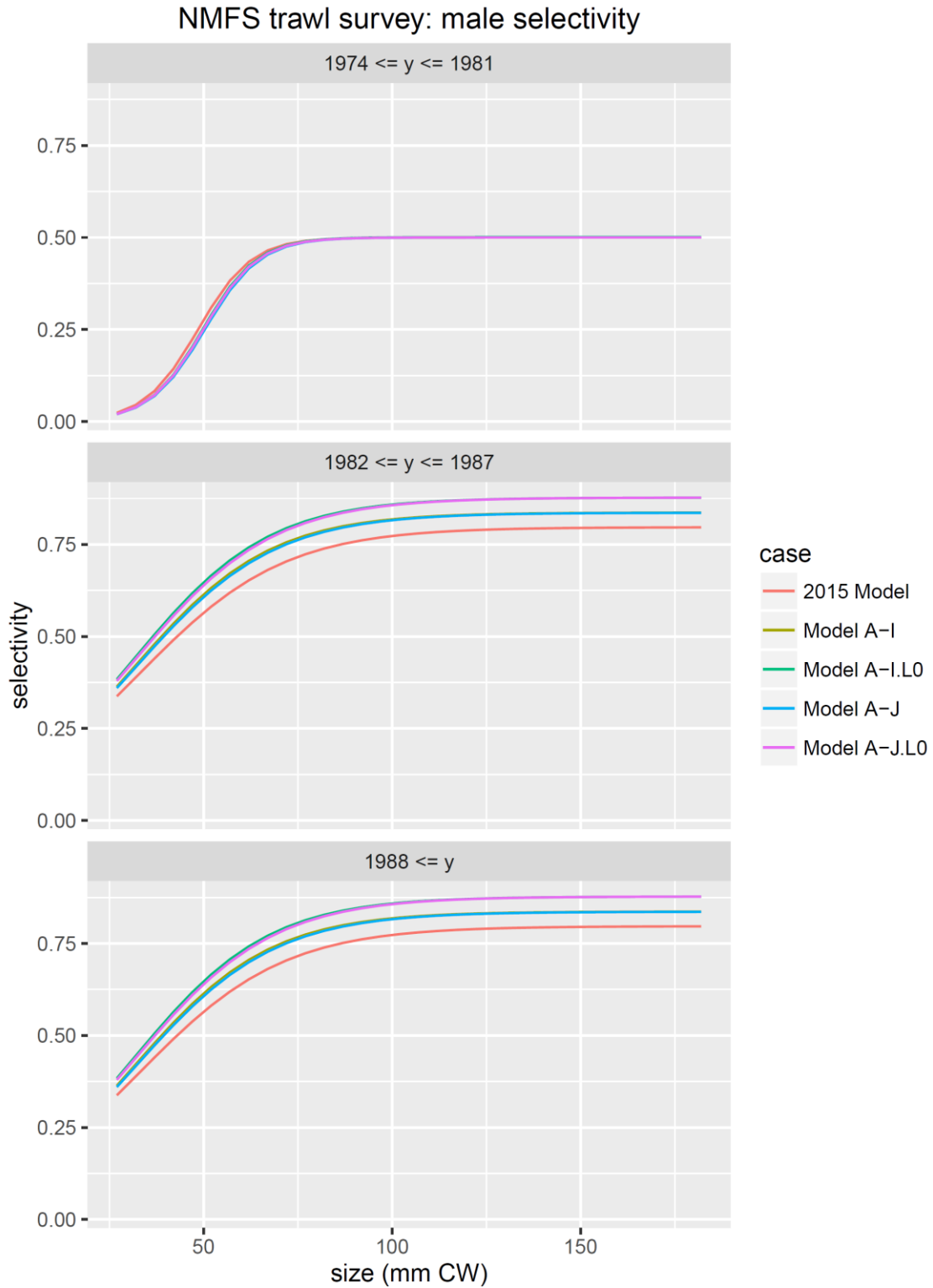


Figure 63. Comparison of model estimates for male selectivity in the NMFS bottom trawl survey during the time periods indicated.

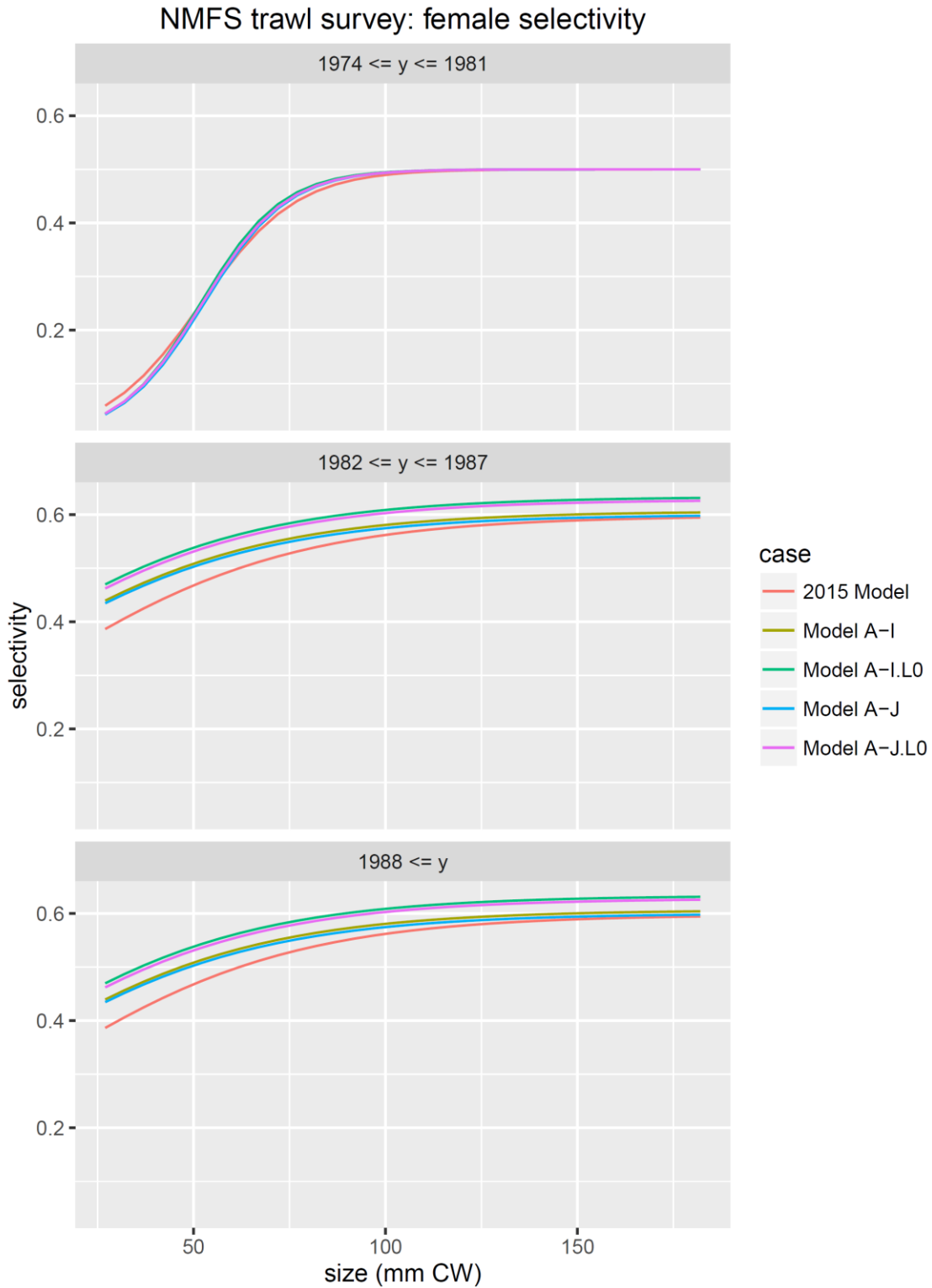


Figure 64. Comparison of model estimates for female selectivity in the NMFS bottom trawl survey during the time periods indicated.

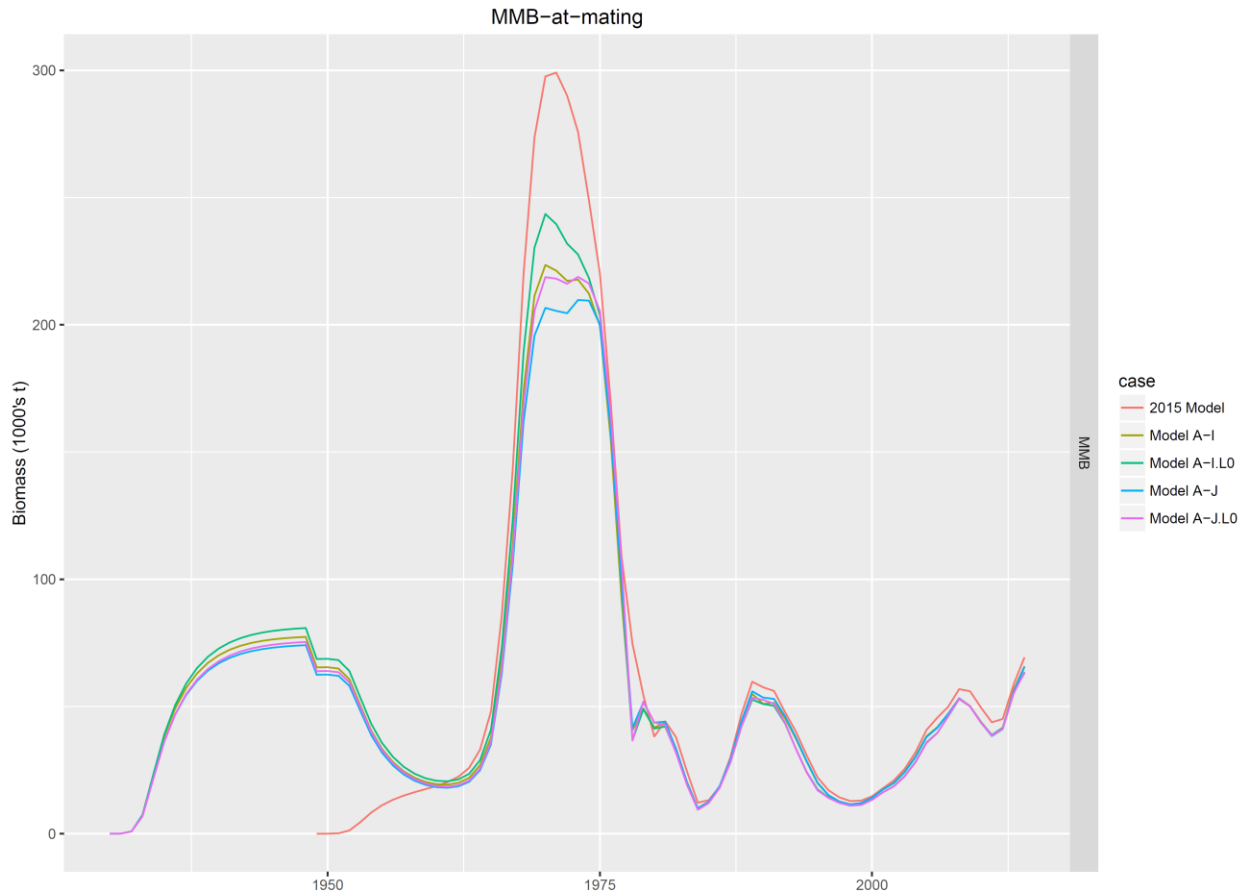


Figure 65. Comparison of model estimates for mature male biomass for the models indicated in the legend.

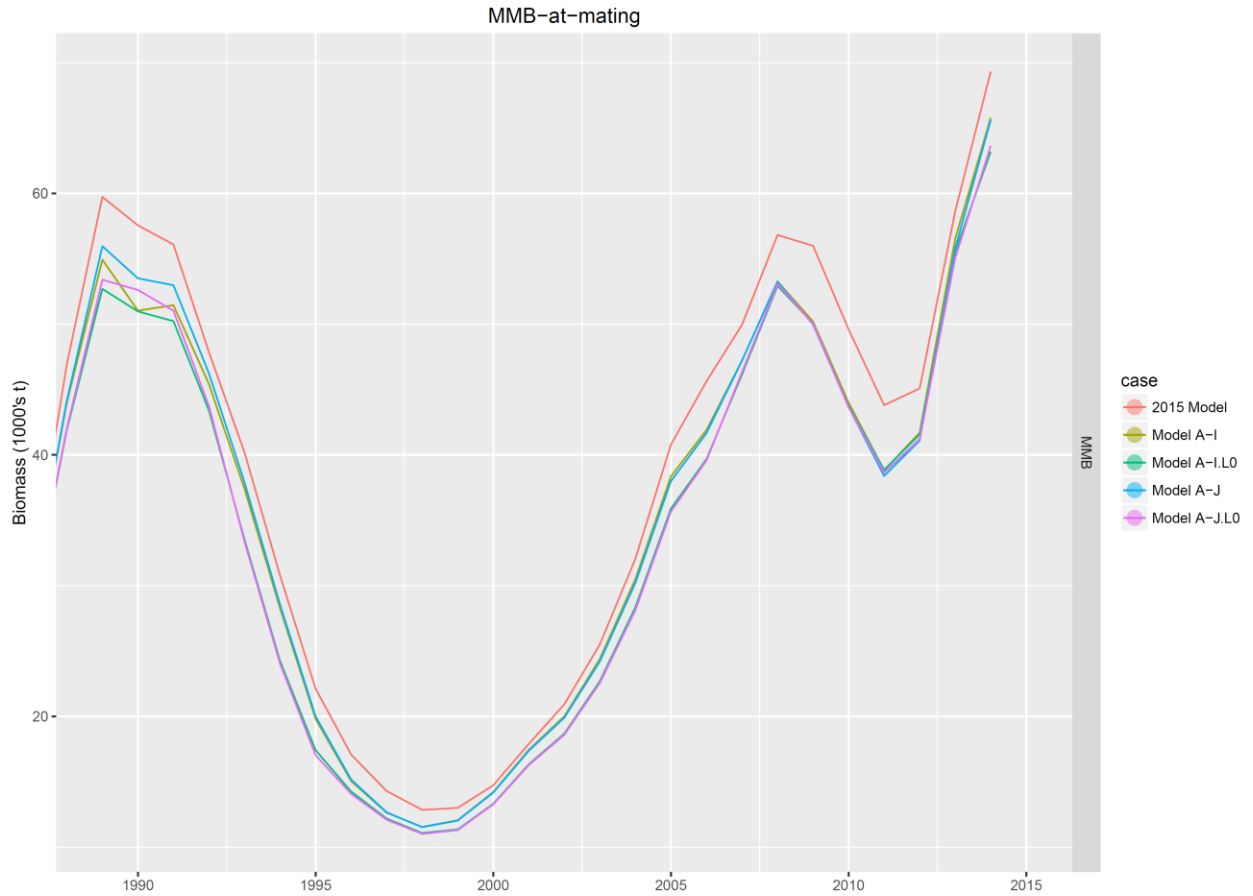


Figure 66. Comparison of model estimates of mature survey biomass, 1989-2015, for the models indicated in the legend.

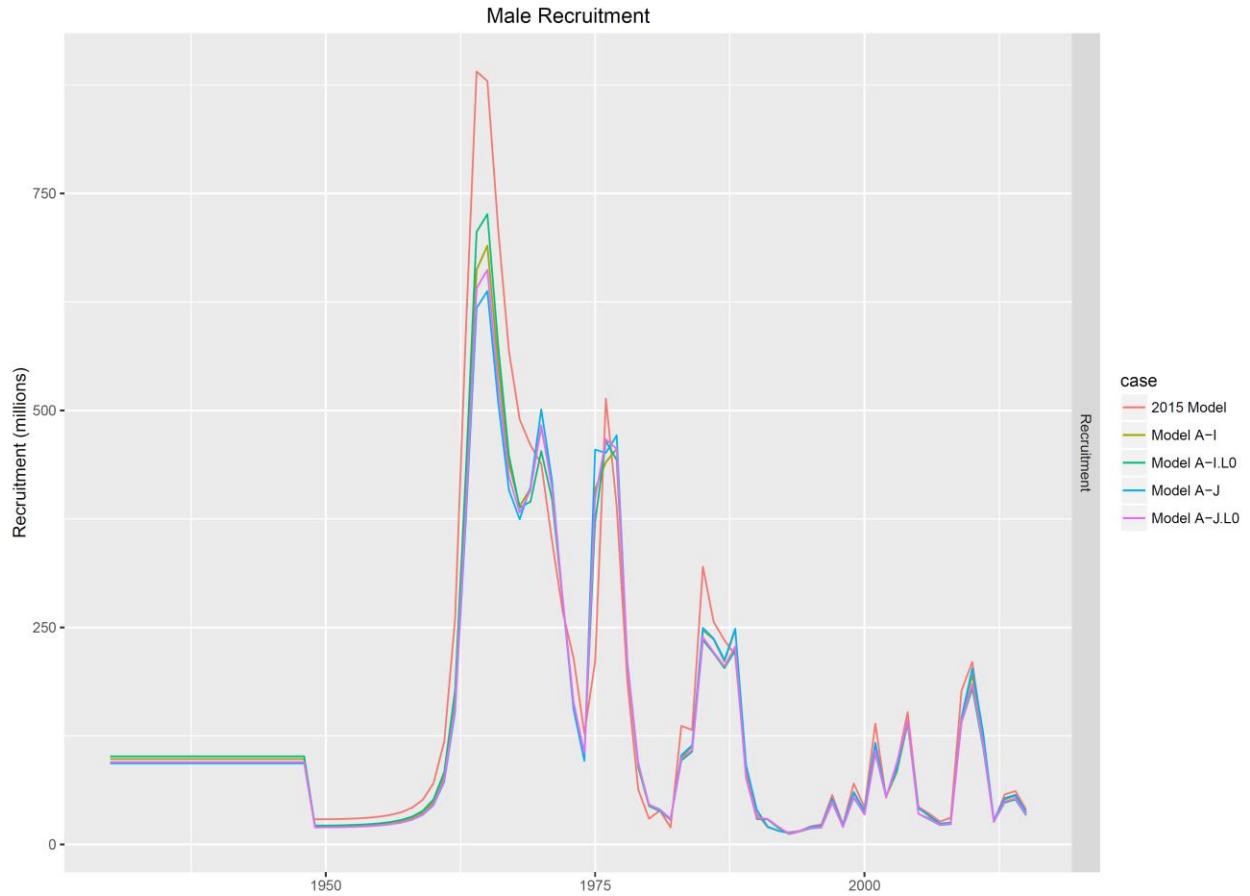


Figure 67. Comparison of model estimates for (male) recruitment for the models indicated in the legend.

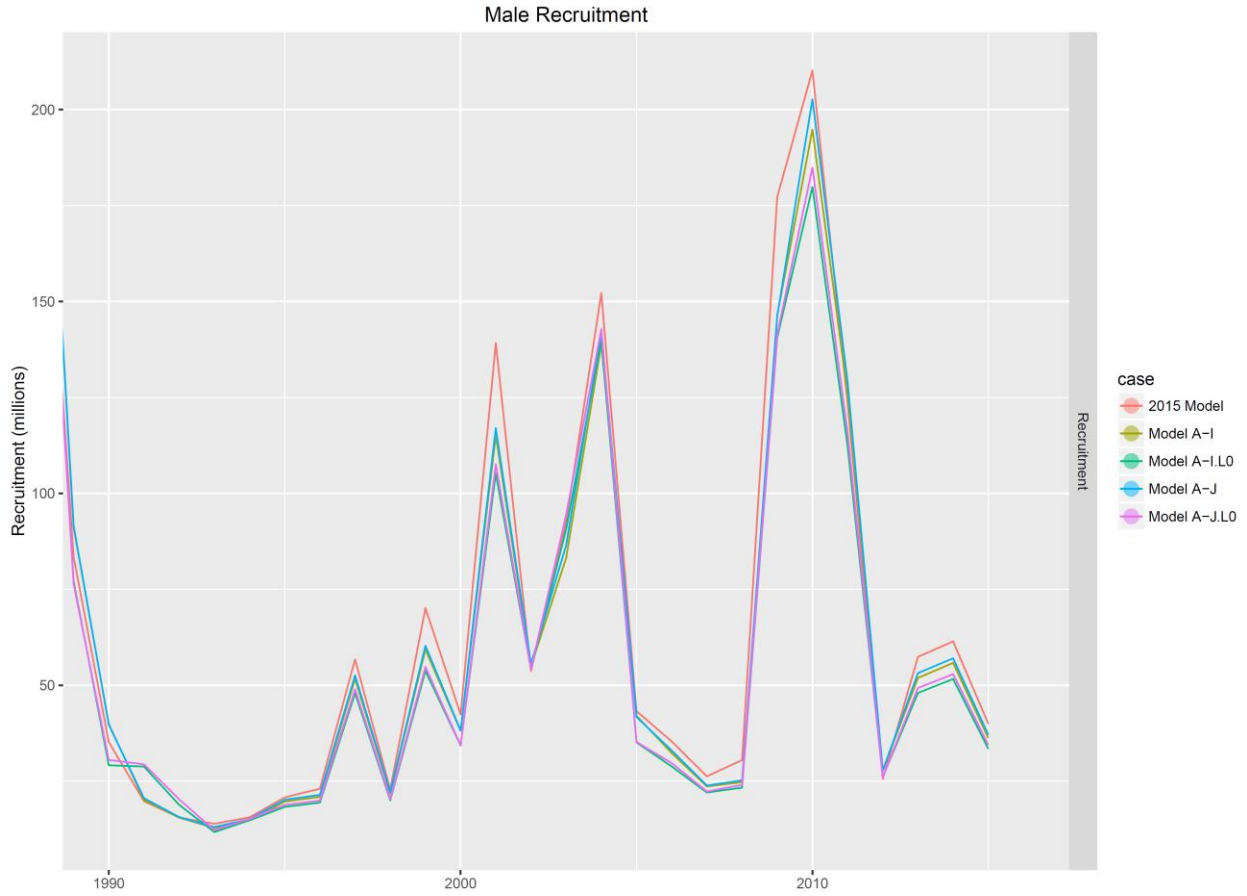


Figure 68. Comparison of model estimates of (male) recruitment, 1989-2015, for the models indicated in the legend.

Appendix A: TCSAM (Tanner Crab Stock Assessment Model) 2013 Description

Introduction

The Tanner crab stock assessment model (TCSAM) is an integrated assessment model developed in C++ using AD Model Builder (Fournier et al., 2012) libraries that is fit to multiple data sources. Model code is publicly available on github (<https://github.com/wStockhausen/wtsTCSAM2013>; the current branch is ‘dev20160316’), and an R package has been developed run the model and plot model output (publicly available on github at <https://github.com/wStockhausen/rTCSAM2013>). While a number of options have been added to the code in recent years, TCSAM2013 suffers “structural” difficulties with a number of hard-wired time periods and other constraints that cannot really be addressed without re-writing the code. The model described herein is the version used in the Sept. 2015 assessment (Stockhausen, 2015; referred to as TCSAM2013). Several recently-added options are also described.

Model parameters in TCSAM2013 are estimated using a maximum likelihood approach, with Bayesian-like priors on some parameters and penalties for smoothness and regularity on others. Data components entering the likelihood include fits to survey biomass, survey size compositions, retained catch, retained catch size compositions, discard mortality in the bycatch fisheries, and discard size compositions in the bycatch fisheries. Population abundance at the start of year y in the model, $n_{y,x,m,s,z}$, is characterized by sex x (male, female), maturity state m (immature, mature), shell condition s (new shell, old shell), and size z (carapace width, CW). Changes in abundance due to natural mortality, molting and growth, maturation, fishing mortality and recruitment are tracked on an annual basis. Because the principal crab fisheries occur during the winter, the model year runs from July 1 to June 30 of the following calendar year.

A. Calculation sequence

Step A1: Survival prior to fisheries

Natural mortality is applied to the population from the start of the model year (July 1) until just prior to prosecution of the pulse fisheries for year y at δt_y^F . The numbers surviving at δt_y^F in year y are given by:

$n_{y,x,m,s,z}^1 = e^{-M_{y,x,m,s,z} \cdot \delta t_y^F} \cdot n_{y,x,m,s,z}$	A1
---	----

where M represents the annual rate of natural mortality in year y on crab classified as x, m, s, z .

Step A2: Prosecution of the fisheries

The directed fishery and bycatch fisheries are modeled as pulse fisheries occurring at δt_y^F in year y . The numbers that remain after the fisheries are prosecuted are given by:

$n_{y,x,m,s,z}^2 = \left(1 - e^{-F_{y,x,m,s,z}^T}\right) \cdot n_{y,x,m,s,z}^1$	A2
---	----

where F^T represents total (across all fisheries) annual fishing mortality in year y on crab classified as x, m, s, z .

Step A3: Survival after fisheries to time of molting/mating

Natural mortality is again applied to the population from just after the fisheries to the time at which molting/mating occurs for year y at δt_y^m . The numbers surviving at δt_y^m in year y are then given by:

$n_{y,x,m,s,z}^3 = e^{-M_{y,x,m,s,z} \cdot (\delta t_y^m - \delta t_y^F)} \cdot n_{y,x,m,s,z}^2$	A3
--	----

where, as above, M represents the annual rate of natural mortality in year y on crab classified as x, m, s, z . In the 2012 and 2013 assessments, molting and mating were taken to occur on Feb. 15 each year ($\delta t_y^m =$

0.625), and the pulse fisheries were taken to occur just prior to this ($\delta t_y^F = 0.625$, also), so the term in the exponent in eq. A3 was 0 for all years.

Step A4: Molting, growth, and maturation

The changes in population structure due to molting, growth and maturation of immature (new shell) crab, as well as the change in shell condition for new shell mature crab due to aging, are given by:

$n_{y,x,MAT,NS,z}^4 = \sum_{z'} \Theta_{y,x,z,z'}^{MAT} \cdot \phi_{y,x,z'} \cdot n_{y,x,IMM,NS,z'}^3$	A4a
$n_{y,x,IMM,NS,z}^4 = \sum_{z'} \Theta_{y,x,z,z'}^{IMM} \cdot (1 - \phi_{y,x,z'}) \cdot n_{y,x,IMM,NS,z'}^3$	A4b
$n_{y,x,MAT,OS,z}^4 = n_{y,x,MAT,OS,z}^3 + n_{y,x,MAT,NS,z}^3$	A4c

where $\phi_{y,x,z}$ is the probability that an immature (new shell) crab of sex x and size z will undergo its terminal molt to maturity and $\Theta_{y,x,z,z'}^m$ is the growth transition matrix from size z' to z for that crab, which may depend on whether ($m=MAT$; eq. A.4a) or not ($m=IMM$; eq. A.4b) the terminal molt to maturity occurs. Additionally, crabs that underwent their terminal molt to maturity the previous year are assumed to change shell condition from new shell (NS) to old shell (OS ; A.4c). Note that the numbers of immature, old shell crab are identically zero in the current model because immature crab are assumed to molt each year until they undergo the terminal molt to maturity; consequently, an equation for $m=IMM$, $s=NS$ above is unnecessary.

Step A5: Survival to end of year, recruitment, and update to start of next year

Finally, population abundance at the start of year $y+1$ due to recruitment of immature new shell crab at the end of year y ($r_{y,x,z}$) and natural mortality on crab from the time of molting in year y until the end of the model year (June 30) are given by:

$r_{y,x,z} = R_y \cdot \rho_{y,x} \cdot \eta_z$	A5a
$n_{y+1,x,m,s,z} = \begin{cases} e^{-M_{y,x,IMM,NS,z} \cdot (1-\delta t_y^m)} \cdot n_{y,x,IMM,NS,z}^4 + r_{y,x,z} & m = IMM, s = NS \\ e^{-M_{y,x,m,s,z} \cdot (1-\delta t_y^m)} \cdot n_{y,x,m,s,z}^4 & otherwise \end{cases}$	A5b

B. Model processes: natural mortality

Natural mortality rates in TCSAM2013 vary across 3 year blocks (model start-1979, 1980-1984, 1985-model end) within which they are sex- and maturity state-specific but do not depend on shell condition or size. They are parameterized in the following manner:

$M_{y,x,m,s,z} = \begin{cases} M_{x,m,s}^{base} \cdot \delta M_{x,m} & otherwise \\ M_{x,m,s}^{base} \cdot \delta M_{x,m} \cdot \delta M_{x,m}^T & 1980 \leq y \leq 1984 \end{cases}$	natural mortality rates	B1 B2
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where y is year, x is sex, m is maturity state and s is shell condition, the $M_{x,m,s}^{base}$ are user constants (not estimated), and the $\delta M_{x,m}$ and $\delta M_{x,m}^T$ are parameters (although not all are estimated).

Priors are imposed on the $\delta M_{x,m}$ parameters in the likelihood using:

$\Pr(\delta M_{x,m}) = e^{-\frac{(\delta M_{x,m} - \mu_{x,m})^2}{2 \cdot \sigma_{x,m}^2}}$	Prior probability function for $\delta M_{x,m}$	B3
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The μ 's and σ^2 , along with bounds, initial values and estimation phases used for the parameters, as well as the values for the constants, used in the 2013 model are:

parameters/constants	$\mu_{x,m}$	$\sigma_{x,m}^2$	lower bound	upper bound	initial value	phase	code name
$M_{x,m,s}^{base}$	--	--	--	--	0.23	NA	baseM_msx
$\delta M_{x,IMM}$	1.0	0.05	0.2	2.0	1.0	7	pMfac_Imm
$\delta M_{MALE,MAT}$	1.0	0.05	0.1	1.9	1.0	7	pMfac_MatM
$\delta M_{FEMALE,MAT}$	1.0	0.05	0.1	1.9	1.0	7	pMfac_MatF
$\delta M_{x,IMM}^T$	--	--	--	--	1.0	NA	--
$\delta M_{MALE,MAT}^T$			0.1	10.0	1.0	7	pMfac_Big (MALE)
$\delta M_{FEMALE,MAT}^T$			0.1	10.0	1.0	7	pMfac_Big (FEMALE)

where constants have phase = NA and estimated parameters have phase > 0. When no corresponding variable exists in the model (code name = NA), the effective value of the parameter/constant is given.

C. Model processes: growth

Growth of immature crab in the 2013 TCSAM model is based on sex-specific transition matrices that specify the probability that crab in pre-molt size bin z grow to post-molt size bin z' . The sex-specific growth matrix $\Theta_{x,z,z'}$ (i.e., the array `len_len[sex,ilen,ilen]` in the model code) is related to the sex-specific parameters a_x , b_x , and β_x by the following equations:

$\Theta_{x,z,z'} = c_{x,z} \cdot \Delta_{z,z'}^{\alpha_{x,z}-1} \cdot e^{-\frac{\Delta_{z,z'}}{\beta_x}}$	Sex-specific (x) transition matrix for growth from pre-molt z to post-molt z' , with $z' \geq z$	C1
$c_{x,z} = \left[\sum_{z'} \Delta_{z,z'}^{\alpha_{x,z}-1} \cdot e^{-\frac{\Delta_{z,z'}}{\beta_x}} \right]^{-1}$	Normalization constant so $1 = \sum_{z'} \Theta_{x,z,z'}$	C2

$\Delta_{z,z'} = z' - z$	Actual growth increment	C3
$\alpha_{x,z} = [\bar{z}_{x,z} - z]/\beta_x$	Mean molt increment, scaled by β_x	C4
$\bar{z}_{x,z} = e^{a_x} \cdot z^{b_x}$	Mean size after molt, given pre-molt size z	C5

$\Theta_{x,z,z'}$ is used to update the numbers-at-size for immature crab following molting using:

$n_{x,z'}^+ = \sum_z n_{x,z} \cdot \Theta_{x,z,z'}$		C6
---	--	----

where z is the pre-molt size and z' is the post-molt size.

Sex-specific priors are imposed on the estimated values \hat{a}_x and \hat{b}_x for the a_x and b_x parameters using:

$\Pr(\hat{a}_x) = e^{-\frac{(\hat{a}_x - \mu_{a_x})^2}{2 \cdot \sigma_{a_x}^2}}$	Prior probability function for a 's	C7
$\Pr(\hat{b}_x) = e^{-\frac{(\hat{b}_x - \mu_{b_x})^2}{2 \cdot \sigma_{b_x}^2}}$	Prior probability function for b 's	C8

The μ 's and σ^2 , along with the bounds, initial values and estimation phases used for the parameters in the 2013 TCSAM are:

parameter	sex (x)	μ_x	σ_x^2	lower bound	upper bound	initial value	phase	code name
a_x	female	0.56560241	0.100	0.4	0.7	0.55	8	pGrAF1
	male	0.43794100	0.025	0.3	0.6	0.45	8	pGrAM1
b_x	female	0.9132661	0.025	0.6	1.2	0.90	8	pGrBF1
	male	0.9487000	0.100	0.7	1.2	0.95	8	pGrBM1
β_x	both	NA	NA	0.75000	0.75001	0.750005	-2	pGrBeta_x

Note that the β_x are treated as constants because the associated estimation phases are negative.

D. Model processes: maturity

Maturation of immature crab in TCSAM2013 is based on sex- and size-specific probabilities of maturation, $\phi_{x,z}$, where size z is pre-molt size. After molting, but before assessing growth, the numbers of crab remaining immature, $n_{x,IMM,NS,z}^+$, and those maturing, $n_{x,MAT,NS,z}^+$, at pre-molt size z are given by:

$n_{x,IMM,NS,z}^+ = (1 - \phi_{x,z}) \cdot n_{x,IMM,NS,z}$		D1a
$n_{x,MAT,NS,z}^+ = \phi_{x,z} \cdot n_{x,IMM,NS,z}$		D1b

where $n_{x,IMM,NS,z}$ is the number of immature, new shell crab of sex x at pre-molt size z .

Two options are now available to parameterize $\phi_{x,z}$ relative to model parameters $p_{x,z}^{mat}$. In the standard parameterization, the $p_{x,z}^{mat}$ are log-scale parameters related to the $\phi_{x,z}$ by:

$\phi_{FEMALE,z} = \begin{cases} e^{p_{FEMALE,z}^{mat}} & z \leq 100 \text{ mm CW} \\ 1 & z > 100 \text{ mm CW} \end{cases}$	female probabilities of maturing at pre-molt size z	D2a
$\phi_{MALE,z} = e^{p_{MALE,z}^{mat}}$	male probabilities of maturing at pre-molt size z	D2b

whereas, for the new option, the $p_{x,z}^{mat}$ are logit-scale parameters related to the $\phi_{x,z}$ by:

$\phi_{FEMALE,z} = \begin{cases} 1/(1 + e^{p_{FEMALE,z}^{mat}}) & z \leq 100 \text{ mm CW} \\ 1 & z > 100 \text{ mm CW} \end{cases}$	female probabilities of maturing at pre-molt size z	D3c
$\phi_{MALE,z} = 1/(1 + e^{p_{MALE,z}^{mat}})$	male probabilities of maturing at pre-molt size z	D3d

For both options, each $p_{FEMALE,z}^{mat}$ is an estimated parameter (16 parameters), as is each $p_{MALE,z}^{mat}$ (32 parameters).

Second difference penalties, $P2_x^{mat}$, on the parameter estimates are applied in the model's objective function to promote relatively smooth changes with size. Penalties on negative first differences, $P1_x^{mat}$, are applied to avoid a decline in the probability of molting-to-maturity at larger sizes. These penalties are of the form

$P1_x^m = posfun(\nabla p_{x,z}^{mat})$	1 st -difference penalties for decreasing probabilities with size	D4a
$P2_x^m = \sum_z [\nabla(\nabla p_{x,z}^{mat})]^2$	2 nd -difference (smoothness) likelihood penalty	D4b
$\nabla p_{x,z}^{mat} = p_{x,z}^{mat} - p_{x,z-1}^{mat}$	first differences	D4c

The bounds, initial values and estimation phases used for the parameters in the 2015 model for the standard option were:

parameters	lower bound	upper bound	initial value	phase	code name
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$p_{MALE,z}^{mat}$	-16	0	-1.0	5	pPrM2MF
$p_{FEMALE,z}^{mat}$	-16	0	-1.0	5	pPrM2MF

E. Model processes: recruitment

Recruitment of immature (new shell) crab in TCSAM2013 has the functional form:

$R_{y,x,z} = \dot{R}_{y,x} \cdot \ddot{R}_z$	recruitment of immature, new shell crab	E1
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where y is year, x is sex, and z is size. $\dot{R}_{y,x}$ represents total sex-specific recruitment in year y and \ddot{R}_z represents the size distribution of recruits, which is assumed identical for males and females.

Sex-specific recruitment, $\dot{R}_{y,x}$, is parameterized as

$\dot{R}_{y,x} = \begin{cases} e^{pLnR^H + \delta R_y^H} & y < y_{rec} \text{ (historic recruitment)} \\ e^{pLnR + \delta R_y} & y_{rec} \leq y \text{ (current recruitment)} \end{cases}$	sex-specific recruitment of immature, new shell crab	E2
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where y_{rec} is the first year of “current” recruitment, the sex ratio at recruitment is assumed to be 1:1 and the δR_y and δR_y^H are “devs” parameter vectors, with the constraint that the elements of a “devs” vector sums to zero. Previously, y_{rec} was hard-wired to 1974, but it is now an input in the model control file. Independent parameter sets are used for the “historic” period during model spin-up (1949-1973) and the “current” period (1974-2013).

The size distribution for recruits, \ddot{R}_z , is based on a gamma-type distribution and is parameterized as

$\ddot{R}_z = c^{-1} \cdot \Delta_z^{\frac{\alpha}{\beta}-1} \cdot e^{-\frac{\Delta_z}{\beta}}$	size distribution of recruiting crab	E3
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where α and β are parameters, $\Delta_z = z + 2.5 - z_{min}$, and $c = \sum_z \Delta_z^{\frac{\alpha}{\beta}-1} \cdot e^{-\frac{\Delta_z}{\beta}}$ is a normalization constant so that $1 = \sum_z \ddot{R}_z$. z_{min} is the smallest model size bin (27 mm) and the constant 2.5 represents one-half the size bin spacing.

Penalties are imposed on the “devs” parameter vectors δR_y and δR_y^H in the objective function as follows:

$P(\delta R) = \sum_y \delta R_y^2$	Penalty function on δR_y	E4
$P(\delta R^H) = \sum_y (\delta R_y^H - \delta R_{y-1}^H)^2$	1 st difference penalty function on δR_y^H	E5

The bounds, initial values and estimation phases used for the parameters used in the 2013 model are:

parameters	lower bound	upper bound	initial value	phase	code name
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$pLnR^H$	--	--	0.0/11.4	1	pMnLnRecHist
$pLnR$	--	--	11.4	1	pMnLnRec
δR_y^H	-15	15	0	1	pRecDevsHist
δR_y	-15	15	0	1	pRecDevs
α	11.49	11.51	11.50	-8	pRecAlpha
β	3.99	4.01	4.00	-8	pRecBeta

where parameters with phase < 0 are not estimated (i.e., treated as constants).

F. Model processes: fisheries

Four fisheries that catch Tanner crab are included in TCSAM2013: 1) the directed Tanner crab fishery, 2) the snow crab fishery, 3) the BBRKC fishery and 4) the various groundfish fisheries (lumped as one bycatch fishery). Crab (males only) are assumed to be retained exclusively in the directed fishery. Bycatch of non-retained Tanner crab (males and females) is assumed to occur in all four fisheries; discard mortality fractions for the (discarded) bycatch are assumed to differ between the crab and groundfish fisheries due to the differences in gear used (pots vs. primarily bottom trawl).

Two options now exist in the TCSAM2013 code to model fishing mortality: the standard option (used in previous assessments) and the Gmacs option. The fundamental difference between these models is illustrated in Figure A1. In both options, the predicted number of crab killed in fishery f by year in TCSAM2013 model has the functional form:

$m_{y,x,m,s,z}^f = \frac{F_{y,x,m,s,z}^f}{F_{y,x,m,s,z}^T} \cdot [1 - e^{-F_{y,x,m,s,z}^T}] \cdot n_{y,x,m,s,z}^1$	estimated crab mortality in fishery f	F1
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where y is year, x is sex, m is maturity state, s is shell condition and z is size, $F_{y,x,m,s,z}^f$ is sex/maturity state/shell condition/size-specific fishing mortality in year y , and $F_{y,x,m,s,z}^T = \sum_f F_{y,x,m,s,z}^f$ is total fishing mortality sex x crab in maturity state m and shell condition s at size z at the time the fisheries occur in year y . Note that $m_{y,x,m,s,z}^f$ represents the estimated *mortality* in numbers associated with fishery f , not the numbers *captured* (i.e., brought on deck). These differ because discard mortality is not 100% in the fisheries).

In the standard option, the total fishing *mortality* rate $F_{y,x,m,s,z}^f$ for each fishery is decomposed into two multiplicative components: 1) the mortality rate on fully-selected crab, $FM_{y,x}^f$, and 2) a size-specific selectivity function $S_{y,x,m,s,z}^f$, as follows:

$F_{y,x,m,s,z}^f = FM_{y,x}^f \cdot S_{y,x,m,s,z}^f$	fishing mortality rate in fishery f	F2s
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In the Gmacs option, the total *capture* $C_{y,x,m,s,z}^f$ rate for each fishery is similarly decomposed into two multiplicative components: 1) the capture rate on fully-selected crab, $FC_{y,x}^f$, and 2) a size-specific selectivity function $S_{y,x,m,s,z}^f$, as follows:

$C_{y,x,m,s,z}^f = FC_{y,x}^f \cdot S_{y,x,m,s,z}^f$	fishing mortality rate in fishery f	F2s
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For the Gmacs option, the fishing mortality rate $F_{y,x,m,s,z}^f$ is related to the capture rate $C_{y,x,m,s,z}^f$ by

$F_{y,x,m,s,z}^f = (r_{y,x,m,s,z}^f + hm_f \cdot [1 - r_{y,x,m,s,z}^f]) \cdot C_{y,x,m,s,z}^f$	fishing mortality rate in fishery f	F2g
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where $r_{y,x,m,s,z}^f$ is the “retention” function and hm_f is the rate of handling mortality on discarded (non-retained) crab.

Fully-selected fishing mortality

The manner in which the fully-selected fishing mortality (or capture) rate is further decomposed is time-dependent and specific to each fishery. Consequently, this decomposition is discussed below specific to each fishery.

Considering total fishing mortality (retained + discards) in the directed Tanner crab fishery (TCF) first, the fully-selected fishing mortality is modeled differently in three time periods. In the standard FMM, total sex-specific fishing mortality is parameterized as

$FM_{y,x}^{TCF} = \begin{cases} 0.05 & y < 1965 \\ 0 & 1965 \leq y, \text{ fishery closed} \\ e^{p\overline{\ln F}^{TCF} + \delta F_y^{TCF} + p\ln F_x^{TCF}} & 1965 \leq y, \text{ fishery open} \end{cases}$	fully-selected fishing mortality rate in the directed Tanner crab fishery	F3s
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where $p\overline{\ln F}^{TCF}$ is a parameter representing the mean ln-scale fishing mortality in the Tanner crab fishery since 1964 (catch data for this fishery begins in 1965), δF_y^{TCF} represents a “devs” parameter vector with elements defined for each year the fishery was open, and $p\ln F_x^{TCF}$ is an optional female-only log-scale offset (i.e., $p\ln F_{MALE}^{TCF} \equiv 0$) added this year. Prior to 1965, a small directed fishing mortality rate (0.05) is assumed.

The parameterization for sex-specific capture rates in the Gmacs FMM looks identical, but the parameters have different interpretations:

$FC_{y,x}^{TCF} = \begin{cases} 0.05 & y < 1965 \\ 0 & 1965 \leq y, \text{ fishery closed} \\ e^{p\overline{\ln F}^{TCF} + \delta F_y^{TCF} + p\ln F_x^{TCF}} & 1965 \leq y, \text{ fishery open} \end{cases}$	fully-selected capture rate in the directed Tanner crab fishery	F3g
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For Tanner crab bycatch in the snow crab fishery (SCF), the fully-selected discard fishing mortality is modeled differently in three time periods using:

$FM_{y,x}^{SCF} = \begin{cases} 0.01 & y < 1978 \\ r^{SCF} \cdot E_y^{SCF} \cdot e^{p\ln F_x^{SCF}} & 1978 \leq y \leq 1991 \\ e^{p\overline{\ln F}^{SCF} + \delta F_y^{SCF} + p\ln F_x^{SCF}} & 1992 \leq y \end{cases}$	fully-selected discard fishing mortality rate in the snow crab fishery	F4s
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where $p\overline{LnF}^{SCF}$ is a parameter representing the mean ln-scale bycatch fishing mortality in the snow crab fishery since 1992 (when reliable observer-based Tanner crab discard data in the snow crab fishery first became available), δF_y^{SCF} represents a “devs” parameter vector with elements defined for each year in this time period, and $pLnF_x^{SCF}$ is an optional female-only log-scale offset (i.e., $pLnF_{MALE}^{SCF} \equiv 0$) added this year. Prior to 1978, a small annual discard mortality rate associated with this fishery (0.01) is assumed. Annual effort data (total potlifts, E_y^{SCF}) is used to extend predictions of Tanner crab discard mortality in this fishery into the period 1978-1991. To do this, the assumption is made that effort in the snow crab fishery is proportional to Tanner crab discard fishing mortality and estimate the proportionality constant, r^{SCF} , using a ratio estimator between effort and discard mortality in the period 1992-present:

$r^{SCF} = \frac{\left\{ \frac{1}{N} \sum_{y=1992}^{present} FM_y^{SCF} \right\}}{\left\{ \frac{1}{N} \sum_{y=1992}^{present} E_y^{SCF} \right\}}$	ratio estimator relating fishing mortality rate to effort in the snow crab fishery	F5
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where N is the number of years, 1992-present.

For Tanner crab bycatch in the BBRKC fishery (RKF), the fully-selected discard fishing mortality when the fishery was open is modeled differently in three time periods using:

$FM_{y,x}^{RKF} = \begin{cases} 0.02 & y < 1953 \\ \max \left\{ 0.01, -\ln \left[1 - r^{RKF} \cdot E_y^{RKF} \cdot e^{pLnF_x^{RKF}} \right] \right\} & 1953 \leq y \leq 1991 \\ e^{p\overline{LnF}^{RKF} + \delta F_y^{RKF} + pLnF_x^{RKF}} & 1992 \leq y \end{cases}$	fully-selected discard fishing mortality rate in the BBRKC fishery	F6
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where $p\overline{LnF}^{RKF}$ is a parameter representing the mean ln-scale bycatch fishing mortality in the BBRKC fishery since 1992 (when observer-based Tanner crab discard data in the BBRKC fishery first became available), δF_y^{RKF} represents a “devs” parameter vector with elements defined for each year in this period that the fishery was open, and $pLnF_x^{RKF}$ is an optional female-only log-scale offset (i.e., $pLnF_{MALE}^{RKF} \equiv 0$) added this year.. Prior to 1953, a small annual discard mortality rate associated with this fishery (0.02) was assumed. Annual effort data (total potlifts, E_y^{RKF}) was used to extend predictions of Tanner crab discard mortality in this fishery into the period 1953-1991. To do this, we made the assumption that effort in the BBRKC fishery is proportional to Tanner crab discard fishing mortality and estimate the proportionality constant, r^{RKF} , using a ratio estimator between effort and discard mortality in the period 1992-present:

$r^{RKF} = \frac{\left\{ \frac{1}{N} \sum_{y=1992}^{present} \left[1 - e^{-FM_y^{RKF}} \right] \right\}}{\left\{ \frac{1}{N} \sum_{y=1992}^{present} E_y^{RKF} \right\}}$	ratio estimator relating fishing mortality rate to effort in the BBRKC fishery	F7
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where N is the number of years, 1992-present, when the BBRKC fishery was open. For any year that the BBRKC fishery was closed, $FM_{y,x}^{RKF}$ was set to 0.

Finally, for Tanner crab bycatch in the groundfish fisheries (GTF), the fully-selected discard fishing mortality in the fishery was modeled differently in two time periods using:

$FM_{y,x}^{GTF} = \begin{cases} \frac{1}{N} \sum_{y=1992}^{present} e^{p\overline{LnF}^{GTF} + \delta F_y^{GTF} + pLnF_x^{GTF}} & y < 1973 \\ e^{p\overline{LnF}^{GTF} + \delta F_y^{GTF} + pLnF_x^{GTF}} & 1973 \leq y \end{cases}$	fully-selected discard fishing mortality rate in the groundfish trawl fisheries	F8
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where $p\overline{\text{LnF}}^{GTF}$ is a parameter representing the mean fully-selected ln-scale bycatch fishing mortality in the groundfish fisheries since 1973 (when observer-based Tanner crab discard data in the groundfish fisheries first became available), δF_y^{GTF} is a “devs” parameter vector with elements representing the annual ln-scale deviation from the mean, and $p\text{LnF}_x^{GTF}$ is an optional female-only log-scale offset (i.e., $p\text{LnF}_{MALE}^{GTF} \equiv 0$) added this year. Prior to 1973, the fully-selected discard mortality rate associated with these fisheries was assumed to be constant and equal to the mean over the 1973-present period.

When the Gmacs FMM option is selected instead of the standard FMM, the previous parameterizations apply to the $FC_{y,x}^f$'s, not the $FM_{y,x}^f$'s.

The bounds (when set), initial values and estimation phases used for the fully-selected fishing mortality parameters and devs vectors in the 2013 model were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\overline{\text{LnF}}^{TCF}$	--	--	-0.7	1	pAvgLnF_TCF
δF_y^{TCF}	-15	15	0	2	pF_DevsTCF
$p\overline{\text{LnF}}^{SCF}$	--	--	-3.0	3	pAvgLnF_SCF
δF_y^{SCF}	-15	15	0	4	pF_DevsSCF
$p\overline{\text{LnF}}^{RKF}$	-5.25	-5.25	-5.25	-4	pAvgLnF_RKF
δF_y^{RKF}	-15	15	0	-5	pF_DevsRKF
$p\overline{\text{LnF}}^{GTF}$	--	--	-4.0	2	pAvgLnF_GTF
δF_y^{GTF}	-15	15	0	3	pF_DevsGTF

where all parameters and parameter vectors were estimated (phase > 0), except for those associated with the BBRKC fishery.

Fishery selectivity

The manner in which fishery selectivity is parameterized is also time-dependent and specific to each fishery, as with the fully-selected fishing mortality. However, the time periods used to define selectivity are not necessarily those used for the fully-selected fishing mortality.

In the directed Tanner crab fishery (TCF), total (retained + discards) selectivity (under the standard FMM) or capture selectivity (under the Gmacs FMM) is modeled using sex-specific ascending logistic functions. For males, in addition, total selectivity is parameterized differently in three time periods, corresponding to differences in information about the fishery (pre-/post-1991) and differences in the fishery itself (pre-/post-rationalization in 2005):

$S_{y,FEMALE,m,s,z}^{TCF} = \left\{ 1 + e^{-p\beta_{FEMALE}^{TCF} \cdot (z - pZ_{50,FEMALE}^{TCF})} \right\}^{-1}$	total selectivity for females in the directed Tanner crab fishery	F9
$S_{y,MALE,m,s,z}^{TCF} = \begin{cases} \left\{ 1 + e^{-p\beta_{MALE}^{TCF(1)} \cdot (z - \bar{z}_{50,MALE}^{TCF})} \right\}^{-1} & y \leq 1990 \\ \left\{ 1 + e^{-p\beta_{MALE}^{TCF(1)} \cdot (z - z_{50,y,MALE}^{TCF})} \right\}^{-1} & 1991 \leq y \leq 1996 \\ \left\{ 1 + e^{-p\beta_{MALE}^{TCF(2)} \cdot (z - z_{50,y,MALE}^{TCF})} \right\}^{-1} & 2005 \leq y \leq 2009 \end{cases}$	total selectivity for males in the directed Tanner crab fishery	F10

where the $p\beta_x^{TCF(t)}$ are parameters controlling the slopes of the associated logistic selectivity curves, $pZ_{50,FEMALE}^{TCF}$ is the parameter controlling the size of females at 50% selection, $\bar{z}_{50,MALE}^{TCF}$ controls the size of 50%-selected males in the pre-1991 period, and $z_{50,y,MALE}^{TCF}$ controls the size of 50%-selected males in the post-1990 period. The latter three quantities are functions of estimable parameters as described in the following:

$\bar{z}_{50,MALE}^{TCF} = \frac{1}{6} \sum_{y=1991}^{1996} z_{50,y,MALE}^{TCF}$	male size at 50%-selected used in pre-1991 period	F11
$z_{50,y,MALE}^{TCF} = e^{pLnZ_{50,MALE}^{TCF} + \delta Z_{50,y,MALE}^{TCF}}$	male size at 50%-selected used in post-1990 period	F12

where $pLnZ_{50,MALE}^{TCF}$ is a parameter controlling the ln-scale mean male size at 50% selectivity post-1990 and $\delta Z_{50,y,MALE}^{TCF}$ is a parameter vector controlling annual ln-scale deviations in male size at 50% selectivity post-1990. As formulated, selectivity in the directed fishery is not a function of maturity state or shell condition.

The bounds, initial values and estimation phases used in the 2013 model for the 5 parameters describing total selectivity in the directed Tanner crab fishery were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\beta_{FEMALE}^{TCF}$	0.1	0.4	0.25	3	slpTCFF_z50
$pZ_{50FEMALE}^{TCF}$	80	150	115	3	selTCFF_z50
$p\beta_{MALE}^{TCF(1)}$	0.05	0.75	0.4	3	selTCFF_z50
$p\beta_{MALE}^{TCF(2)}$	0.1	0.4	0.25	3	fish_slope_yr_3
$pLnZ_{50MALE}^{TCF}$	4.0	5.0	4.5	3	log_avg_sel50_3

where all parameters were estimated. The bounds, initial values and estimation phase used in the 2013 model for the ln-scale “devs” parameter vector $\delta Z_{50y,MALE}^{TCF}$ describing annual deviations in male size at 50%-selected (1991-1996, 2005-2009) were:

parameters	lower bound	upper bound	initial value	phase	code name
$\delta Z_{50y,MALE}^{TCF}$	-0.5	0.5	0	3	log_sel50_dev_3

In the snow crab fishery (SCF), bycatch (discard) selectivity is modeled using three time periods (model start to 1996, 1997-2004, 2005 to present). Male selectivity is described using dome-shaped (double logistic) functions in each period, with:

$S_{y,MALE,m,s,z}^{SCF} = \begin{cases} S_{MALE,z}^{SCF(1)} & y \leq 1996 \\ S_{MALE,z}^{SCF(2)} & 1997 \leq y \leq 2004 \\ S_{MALE,z}^{SCF(3)} & 2005 \leq y \end{cases}$	male selectivity in the snow crab fishery	F13
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where the double logistic functions $S_{MALE,z}^{SCF(t)}$ are parameterized using:

$S_{MALE,z}^{SCF(t)} = \left\{ 1 + e^{-p\beta_{MALE}^{SCF(ta)} \cdot (z - pZ_{50MALE}^{SCF(ta)})} \right\}^{-1} \cdot \left\{ 1 + e^{+p\beta_{MALE}^{SCF(td)} \cdot (z - \exp[pZ_{50MALE}^{SCF(td)}])} \right\}^{-1}$	dome-shaped	F14
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where $p\beta_x^{SCF(ta)}$ and $pZ_{50x}^{SCF(ta)}$ are the 6 parameters controlling the ascending limb of the double logistic function and $p\beta_x^{SCF(td)}$ and $pZ_{50x}^{SCF(td)}$ are the 6 parameters controlling the descending limb for each period t . Note that $pZ_{50x}^{SCF(td)}$ is evaluate on the log-scale to ensure positivity.

Female selectivity is described using ascending logistic functions in each period, with:

$S_{y,FEMALE,m,s,z}^{SCF} = \begin{cases} S_{FEMALE,z}^{SCF(1)} & y \leq 1996 \\ S_{FEMALE,z}^{SCF(2)} & 1997 \leq y \leq 2004 \\ S_{FEMALE,z}^{SCF(3)} & 2005 \leq y \end{cases}$	female selectivity in the snow crab fishery	F15
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where the ascending logistic functions $S_{FEMALE,z}^{SCF(t)}$ are parameterized using:

$S_{FEMALE,z}^{SCF(t)} = \left\{ 1 + e^{-p\beta_{FEMALE}^{SCF(t)} \cdot (z - pZ_{50}^{SCF(t)})} \right\}^{-1}$	ascending logistic selectivity	F16
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where the $p\beta_x^{SCF(p)}$ are the 3 parameters controlling the slopes of the associated logistic selectivity curves and the $pZ_{50}^{SCF(p)}$ are the 3 parameters controlling size at 50%-selection.

As formulated, selectivity in the snow crab fishery is not a function of maturity state or shell condition.

The bounds, initial values and estimation phases used in the 2013 model for the 12 parameters describing male selectivity in the snow crab fishery were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\beta_{MALE}^{SCF(1a)}$	0.01	0.50	0.255	4	selSCFM_slpA1
$pZ_{50MALE}^{SCF(1a)}$	60	150	122.5	4	selSCFM_z50A1
$p\beta_{MALE}^{SCF(1d)}$	0.01	0.50	0.255	4	selSCFM_slpD1
$pZ_{50MALE}^{SCF(1d)}$	40	200	120	4	selSCFM_lnZ50D1
$p\beta_{MALE}^{SCF(2a)}$	0.01	0.50	0.255	4	selSCFM_slpA2
$pZ_{50MALE}^{SCF(2a)}$	60	150	122.5	4	selSCFM_z50A2
$p\beta_{MALE}^{SCF(2d)}$	0.01	0.50	0.255	4	selSCFM_slpD2
$pZ_{50MALE}^{SCF(2d)}$	40	200	120	4	selSCFM_lnZ50D2
$p\beta_{MALE}^{SCF(3a)}$	0.01	0.50	0.255	4	selSCFM_slpA3
$pZ_{50MALE}^{SCF(3a)}$	60	150	122.5	4	selSCFM_z50A3
$p\beta_{MALE}^{SCF(3d)}$	0.01	0.50	0.255	4	selSCFM_slpD3
$pZ_{50MALE}^{SCF(3d)}$	40	200	120	4	selSCFM_lnZ50D3

where all parameters were estimated.

The bounds, initial values and estimation phases used in the 2013 model for the 6 parameters describing female selectivity in the snow crab fishery were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\beta_{FEMALE}^{SCF(1)}$	0.05	0.5	0.275	4	selSCFF_slpA1
$pZ_{50FEMALE}^{SCF(1)}$	50	150	100	4	selSCFF_z50A1
$p\beta_{FEMALE}^{SCF(2)}$	0.05	0.5	0.275	4	selSCFF_slpA2
$pZ_{50FEMALE}^{SCF(2)}$	50	120	85	4	selSCFF_z50A2
$p\beta_{FEMALE}^{SCF(3)}$	0.05	0.5	0.275	4	selSCFF_slpA3
$pZ_{50FEMALE}^{SCF(3)}$	50	120	85	4	selSCFF_z50A3

where all parameters were estimated.

In the BBRKC fishery (RKF), bycatch (discard) selectivity is also modeled using the three time periods used to model selectivity in the snow crab fishery (model start to 1996, 1997-2004, 2005 to present), with sex-specific parameters estimated in each period. All sex/period combinations are modeled using ascending logistic functions:

$S_{y,x,m,s,z}^{RKF} = \begin{cases} \left\{ 1 + e^{-p\beta_x^{RKF(1)} \cdot (z - pZ_{50x}^{RKF(1)})} \right\}^{-1} & y \leq 1996 \\ \left\{ 1 + e^{-p\beta_x^{RKF(2)} \cdot (z - pZ_{50x}^{RKF(2)})} \right\}^{-1} & 1997 \leq y \leq 2004 \\ \left\{ 1 + e^{-p\beta_x^{RKF(3)} \cdot (z - pZ_{50x}^{RKF(3)})} \right\}^{-1} & 2005 \leq y \end{cases}$	selectivity in the BBRKC fishery	F17
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where the $p\beta_x^{RKF(p)}$ are 6 parameters controlling the slopes of the associated logistic selectivity curves and the $pZ_{50x}^{RKF(p)}$ are 6 parameters controlling size at 50%-selection. As formulated, selectivity in the BBRKC fishery is not a function of maturity state or shell condition.

The bounds, initial values and estimation phases used in the 2013 model for the 12 parameters describing male selectivity in the BBRKC fishery were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\beta_{MALE}^{RKF(1)}$	0.01	0.50	0.255	3	selRKFM_slpA1
$pZ_{50MALE}^{RKF(1)}$	95	150	122.5	3	selRKFM_z50A1
$p\beta_{MALE}^{RKF(2)}$	0.01	0.50	0.255	3	selRKFM_slpA2
$pZ_{50MALE}^{RKF(2)}$	95	150	122.5	3	selRKFM_z50A2
$p\beta_{MALE}^{RKF(3)}$	0.01	0.50	0.255	3	selRKFM_slpA3
$pZ_{50MALE}^{RKF(3)}$	95	150	122.5	3	selRKFM_z50A3

where all parameters were estimated.

The bounds, initial values and estimation phases used in the 2013 model for the 6 parameters describing female selectivity in the BBRKC fishery were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\beta_{FEMALE}^{RKF(1)}$	0.005	0.50	0.2525	3	selRKFF_slpA1
$pZ_{50FEMALE}^{RKF(1)}$	50	150	100	3	selRKFF_z50A1
$p\beta_{FEMALE}^{RKF(2)}$	0.005	0.50	0.255	3	selRKFF_slpA2
$pZ_{50FEMALE}^{RKF(2)}$	50	150	100	3	selRKFF_z50A2
$p\beta_{FEMALE}^{RKF(3)}$	0.01	0.50	0.255	3	selRKFF_slpA3
$pZ_{50FEMALE}^{RKF(3)}$	50	170	110	3	selRKFF_z50A3

where all parameters were estimated.

In the groundfish fisheries (GTF), bycatch (discard) selectivity is also modeled using three time periods (model start to 1986, 1987-1996, 1997 to present), but these are different from those used in the snow

crab and BBRKC fisheries. Sex-specific parameters are estimated in each period; all sex/period combinations are modeled using ascending logistic functions:

$S_{y,x,m,s,z}^{GTF} = \begin{cases} \left\{1 + e^{-p\beta_x^{GTF(1)} \cdot (z - pZ_{50x}^{GTF(1)})}\right\}^{-1} & y \leq 1986 \\ \left\{1 + e^{-p\beta_x^{GTF(2)} \cdot (z - pZ_{50x}^{GTF(2)})}\right\}^{-1} & 1987 \leq y \leq 1996 \\ \left\{1 + e^{-p\beta_x^{GTF(3)} \cdot (z - pZ_{50x}^{GTF(3)})}\right\}^{-1} & 1997 \leq y \end{cases}$	selectivity in the groundfish fisheries	F18
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where the $p\beta_x^{GTF(p)}$ are 6 parameters controlling the slopes of the associated logistic selectivity curves and the $pZ_{50x}^{GTF(p)}$ are 6 parameters controlling size at 50%-selection. As formulated, selectivity in the groundfish fisheries is not a function of maturity state or shell condition.

The bounds, initial values and estimation phases used in the 2013 model for the 12 parameters describing male selectivity in the groundfish fisheries were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\beta_{MALE}^{GTF(1)}$	0.01	0.50	0.255	3	selGTFM_slpA1
$pZ_{50MALE}^{GTF(1)}$	40	120.01	80.005	3	selGTFM_z50A1
$p\beta_{MALE}^{GTF(2)}$	0.01	0.50	0.255	3	selGTFM_slpA2
$pZ_{50MALE}^{GTF(2)}$	40	120.01	80.005	3	selGTFM_z50A2
$p\beta_{MALE}^{GTF(3)}$	0.01	0.50	0.255	3	selGTFM_slpA3
$pZ_{50MALE}^{GTF(3)}$	40	120.01	80.005	3	selGTFM_z50A3

where all parameters were estimated.

The bounds, initial values and estimation phases used in the 2013 model for the 6 parameters describing female selectivity in the groundfish fisheries were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\beta_{FEMALE}^{GTF(1)}$	0.01	0.50	0.255	3	selGTFF_slpA1
$pZ_{50FEMALE}^{GTF(1)}$	40	125.01	82.505	3	selGTFF_z50A1
$p\beta_{FEMALE}^{GTF(2)}$	0.005	0.50	0.255	3	selGTFF_slpA2
$pZ_{50FEMALE}^{GTF(2)}$	40	250.01	145.005	3	selGTFF_z50A2
$p\beta_{FEMALE}^{GTF(3)}$	0.01	0.50	0.255	3	selGTFF_slpA3
$pZ_{50FEMALE}^{GTF(3)}$	40	150.01	95.005	3	selGTFF_z50A3

where all parameters were estimated.

Retention in the directed fishery

Retention of male crab in the directed fishery is modeled as a multiplicative size-specific process “on top” of total (retention + discards) fishing selectivity. The number of crab (males only) retained in the directed Tanner crab fishery is given by

$r_{y,m,s,z}^{TCF} = \frac{R_{y,m,s,z}^{TCF}}{F_{y,MALE,m,s,z}^T} \cdot \left[1 - e^{-F_{y,MALE,m,s,z}^T} \right] \cdot n_{y,MALE,m,s,z}^1$	retained male crab (numbers) in the directed fishery	F19
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where $R_{y,m,s,z}^{TCF}$ is the retained mortality rate associated with retention, which is related to the total fishing mortality rate on male crab in the directed fishery, $F_{y,MALE,m,s,z}^{TCF}$, by

$R_{y,m,s,z}^{TCF} = \rho_{y,m,s,z}^{TCF} \cdot F_{y,MALE,m,s,z}^{TCF} = FM_y^{TCF} \cdot \rho_{y,m,s,z}^{TCF} \cdot S_{y,MALE,m,s}^{TCF}$	retained mortality rate in the directed fishery	F20
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where $\rho_{y,m,s,z}^{TCF}$ represents size-specific retention of male crab. Retention at size, $\rho_{y,m,s,z}^{TCF}$, in the directed fishery is modeled as an ascending logistic function, with different parameters in two time periods, as follows:

$\rho_{y,m,s,z}^{TCF} = \begin{cases} \left\{ 1 + e^{-p\beta^{TCFR(1)} \cdot (z - pZ_{50}^{TCFR(1)})^{-1}} \right\}^{-1} & y \leq 1990 \\ \left\{ 1 + e^{-p\beta^{TCFR(2)} \cdot (z - pZ_{50}^{TCFR(2)})^{-1}} \right\}^{-1} & 1991 \leq y \end{cases}$	size-specific retention in the directed fishery	F21
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where $p\beta^{TCFR(t)}$ is the parameter controlling the slope of the function in the each period ($t=1,2$) and $pZ_{50}^{TCFR(t)}$ is the parameter controlling the size at 50%-selected. As formulated, retention is not a function of maturity state or shell condition.

The bounds, initial values and estimation phases used for the size-specific retention parameters in the 2013 model were:

parameters	lower bound	upper bound	initial value	phase	code name
$p\beta^{TCFR(1)}$	0.25	1.01	0.63	3	fish_fit_slope_mn1
$pZ_{50}^{TCFR(1)}$	85	160	122.5	3	fish_fit_sel50_mn1
$p\beta^{TCFR(2)}$	0.25	2.01	1.13	3	fish_fit_slope_mn2
$pZ_{50}^{TCFR(2)}$	85	160	122.5	3	fish_fit_sel50_mn2

where all parameters were estimated.

G. Model indices: surveys

The predicted number of crab caught in the survey by year in the 2013 TCSAM model has the functional form:

$n_{y,x,m,s,z}^{srv} = q_{y,x} \cdot S_{y,x,z} \cdot n_{y,x,m,s,z}$	predicted number of crab caught in survey	G1
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where y is year, x is sex, m is maturity state, s is shell condition and z is size, $q_{y,x}$ is sex-specific survey catchability in year y , $S_{y,x,z}$ is sex-specific size selectivity in year y , and $n_{y,x,m,s,z}$ is the number of sex x crab in maturity state m and shell condition s at size z at the time of the survey in year y .

Three time periods that were used to test hypotheses regarding changes in catchability and selectivity in the survey over time are defined in the model. These periods are defined as: 1) $y < 1982$, 2) $1982 \leq y \leq 1987$, and 3) $1988 \leq y$. As parameterized in the 2013 model, catchabilities in periods 2 and 3 were assumed to be identical, so only two sets of sex-specific parameters reflecting catchability were used in the model. In terms of the three time periods, catchability was parameterized using the sex-specific parameters q_x^I and q_x^{II} in the following manner:

$q_{y,x} = \begin{cases} q_x^I & y < 1982 \\ q_x^{II} & 1982 \leq y \leq 1987 \\ q_x^{II} & 1988 \leq y \end{cases}$	survey catchability	G2
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The bounds, initial values and estimation phases used for these parameters in the 2013 model were:

parameters	lower bound	upper bound	initial value	phase	code name
q_{MALE}^I	0.50	1.001	0.7505	4	srv2_q

q_{FEMALE}^I	0.50	1.001	0.7505	4	srv2_femQ
q_{MALE}^{II}	0.20	2.00	1.1	4	srv3_q
q_{FEMALE}^{II}	0.20	1.00	0.6	4	srv3_femQ

where all parameters were estimated (phase > 0).

Similarly, survey selectivity in periods 2 and 3 was assumed identical and only two sets of sex-specific parameters were used to describe survey selectivity using logistic functions:

$S_{y,z} = \begin{cases} \left\{ 1 + e^{-[\ln(19) \cdot (z - z_{50}^I) / \delta z_{95}^I]} \right\}^{-1} & y < 1982 \\ \left\{ 1 + e^{-[\ln(19) \cdot (z - z_{50}^{II}) / \delta z_{95}^{II}]} \right\}^{-1} & 1982 \leq y \leq 1987 \\ \left\{ 1 + e^{-[\ln(19) \cdot (z - z_{50}^{II}) / \delta z_{95}^{II}]} \right\}^{-1} & 1987 \leq y \end{cases}$	survey selectivity	G3
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where the z_{50} 's are parameters reflecting the inflection point of the logistic curve (i.e., size at 50% selected) and the δz_{95} 's are parameters reflecting the difference the sizes at 50% and 95% selected.

The bounds, initial values and estimation phases used for the selectivity parameters used in the 2013 model were:

parameters	lower bound	upper bound	initial value	phase	code name
$Z_{50}^I_{MALE}$	0	90	45	4	srv2_sel150
$Z_{50}^I_{FEMALE}$	-200	100.01	-49.005	4	srv2_sel150_f
$\delta Z_{95}^I_{MALE}$	0	100	50	4	srv2_seldiff
$\delta Z_{95}^I_{FEMALE}$	0	100	50	4	srv2_seldiff_f
$Z_{50}^{II}_{MALE}$	0	69	34.5	4	srv3_sel150
$Z_{50}^{II}_{FEMALE}$	-50	69	9.5	4	srv3_sel150_f
$\delta Z_{95}^{II}_{MALE}$	0	100	50	4	srv3_seldiff
$\delta Z_{95}^{II}_{FEMALE}$	0	100	50	4	srv3_seldiff_f

where all parameters were estimated (phase > 0).

H. Model fitting: objective function equations

The TCSAM2013 model is fit by minimizing an objective function, σ , with additive components consisting of: 1) several penalty functions, 2) several negative log-likelihood functions based on assumed prior probability distributions for model parameters, and 3) several negative log-likelihood functions based on input data components, of the form:

$\sigma = \sum_f \lambda_f \cdot \mathcal{F}_f - 2 \sum_p \lambda_p \cdot \ln(\wp_p) - 2 \sum_l \lambda_l \cdot \ln(\mathcal{L}_l)$	model objective function	H1
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where \mathcal{F}_f represents the f th penalty function, \wp_p represents the p th prior probability function, \mathcal{L}_l represents the l th likelihood function, and the λ 's represent user-adjustable weights for each component.

Penalty Functions

The penalty functions associated with various model quantities are identified in the section (B-F) concerning the associated process.

Prior Probability Functions

The prior probability functions associated with various model parameters are identified in the section (B-F) concerning the associated parameter.

Likelihood Functions

The model's objective function includes likelihood components based on 1) retained catch size frequencies (i.e., males only) in the directed fishery from dockside observer sampling; 2) total catch (retained + discarded) size frequencies by sex in each fishery from at-sea observer sampling; 3) size frequencies for immature males, mature males, immature females, and mature females, respectively, from trawl survey data; 4) dockside retained catch biomass (i.e., males only) in the directed fishery from fish ticket data; 5) estimated total catch (retained + discarded) mortality in biomass by sex in the crab and groundfish fisheries from at-sea observer sampling; and 6) estimated mature biomass by sex from trawl survey data. As discussed in more detail below, size frequency-related likelihood components are based on the multinomial distribution while those related to biomass are based on either the normal or lognormal distributions.

Size frequency components

Fishery-related (log-scale) likelihood components involving sex-specific size frequencies are based on the following equation for multinomial sampling:

$\ln(\mathcal{L}^M)_x^f = \sum_y n_{y,x}^f \cdot \sum_z p_{y,x,z}^{obs.f} \cdot \ln(p_{y,x,z}^{mod.f} + \delta) - p_{y,x,z}^{obs.f} \cdot \ln(p_{y,x,z}^{obs.f} + \delta)$	multinomial log-likelihood	H2
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where f indicates the fishery, x indicates sex, the y 's are years for which data exists, $n_{y,x}^f$ is the sex-specific effective sample size for year y , $p_{y,x,z}^{obs.f}$ is the observed size composition in size bin z (i.e., the size frequency normalized to sum to 1 across size bins for each year), $p_{y,x,z}^{mod.f}$ is the corresponding model estimate, and δ is a small constant.

Size compositions for retained catch (male only) in the directed Tanner crab fishery are obtained from dockside observer sampling and calculated from shell condition-specific size frequencies $r_{y,MALE,s,z}^{obs.TCF}$ using:

$p_{y,MALE,z}^{obs.TCF} = \frac{\sum_s r_{y,MALE,s,z}^{obs.TCF}}{\sum_s \sum_z r_{y,MALE,s,z}^{obs.TCF}}$	retained size compositions for the directed fishery from dockside observer sampling	H3
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where s indicates shell condition (new shell, old shell) and z indicates the size bin. The corresponding model size compositions are calculated from the predicted numbers retained in the directed fishery $r_{y,MALE,m,s,z}^{mod.TCF}$ using

$p_{y,MALE,z}^{mod.TCF} = \frac{\sum_m \sum_s r_{y,MALE,m,s,z}^{mod.TCF}}{\sum_m \sum_s \sum_z r_{y,MALE,m,s,z}^{mod.TCF}}$	model-predicted retained catch size compositions for the directed fishery	H4
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where, additionally, m is maturity state (immature, mature).

Size compositions for total (retained + discarded) catch in fishery f ($f = 1-4$) are sex-specific and are calculated from sex/shell condition-specific size frequencies $r_{y,x,s,z}^{obs.f} + d_{y,x,s,z}^{obs.f}$ obtained from at-sea observer sampling using:

$p_{y,x,z}^{obs.f} = \frac{\sum_s [r_{y,x,s,z}^{obs.f} + d_{y,x,s,z}^{obs.f}]}{\sum_s \sum_z [r_{y,x,s,z}^{obs.f} + d_{y,x,s,z}^{obs.f}]}$	sex-specific size compositions for total catch for fishery f from at-sea observer sampling	H5
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where s indicates shell condition (new shell, old shell) and z indicates the size bin. In the above equation, $d_{y,x,s,z}^{obs.f}$ has *not* been discounted for discard survival (i.e., it's consistent with setting discard mortality to 100%). The corresponding model size compositions are calculated from the predicted total fishing mortality (numbers) in each fishery f , $m_{y,x,m,s,z}^{mod.f} (= r_{y,x,m,s,z}^{mod.f} + \delta_f \cdot d_{y,x,m,s,z}^{mod.f})$, using

$p_{y,x,z}^{mod.f} = \frac{\sum_m \sum_s m_{y,x,m,s,z}^{mod.f}}{\sum_m \sum_s \sum_z m_{y,x,m,s,z}^{mod.f}}$	model-predicted total catch mortality size compositions for fishery f	H6
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where, again, the subscript m is maturity state (immature, mature). In eq. H6, $m_{y,x,m,s,z}^{mod.f}$ does not assume any particular value for discard mortality.

Log-scale likelihood components for the trawl survey involve size frequencies that are sex- and maturity state-specific, and thus are based on the following equation for multinomial sampling:

$\ln(\mathcal{L}^M)_{x,m}^{srv} = \sum_y n_{y,x,m}^{srv} \cdot \sum_z \{p_{y,x,m,z}^{obs.srv} \cdot \ln(p_{y,x,m,z}^{mod.srv} + \delta) - p_{y,x,m,z}^{obs.srv} \cdot \ln(p_{y,x,m,z}^{obs.srv} + \delta)\}$	multinomial log-likelihood	H7
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where x indicates sex, the y 's are years for which data exists, $n_{y,x,m}^{srv}$ is the sex- and maturity-state specific effective sample size for year y , $p_{y,x,z}^{obs.srv}$ is the observed size composition in size bin z (i.e., the size frequency normalized to sum to 1 across size bins for each year), $p_{y,x,z}^{mod.srv}$ is the corresponding model estimate, and δ is a small constant.

Fishery biomass components

Likelihood components related to fishery biomass totals are based on the assumption of normally-distributed sampling, and generally have the simple form:

$\ln(\mathcal{L}^N)_x^f = -0.5 \sum_y [b_{y,x}^{obs.f} - b_{y,x}^{mod.f}]^2$	normal log-likelihood	H8
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where $b_{y,x}^{obs.f}$ is the sex-specific catch mortality (as biomass) in fishery f for year y and $b_{y,x}^{mod.f}$ is the corresponding value predicted by the model. Components of this sort are calculated for retained biomass in the directed fishery, total (retained + discard) sex-specific fishery-related mortality in the model crab fisheries, and discard-related (not sex-specific) mortality in the groundfish fishery. The observed components of discard-related mortality for each fishery are obtained by multiplying the observed discard biomass by the assumed discard mortality fraction.

This year, an option to apply a lognormal likelihood to fishery biomass totals was implemented using:

$\ln(\mathcal{L}^N)_x^f = -0.5 \sum_y \frac{[\ln(b_{y,x}^{obs.f} + \delta) - \ln(b_{y,x}^{mod.f} + \delta)]^2}{2 \cdot \ln(1 + cv_f^2)}$	lognormal log-likelihood	H9
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where the cv_f 's represent assumed error cv's, by fishery.

Survey biomass components

Likelihood components related to survey biomass are based on the assumption of lognormally-distributed sampling errors, and have the form:

$\ln(\mathcal{L}^N)_x^{srv} = - \sum_y \frac{[\ln(b_{y,x}^{obs.srv} + \delta) - \ln(b_{y,x}^{mod.srv} + \delta)]^2}{2 \cdot \ln(1 + cv_{y,x}^2)}$	lognormal log-likelihood	H9
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where $b_{y,x}^{obs.srv}$ is sex-specific mature biomass estimated from the trawl survey data for year y , $b_{y,x}^{mod.srv}$ is the corresponding value predicted by the model, and $cv_{y,x}$ is the cv of the observation. Survey numbers-at-size $n_{y,x,m,s,z}^{obs.srv}$, classified by sex, shell condition and maturity state, are combined with sex- and maturity state-specific weight-at-size relationships $w_{x,m,z}$ to estimate sex-specific mature biomass $b_{y,x}^{obs.srv}$ using

$b_{y,x}^{obs.srv} = \sum_s \sum_z n_{y,x,MATURE,s,z}^{obs.srv} \cdot w_{x,MATURE,z}$	mature biomass	H10
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An equivalent equation is used to calculate $b_{y,x}^{mod.srv}$.

Literature cited

Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. *Optim. Methods Softw.* 27:233-249.

Rugolo, L.J., and B.J. Turnock. 2012. 2012 Stock Assessment and Fishery Evaluation Report for the Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. In: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands: 2012 Crab SAFE. North Pacific Fishery Management Council. Anchorage, AK. pp. 267-416.

Stockhausen, W.T., B.J. Turnock and L. Rugolo. 2015. 2015 Stock Assessment and Fishery Evaluation Report for the Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. In: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands: 2013 Crab SAFE. North Pacific Fishery Management Council. Anchorage, AK.

Whitten, A.R., A.E. Punt, J.N. Ianelli. 2013. Gmacs: Generalized Modeling for Alaskan Crab Stocks. http://www.afsc.noaa.gov/REFM/stocks/Plan_Team/crab/Whitten%20et%20al%202014%20-%20Gmacs%20Model%20Description.pdf

Figures

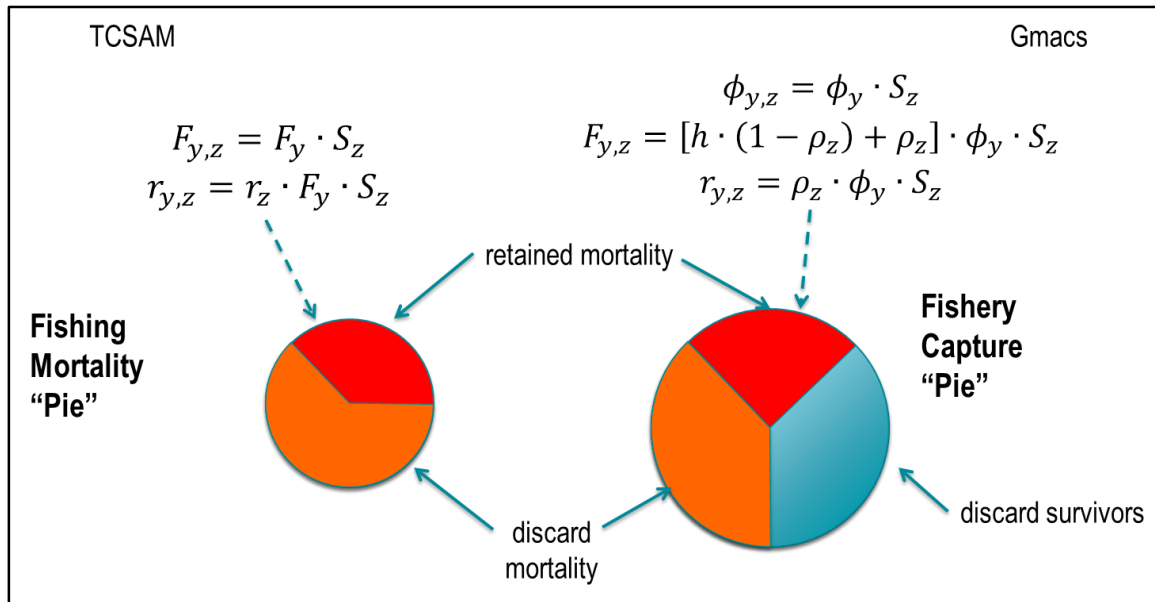


Figure A1. Comparison of models for fishing mortality in TCSAM2013 (left) and Gmacs (right). The *areas* associated with retained mortality and discard mortality are the same in both pies. r_z is the fraction of the fishing mortality pie related to retained crab. ρ_z is the fraction of the fishery capture pie related to retained crab.