

Exploring assumptions about population processes in the stock assessment for the eastern Bering Sea snow crab fishery

Cody Szuwalski
April 19, 2019

Executive summary

The SSC and CPT had many comments related to the assessment for snow crab based on the presentation from September 2018. Many of these were requests to explore the knowledge base and impact of assumptions related to population processes. Others were requests for model runs. One of the persistent questions around the snow crab assessment revolves around the stability of parameter estimates resulting from model structure and the information content of data. In the following documents, I outline the knowledge base for snow crab population processes in the Bering Sea, examine some assumptions made in the assessment, perform model scenarios requested by the CPT, and present preliminary analyses from a simplified assessment meant to aid in evaluating the information content in the data related to key management outputs. Three documents describing these points are enclosed and should be read in the following order:

1. ***“Exploring assumptions about population process in the stock assessment for the eastern Bering Sea snow crab fishery.”***

This document is a summary and response to high level comments from the SSC and CPT and organized by population process. Identified sources of uncertainty in the assessment are summarized. Conflicts between sources of information were identified (e.g. shell condition, age estimates, and natural mortality) and priorities for research are discussed.

2. ***“Appendix 1. A summary of model runs requested by the CPT.”***

This appendix presents specific model scenarios requested by the CPT. Priors on the sex ratio for recruitment are included, but identifying appropriate priors is difficult. Growth data are both weighted more heavily and fixed such that a linear relationship between pre-molt and post-molt carapace width is realized, but both of these model formulations did not converge. Finally, a run with VAST estimates of numbers and CVs is included and resulted in ~17% decreases in the OFL compared to design-based estimators.

3. ***“Appendix 2. A description and preliminary model runs of a simplified snow crab assessment model.”***

A simple model that begins by removing data related to the BSFRF survey, females, shell condition, and simplifies models of population processes like growth and selectivity is presented with the intent to evaluate the stability of estimated parameters within a simple model, then build up in complexity. The most stripped down model displays no instability under jittering, but some instability reappears with the addition of the BSFRF data and management quantities depart strongly from the status quo. This is a work in progress and should not be considered for management advice.

Based on these documents, recommended modeling efforts in the immediate future include: 1) work identifying stable model and data configurations through progressive addition of complexity to the simplified assessment described in appendix 2, and 2) further work developing GMACS to accommodate species with a terminal molt. Priorities for biological research efforts include studies aimed at estimating natural mortality and time-varying catchability.

Preface

SSC and CPT comments are listed below under the relevant population process, in no particular order. Brief background is provided on each population process with responses to SSC or CPT inquiries. Given the large number of research questions posed by the CPT and SSC, this document concludes with an attempt at prioritizing these questions, with attention paid to attempting to ameliorate the instability in the snow crab model as seen through retrospective patterns and instability of management quantities to jittered starting values.

Growth

SSC: “We encourage efforts to collect additional growth information because the new observations that were added this year were concentrated within a narrow range of pre-molt sizes so the new growth information was not as informative in the assessment as expected.”

CPT: “Consider a model in which growth differs for animals that are about to mature.”

Growth for both males and females is currently modeled as a piece-wise linear model with an estimated breakpoint denoting a carapace width at which the growth per molt changes (‘kinked growth curve’) in the snow crab assessment. The original rationale for these methods was that animals would devote fewer resources to somatic growth as they become reproductively active. This is suggested for Canadian snow crab based in Sainte Marie et al. (1995, Figure 1). However, the kinked growth curve has been a source of instability in the snow crab assessment for several years, producing bimodality in management quantities (e.g. Szuwalski and Turnock, 2017). New data added to the assessment in 2017 suggest that growth is much more linear than the model estimated in previous years (Figure 2), but the assessment still estimates a substantial decrease in the slope of the relationship between molt increment and pre-molt carapace width around 40mm carapace width.

Efforts to linearize the growth curves in the snow crab assessment model resulted in models that did not converge (large gradients and non-positive definite Hessians; e.g. Szuwalski and Turnock, 2018). Models in which the input data were truncated above the estimated change point were also attempted, but resulted in large changes in other estimated parameters leading to population dynamics inconsistent with what is known about snow crab (Szuwalski, 2017; figure 3, model “Chop growth”).

Using a kinked growth curve with a fixed inflection point is potentially problematic because crabs mature at different sizes within the snow crab assessment model. There is some estimated probability of molting to maturity at all sizes above 40 mm carapace width (Szuwalski, 2018; figure 4). In Sainte-Marie et al. (1995), the crabs within the study did not terminally molt until 70mm carapace width, which calls into question the appropriateness of a fixed changepoint in growth for modeling snow crab population dynamics in which there appears to be molts to maturity over a large size range. If the changepoint is fixed, the assumption that the change in growth curves is related to the timing of maturity is not internally consistent with the model structure.

The CPT suggested considering a model in which growth differs for individuals about to mature, which could address this issue. However, the available growth data for Bering Sea snow crab are not separated into ‘terminal molt’ vs. ‘non-terminal molt’. So, we cannot separate the data to inform the proposed growth curves for ‘terminal molters’ vs. ‘non-terminal molters’. Even if this additional information was available for the current pre/post molt observations, it is not clear that a large difference would exist in the estimated curves, given the growth increments look quite linear over the range of available sizes (figure 2).

Additional growth data are currently being collected on BSFRF research cruises (April 2019) and collection efforts have been focused on the gaps in pre-molt length data. The Kodiak Lab is writing up studies on the

impact of ocean acidification on survival and growth of snow crab. Preliminary results indicate no effect on survival, but increases in growth (Foy, personal communication).

Natural mortality and priors

CPT: “Further explore the basis for the existing priors for M; for example, from the estimated ages post terminal molt.”

The mean for the normal priors placed on estimated natural mortality in the most recent assessment are based on an assumed maximum age of crab derived from radiometric aging data (Nevisi et al. 1995). The standard deviation around this mean is derived from a standard error of maximum age based on dactyl wear (Fonseca, 2008). Turnock and Rugulo (2006) described the rationale for choosing these values based on these two studies:

“Of the 3 SC5 crab aged (SC5 = very, very old shell) the maximum age found was 6.85 years (s.d. 0.58, 95% CI approximately 5.69 to 8.01 years; figure 5). Given the small sample size, crabs older than the maximum age of 7 to 8 years are reasonably expected in the population. Maximum life span defined for a virgin stock is reasonably expected to be longer than these observed maximum ages of exploited populations.

Male snow crab during the mid to late 1980’s were subjected to increasing exploitation with the maximum catch occurring in 1991. The maximum age in the sample of 6.85 years would be the result of fishing mortality as well as natural mortality. Using this maximum age would result in an upper bound on natural mortality. If crabs mature at about age 7 to 9, an additional 7 or 8 years gives a maximum total age of about 14 to 17 years. However, due to exploitation occurring at the same time, the maximum age that would occur due to M alone would be greater than 14 to 17 years.”

“...ongoing tag recovery evidence from eastern Canada reveal observed maximum ages in exploited populations of 17-19 years. We reasoned that in a virgin population of snow crab, longevity would be at least 20 years. Hence, we used 20 years as a proxy for longevity and assumed that this age would represent the upper 99th percentile of the distribution of ages in an unexploited population if observable. Under negative exponential depletion, the 99th percentile corresponding to age 20 of an unexploited population corresponds to a natural mortality rate of 0.23.”

Given this background, mature male natural mortality has been estimated in the assessment with a prior constraint of mean of 0.23 yr⁻¹ with a standard error equal to 0.054 (estimated from using the 95% CI of +1.7 years on maximum age estimates from dactal wear and tag return analysis in Fonseca, et al. (2008)).

With the addition of an estimated immature M, the relationship between maximum age and a given estimated natural mortality (both immature and mature) becomes somewhat fuzzier (more so when the correlation between estimated recruitment and natural mortality [discussed below] is considered).

CPT: “The level of recruitment is likely correlated with immature M. This should be explored in future analyses. “

The estimated multipliers on natural mortality were positively correlated (to varying degrees) with recruitment for both immature and mature males and females in the accepted model from 2018:

- Mean log female recruitment vs. immature males and females: 0.29
- Mean log male recruitment vs. immature males and females: 0.53

- Mean log female recruitment vs. mature males: 0.33
- Mean log male recruitment vs. mature females: 0.43

This should be intuitive, because, all else constant, if natural mortality increases, recruitment must as well to fit the data, which do not change.

Recently, Murphy et al. (2018) produced estimates of time-varying natural mortality for snow crab in the Bering Sea. Estimated mean female natural mortality was 0.49 (ranging from 0.04 to 3.34) and mean male natural mortality was 0.36 (ranging from 0.03 to 0.91; figure 6). They leveraged the information in female shell condition, the existence of a terminal molt, and the fact that females are essentially unfished and a fraction of the mature male population is unfished to reach these estimates. For males, the reason the model predicts higher natural mortality than would be suggested by the maximum age data can be seen most easily by examining the abundance by year of mature males in the size classes that are not captured by the fishery (figure 7). For example, the large peak seen in the mid 1990s is a large year class that has terminally molted. It disappears from each of the size classes in figure 7 in 2 to 3 years, implying a relatively high natural mortality and standing contrast to the radiometric data. These size classes are not selected in the fishery, so all mortality here is assumed to be natural.

Shell condition

SSC: We recommend research on the relationship between shell condition and time since last molt.

Shell condition (SC) is a subjective measure of the appearance of the carapace of crab and has 6 classes: ‘molting (0), ‘soft shell’ (1), ‘new shell’ (2), ‘old shell’ (3), ‘very old shell’ (4) and ‘extremely old shell’ (5). In theory, the appearance of the carapace of a crab could be an indicator for the time since last molt. Radiometric estimates of shell age compared to shell condition indices suggest a rough correspondence between shell condition and time since last molt (Nevisi et al., 1995; Ernst et al., 2005; figure 5). However, the transition between new shell and old shell (SC 2-3) is poorly resolved (figure 5) and these shell conditions make up the majority of reported shell conditions for crab caught in the NMFS summer survey (Lang et al., 2018; figure 8). Given the inability of shell condition to satisfactorily resolve the transition between new and old shell (particularly for males), shell condition is not currently considered in the assessment for snow crab in the Bering Sea.

Shell condition’s most promising contribution would be a proxy for age, which would help in determining natural mortality. However, if research is to be designed to better understand natural mortality, it likely makes more sense to directly target that process, rather than try to understand if a proxy is a useful metric or not. The demonstrated lack of resolving power among the classes contributing to the biomass of snow crab in the Bering Sea (with an admittedly small sample size) suggest that we may not be able to distinguish between ‘new’ and ‘old’ shell reliably. This is likely further complicated by a spatial effect—the apparent ‘age’ as seen through shell condition is likely related to the substrate on which a crab lives, which varies over the surveyed area in which snow crab are found.

Catchability

SSC: “re-examine catchability for snow crab, given the large number of snow crab that occur outside the standard survey area. We note that the snow crab assessment is a prime candidate for including available NBS data in the assessment in the future.”

At least three catchability related problems exist for snow crab: what is the average catchability within each era, does catchability vary over time within these eras, and, if catchability varies over time, what is driving the changes?

Average catchability by era

Currently, two catchability parameters are estimated within the assessment: one for the period spanning 1982-1988, one for 1989-present. Data from experimental surveys performed by the BSFRF during 2009 and 2010 are included in the assessment with the aim of informing catchability from 1989-present. Estimates of catchability have decreased over time, with a notable drop after the 2009 and 2010 experimental survey data were incorporated into the assessment (Figure 9). Even with the incorporation of the experimental survey data into the assessment, the estimated catchability over the past several years for survey era 2? does not reach the levels of the catchability suggested by the ratio of crab observed at length in the NMFS gear vs. the BSFRF nephrops gear (~0.4; compare figure 9 to figure 10). Fitting to the ratio of pooled crab observed at length in the NMFS gear vs. the BSFRF gear (or fixing the NMFS summer survey selectivity curves in the assessment to the inferred selectivity) resulted in large increases in the OFL (e.g. 89 vs. 24 thousand tons in 2017; Figure 3, model “Obs sel” vs “Base”).

The BSFRF data are fit as an extra survey in the assessment with a freely estimated ‘availability’ curve (with smoothing penalties) that denotes the fraction of the modeled population that is sampled under the selectivity experiments. Freely estimating the availability allows the model ample freedom to fit the observed BSFRF data and it is unclear how effective this method is at capturing the information content in the BSFRF data. Simulation studies may be useful to understand the performance of these methods. Further, the current method for incorporating the BSFRF data into the assessment assumes that catchability for the BSFRF gear is 1. While this seems a reasonable assumption, it is difficult to verify (and is the reason for which the survey experiments were done for the NMFS gear to begin with).

Time variation in catchability

In addition to issues surrounding the estimation of a single catchability coefficient within each survey era, it is also possible that survey catchability varies over time. There are years in which the assessment model is unable to fit the survey index and the length composition data suggest that the observed changes in MMB in the survey are not a result of recruitment or natural mortality, suggesting that the change is related to a change in catchability (e.g. 2014, Figure 11).

Catchability has been shown to vary based on bottom conditions. Somerton et al (2013) reported that selectivity was greater in sand than in mud based on data from the side by side selectivity experiments done with the BSFRF (Figure 12). So, depending upon the spatial distribution of crab caught in a given year, the substrate alone could account for some variation in catchability.

Another potential hypothesis to explain apparent time variation in catchability involves an environmental variable (e.g. bottom temperatures or food availability) influencing activity levels of snow crab. If crabs are active at the time of the survey in a given year, catchability will likely be higher than when compared to years in which crab are less active due to the change in body position between ambulating crab and burrowed crab (citation?).

Another potential hypothesis for apparent time variation in catchability relates to the movement of crab into and out of the survey area. Recent surveys in 2017 and 2018 in the northern Bering Sea have recorded substantial densities of small, immature crab north of the traditional survey grounds (Figure 13). The

inability of the assessment model to fit years like 2014 could be a result of crab from the northern area moving down into the traditional survey grounds, then moving out the year after. Discerning the validity of this hypothesis would require some measure of the motility of crab by size class.

This uncertainty surrounding catchability can present problems in the TAC setting process because the State of Alaska control rules have the flexibility to use a variety of measures for mature male biomass. In years in which the observed survey MMB and the model estimated MMB are quite different, a decision must be made on which metric to use. A better understanding of the variation in catchability over time would aid in making this decision.

The hypotheses presented above could be tested with available data.

Recruitment deviations

SSC: “While the SSC accepted the model, we believe that using separate recruitment deviations that are independent between males and females is not the best approach to address differences in mortality and it requires a large number of additional parameters. Male and female crab are expected to be produced in relatively constant ratios and may diverge as young crab grow. Therefore, the model should try to capture possible mechanisms that result in divergence and constrain the divergence, rather than allowing for completely independent recruitment deviations by sex.”

It is not immediately clear why there appears to be a difference between male and female recruitment, only that there is and ignoring the difference results in unreliable estimates of quantities used in management. It is also unclear how the assessment model and harvest control rules could capture a possible mechanism given it uses aggregate measures of biomass and does not consider any environmental influences. This, in addition to the bimodal management quantities resulting from estimating a kinked growth curve for females, is one of the primary reason for developing a simplified assessment model that only tracks males presented in Appendix 2.

Maturity

CPT: “Consider including the chela height data in the same manner as for EBS Tanner crab.”

Currently the probability of terminal molt to maturity at length is a freely estimated vector with a small smoothness penalty. The estimates of the probability of maturing are informed by the priors on natural mortality and the length composition data separated by maturity state (among other processes and data sources). The length composition data for females are easily separated into mature and immature by the presence of eggs. The length composition data for males, however, are separated to maturity state by chela height and shell condition (figure 14). So, since the length composition data are defined by the chela height data, these data are already incorporated into the assessment. However, they are not directly fit to. Directly fitting to these data may stabilize the estimates of the probability of maturing (and by extension MMB) because it would link the immature and mature length composition data more strongly through an expected ratio of immature to mature crab in a given length class. More informed estimates of maturity could potentially stabilize the model by anchoring one of the confounding processes in the assessment.

There are currently several other studies underway related to maturity that may influence the treatment of maturity and reproduction in the assessment. The Kodiak Lab has a manuscript in prep on the relationship between biennial spawning and the size of the cold pool. They also are nearing submission of a manuscript related to a latitudinal gradient in size of maturity for male snow crab based on chela height, similar to Ernst et al.’s 2005 paper on female snow crab spatial dynamics and maturity states. Although changes in biennial

spawning would not directly affect the current management strategy, changes in the size at maturity for males could influence estimates of MMB in a given year, which feeds directly into the harvest control rule.

Skip molting

CPT: “Examine the possibility and implications of skip molting.”

The Kodiak Lab is currently researching the relationship between changes in water temperature and skip molting. Their basic findings are that colder temperatures may precipitate a skipped molt (more to come upon publication). Research is concurrently underway on Canadian populations that suggest skip molting may also be influenced by population density, but this is likely to be less of an issue in the Bering Sea given the larger geographical distribution. The potential for skip molting further complicates the use of shell condition as a proxy for age. Generally, skip molting may be less of a problem as waters warm in the Bering Sea, depending on the movement of the population in response to warming.

Data weighting

SSC: “Re-visit appropriate weights for different data sources included in the model. We note that a recent working group made useful recommendations on data weighting that should be assessed for implementation in the snow crab assessment.”

I agree that data weighting should be revisited, and this will be considered in the process of building a more complex model from simple beginnings.

Incidental catch

In previous years, incidental catch of snow crab in other crab fisheries was incorporated into the directed snow crab catch. That is, all crab caught in crab fisheries were included in the catch reported in the directed fishery. This practice was historically used in the Tanner crab assessment as well. However, in 2017, the Tanner crab assessment split the incidental catch out and the result were rather dramatic changes in recruitment. The incidental catches were provided by the State of Alaska for snow crab in 2018. Based on these new data, a maximum of 0.4% of snow crab catch was caught incidentally in other fisheries during the years 2005 to 2017 (Figure 15). The reason such a small percentage of total snow crab catch is caught incidentally in other fleets is likely related to the size difference between snow crab and other crab and the selectivities of other fleets. Currently, all bycatch in other fisheries is lumped in with trawl bycatch because trawl bycatch is by far the largest source of mortality other than the directed fishery for snow crab (though trawl mortality is still dwarfed by directed mortality). The estimated selectivity of the ‘bycatch’ fishery in the snow crab model is shifted quite far to the left of the selectivity of the snow crab fishery. Because of the small amounts of incidental catch and the large difference in selectivities between the other fleets and the currently modeled catch-all ‘bycatch fishery’ in the snow crab assessment, the catch time series in the assessment were not altered.

Conclusions

Differing estimates of parameters determining population processes exist in the literature for natural mortality and catchability. These same parameters are confounded in the assessment and are sometimes not strongly informed by data, which influences the stability of model output. Differences also appear to exist for males and females in key population processes like recruitment, yet there are few data (or hypotheses even) for why these differences exist.

I plan to attempt to address these problems with several (hopefully concurrent) research directions:

- Continue using the current assessment model for the immediate future with changes suggested by the CPT
- Build a simple assessment model for snow crab that eliminates known sources of instability, then gradually increase it in complexity to identify when model instability occurs,
- Modify the GMACS code to allow for terminal molt,
- Incorporate all available data on catchability and maturity into the assessment method
- Develop a proposal to find funding to examine the multiple hypotheses for time-varying catchability with the hope of identifying a method going forward to address it in the assessment

Appendix 1 presents the current assessment model with some of the requested changes by the CPT.

Appendix 2 presents preliminary analyses with a simple model that starts by excluding females, shell condition, the kinked growth curve, and the BSFRF data. In the long term, it is desirable to keep females within the assessment model. However, the largest issues related to model stability appear to stem from female processes and measures of female biomass play a very small role in the harvest control rule for snow crab. A small fraction of the OFL is devoted to female mortality associated with discard from the directed and trawl fisheries, but the discarded female catch is 2% of the total discards in numbers—less in biomass.

The remaining points will hopefully be more closely addressed in the January 2020 modeling meeting.

References

- Ernst, B., J.M.(Lobo) Orensanz and D.A. Armstrong. 2005. Spatial dynamics of female snow crab (*Chionoecetes opilio*) in the eastern Bering Sea. *Can. J. Fish. Aquat. Sci.* 62: 250-268.
- Fonseca, D. B., B. Sainte-Marie, and F. Hazel. 2008. Longevity and change in shell condition of adult male snow crab *Chionoecetes opilio* inferred from dactyl wear and mark-recapture data. *Transactions of the American Fisheries Society* 137:1029-1043.
- Lang, C., Richar, J., Foy, R. 2018. The 2018 eastern Bering Sea continental shelf and northern Bering n Sea trawl surveys; results for commercial crab species. NOAA Technical memorandum NMFS-AFSC-386.
- Murphy, J.T. Rugolo, L.J., Turnock, B.J. 2018. Estimation of annual, time-varying natural mortality and survival for Eastern Bering Sea snow crab (*Chionoecetes opilio*) with state-space population models. *Fish Res* 205: 122-131.
- Nevissi, A.E., J.M. Orensanz, A.J.Paul, and D.A. Armstrong. 1995. Radiometric Estimation of shell age in Tanner Crab, *Chionoecetes opilio* and *C. bairdi*, from the eastern Bering Sea, and its use to interpret indices of shell age/condition. Presented at the International symposium on biology, management and economics of crabs from high latitude habitats October 11-13, 1995, Anchorage, Alaska.
- Turnock, B.J. and Rugolo, L. 2006. Unresolved issues concerning proposed overfishing definitions for Bering Sea and Aleutian Islands King and Tanner crab stocks. NMFS publication.
- Sainte-Marie, B. 1993. Reproductive cycle and fecundity of primiparous and multiparous female snow crab, *Chionoecetes opilio*, in the northwest Gulf of St. Lawrence. *Can. J. Fish. Aquat. Sci.* 50:2147-2156.
- Sainte-Marie, B., Raymond, S., and Brethes, J. 1995. Growth and maturation of the male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). *Can.J.Fish.Aquat.Sci.* 52:903-924.
- Sainte-Marie, B., J. Sevigny and M. Carpentier. 2002. Interannual variability of sperm reserves and fecundity of primiparous females of the snow crab.
- Somerton, D., Weinberg, K., Goodman, S. 2013. Catchability of snow crab by the eastern Bering Sea bottom trawl survey estimated using a catch comparison experiment. *CJFAS.* 70:1700-1708.
- Szuwalski and Turnock. (2017) Exploring selectivity, growth, and natural mortality in the assessment for snow crab in the eastern Bering Sea. NMFS publication available on nfmfc.org.

Fig. 8. Carapace growth per moult for male *C. opilio* from Baie Sainte-Marguerite. Data come from laboratory (circles) and field (triangles) observations, and from the mean carapace width of the first seven postlarval instars (+) as determined by size frequency analyses (from Table 1). Open symbols indicate a regular moult, solid symbols indicate a terminal moult. The oblique broken and solid lines are the Hiatt growth models for immature and adolescent males, respectively. The vertical broken line indicates the abscissa value at which the two regressions intersect (*I*).

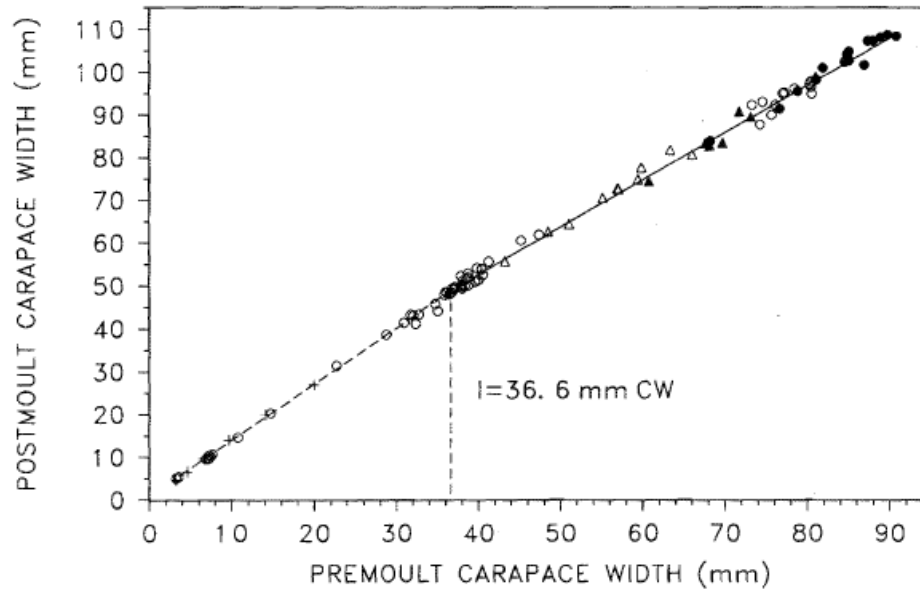


Figure 1. Post molt carapace width vs. premolt carapace width for Canadian snow crab. Reproduced from Sainte-Marie et al. 2005.

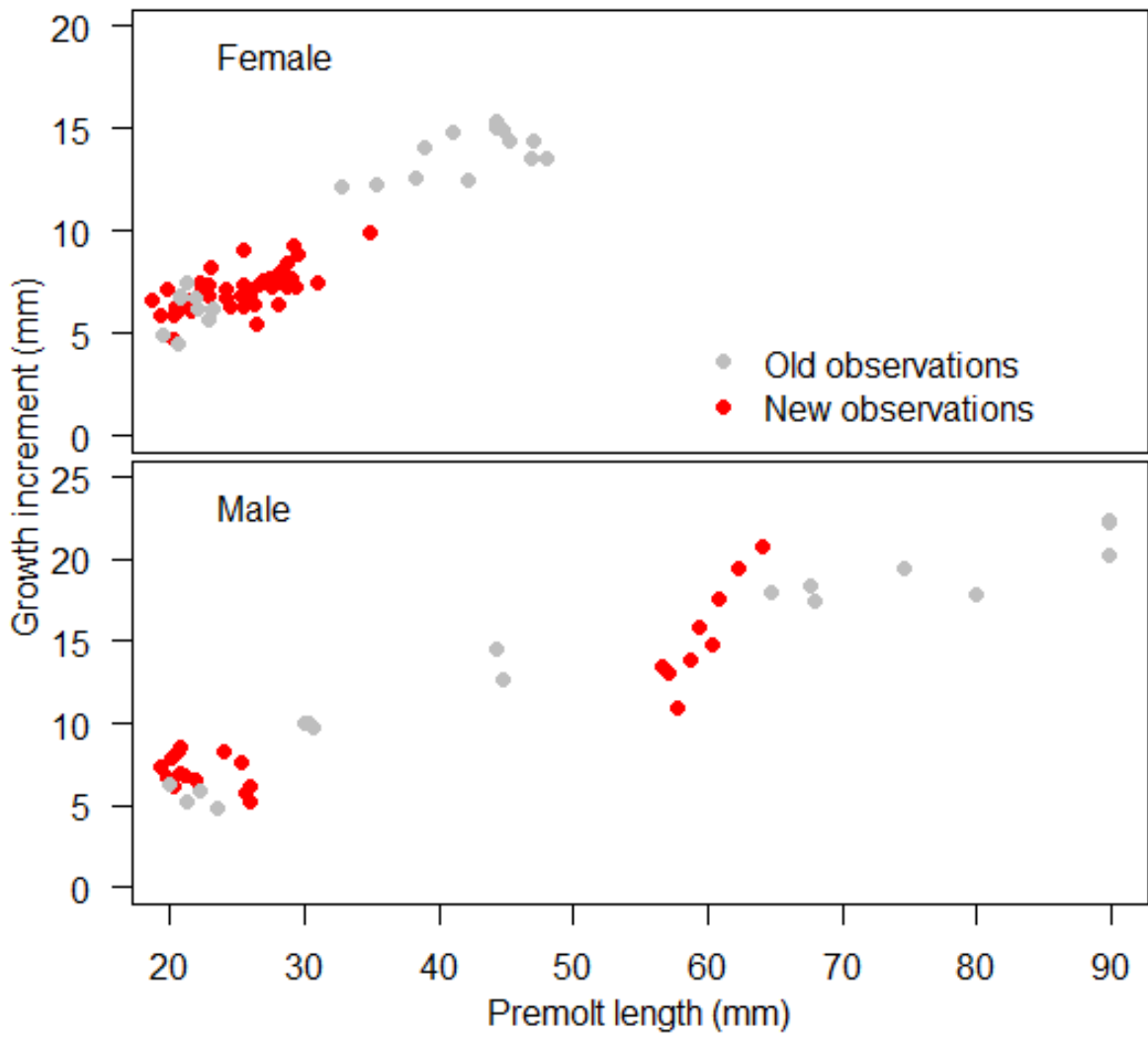


Figure 2. Growth increment data used in the assessment for eastern Bering Sea snow crab. “New” observations were new in 2017.

Table 1: Changes in management quantities for each scenario considered. Reported quantities are the MLEs because running MCMC for every model was prohibitively time-consuming. The MLEs for scenarios in which MCMCs were performed are very close to the medians of the posterior distributions.

Model	MMB	B35	F35	FOFL	OFL
Base	92.09	152.3	1.91	1.14	24.59
Trim data	83.8	152.3	1.42	0.81	19.97
Fixed obs sel	221.6	215.3	3.49	2.62	82.68
No BSFRF	60.86	142.3	1.17	0.56	11.5
Est female M	74.29	139.6	1.21	0.68	18.38
Chop growth	79.57	149.8	1.34	0.75	18.66
Growth + M	70.89	137.4	1.17	0.64	17.35

Figure 3. Estimated management quantities from model scenarios presented in 2018.

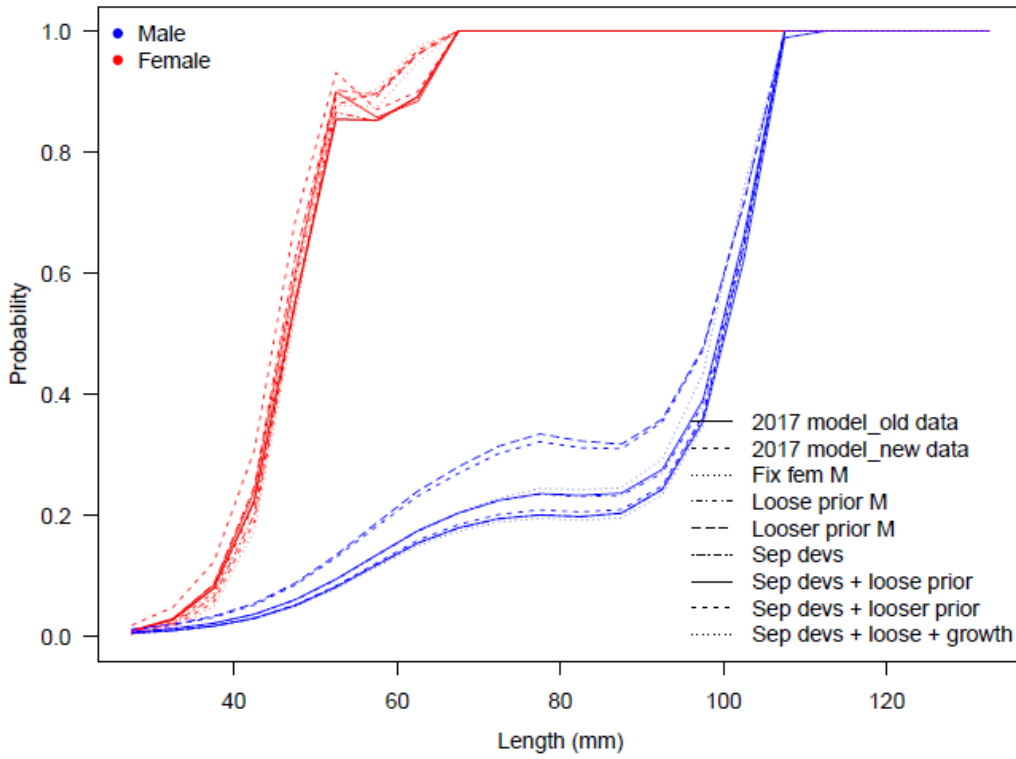


Figure 4. Estimated probability of maturing from the 2018 assessment for eastern Bering Sea snow crab.

Table 1. Radiometric estimates of shell age in male snow crabs (*Chionectes opilio*) and Tanner crabs (*Chionoecetes bairdi*) ($n = 21$) collected in the eastern Bering Sea during the NMFS survey of 1992.

Shell condition	CW (mm)	Age (years)	Error (years)	Coordinates	Depth (m)	Species
0+	121	0.05	0.26	59°20'N, 171°49'W	43	<i>C. opilio</i>
0+	110	0.11	0.27	59°20'N, 171°49'W	43	<i>C. opilio</i>
0+	132	0.11	0.19	59°20'N, 171°49'W	43	<i>C. opilio</i>
1	118	0.15	0.26	59°20'N, 171°49'W	43	<i>C. opilio</i>
1	130	0.23	0.27	59°20'N, 171°49'W	43	<i>C. opilio</i>
1	116	0.25	0.24	59°20'N, 171°49'W	43	<i>C. opilio</i>
2+	93	0.33	0.28	57°00'N, 167°43'W	42	<i>C. bairdi</i>
2+	122	0.42	0.26	57°00'N, 167°43'W	42	<i>C. bairdi</i>
2+	97	0.66	0.30	59°00'N, 171°47'W	46	<i>C. opilio</i>
2+	123	0.78	0.32	59°00'N, 171°47'W	46	<i>C. opilio</i>
2+	121	0.85	0.27	57°00'N, 167°43'W	42	<i>C. opilio</i>
2+	66	1.07	0.29	59°00'N, 171°47'W	46	<i>C. opilio</i>
3	117	0.92	0.34	59°00'N, 171°47'W	46	<i>C. opilio</i>
3	69	1.04	0.28	59°00'N, 171°47'W	46	<i>C. opilio</i>
3	78	1.10	0.30	59°00'N, 171°47'W	46	<i>C. opilio</i>
4	100	4.43	0.33	57°21'N, 167°45'W	39	<i>C. opilio</i>
4	93	4.89	0.37	58°20'N, 171°38'W	52	<i>C. bairdi</i>
4	100	6.60	0.33	57°00'N, 167°43'W	42	<i>C. opilio</i>
5	111	2.70	0.44	58°60'N, 169°12'W	28	<i>C. opilio</i>
5	100	4.21	0.34	59°00'N, 171°47'W	46	<i>C. bairdi</i>
5	110	6.85	0.58	58°60'N, 169°12'W	28	<i>C. opilio</i>

Figure 5. A summary of radiometric aging data printed in Ernst et al. (2005), replicated from Nevissi et al. 1995.

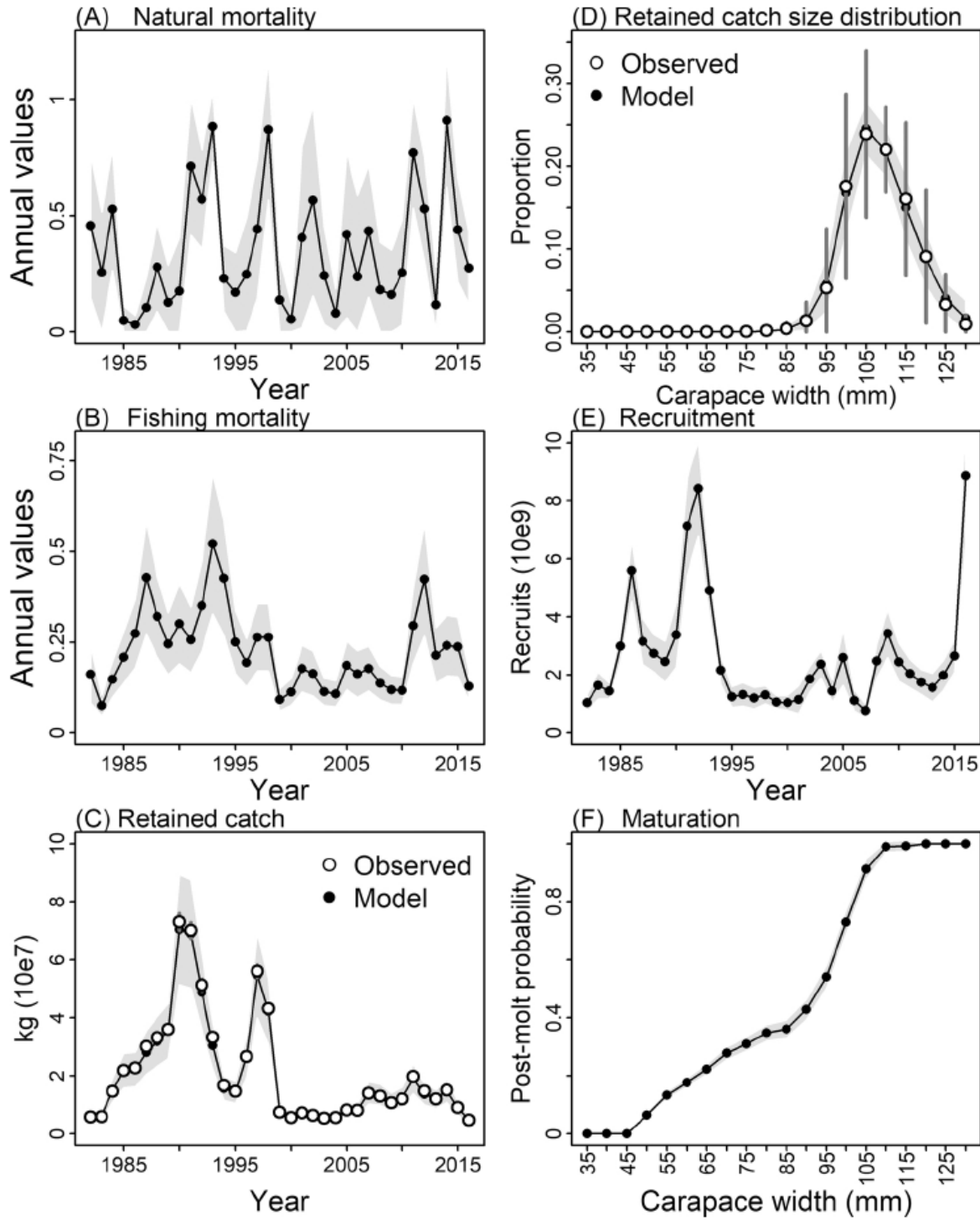


Figure 6. Estimates of time-varying natural mortality (among other processes) from Murphy et al. 2018.

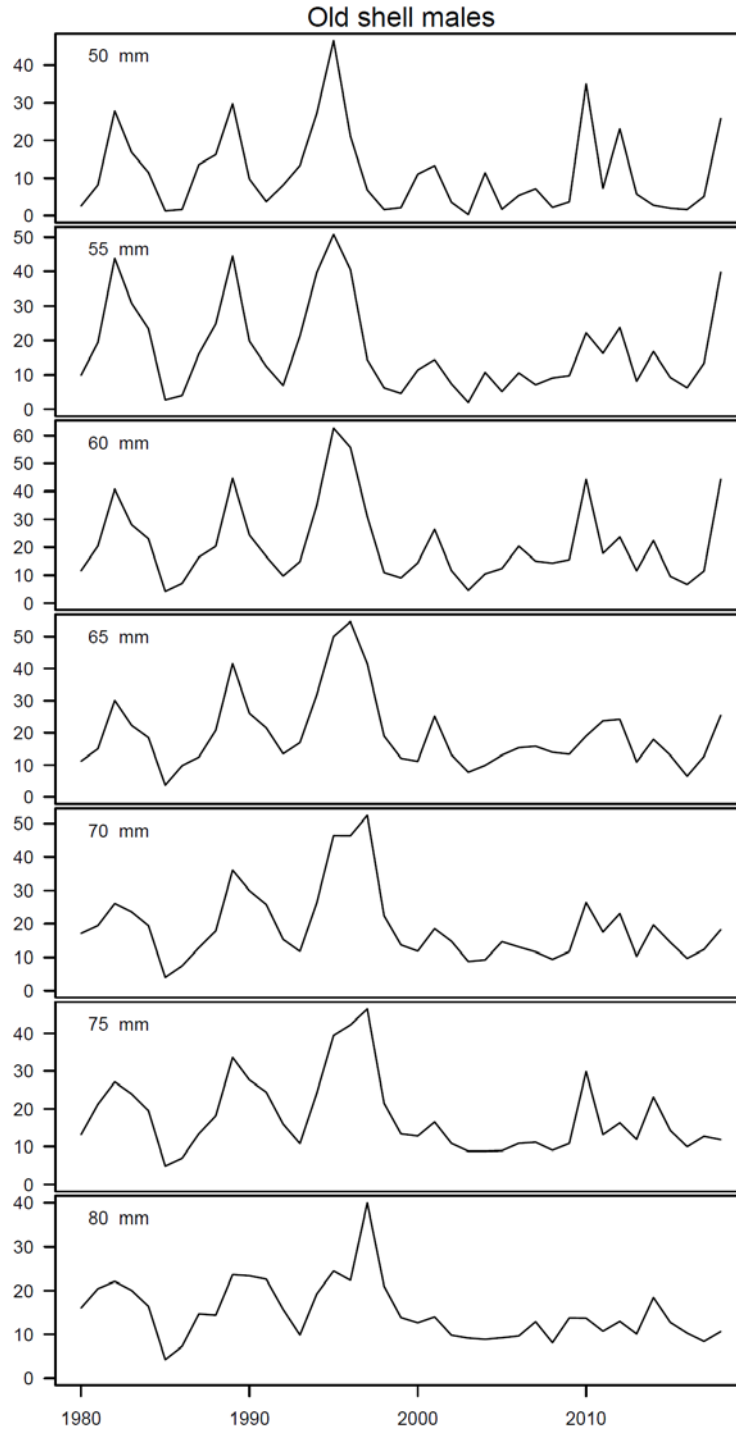


Figure 7. Abundance of mature snow crab in the Bering Sea by size class.

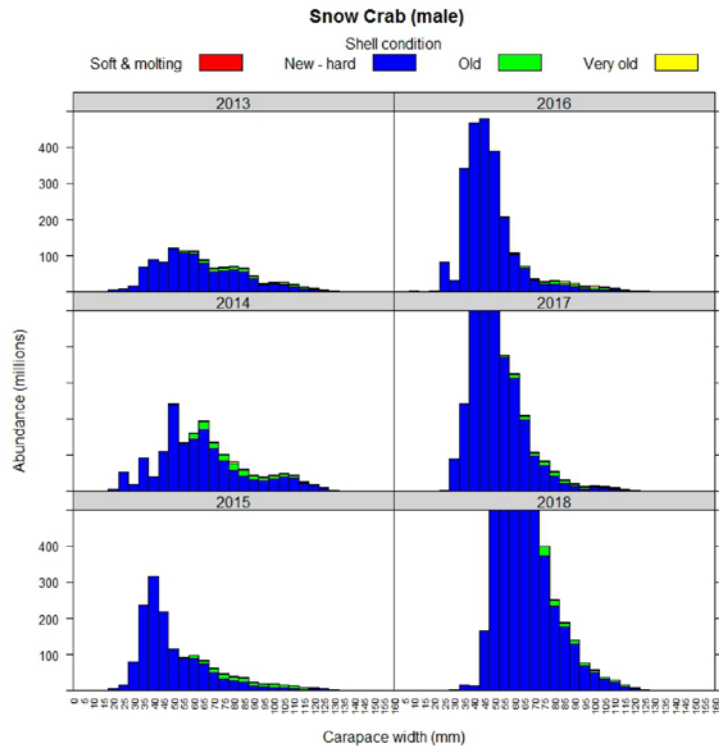


Figure 8. Relative proportions of shell condition types from the Bering Sea NMFS summer survey report (Lang et al. 2018).

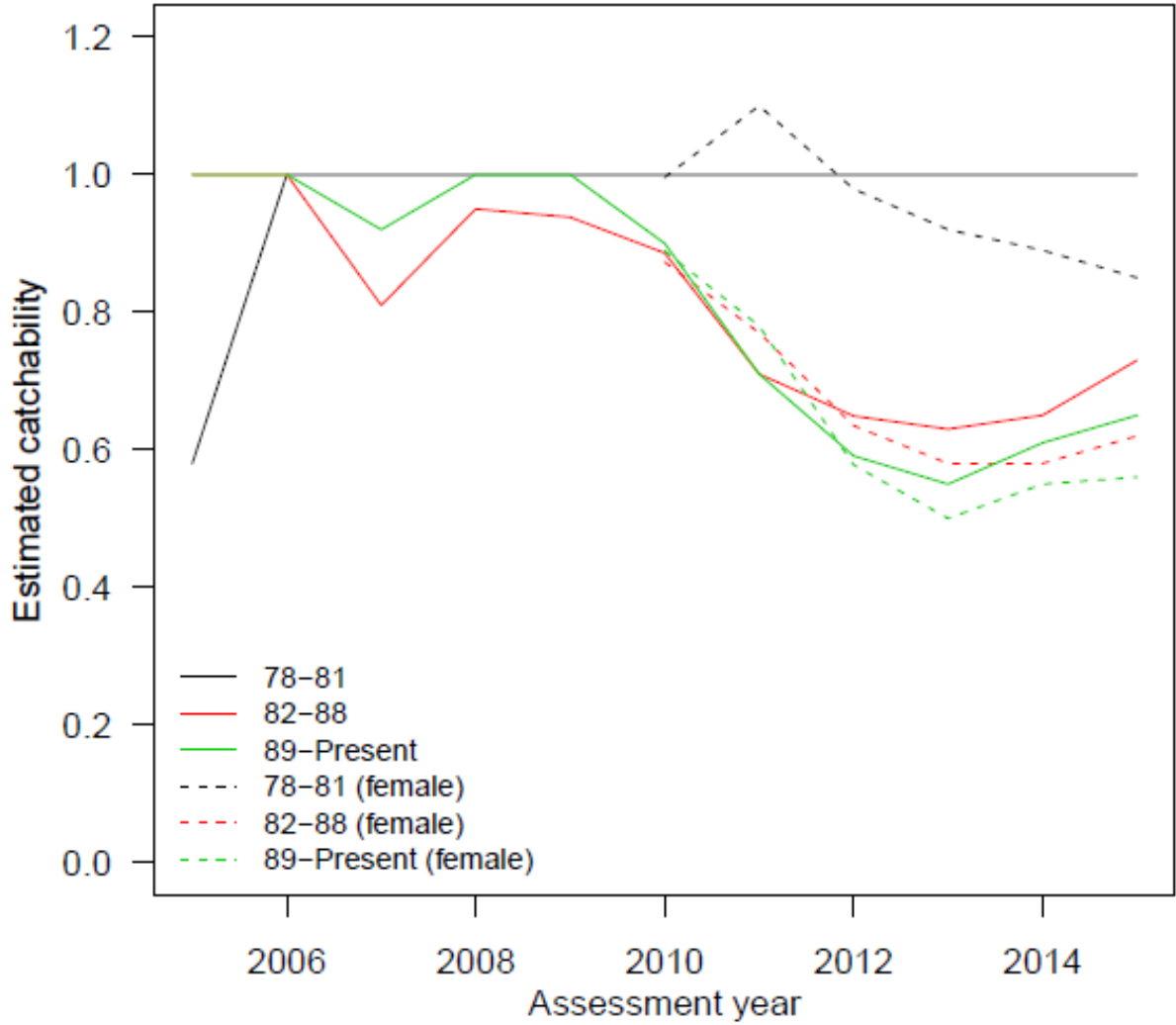


Figure 9. Estimated catchability from assessments reaching back to 2005. BSFRF survey data were collected in 2009 and 2010 and incorporated into the assessment in 2012.

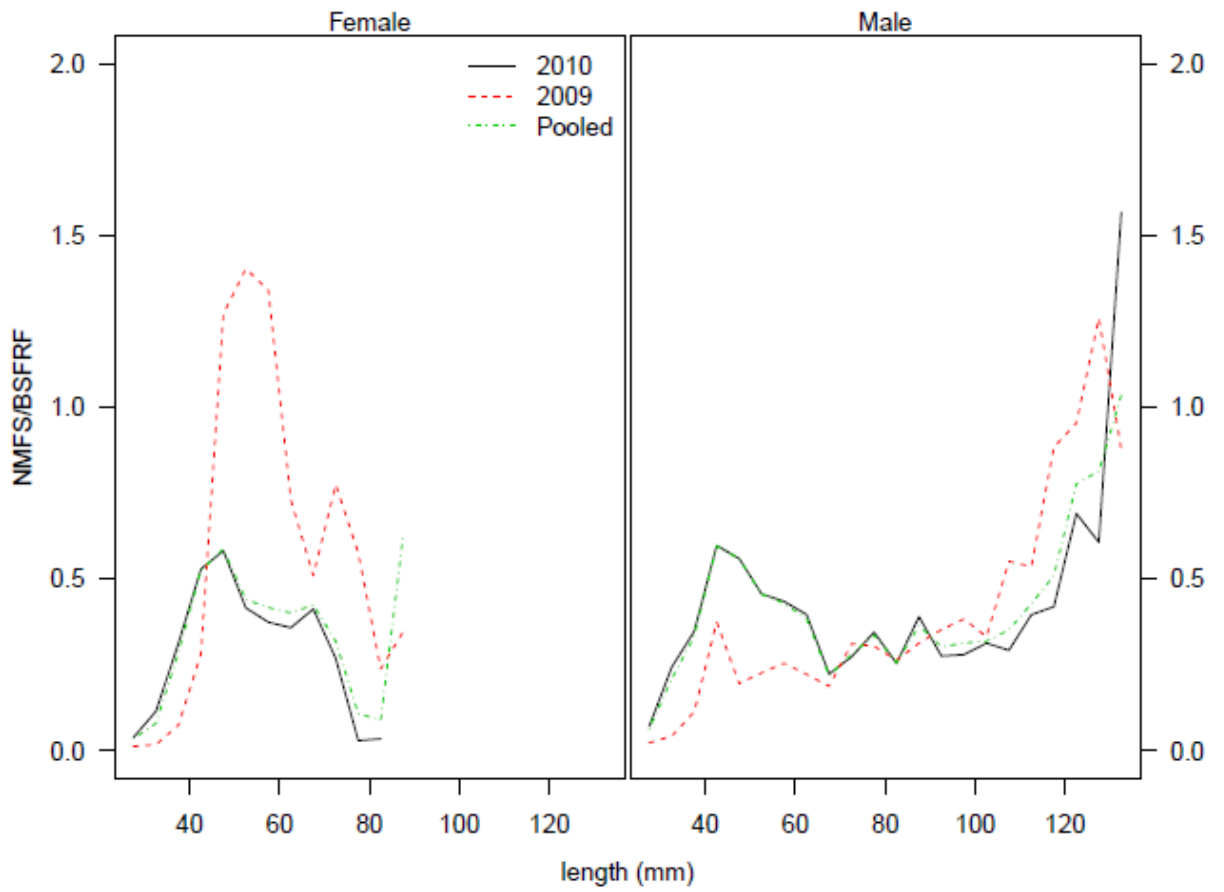


Figure 10. The ratio of crab caught in NMFS gear vs. BSFRF gear by size class, year, and sex.

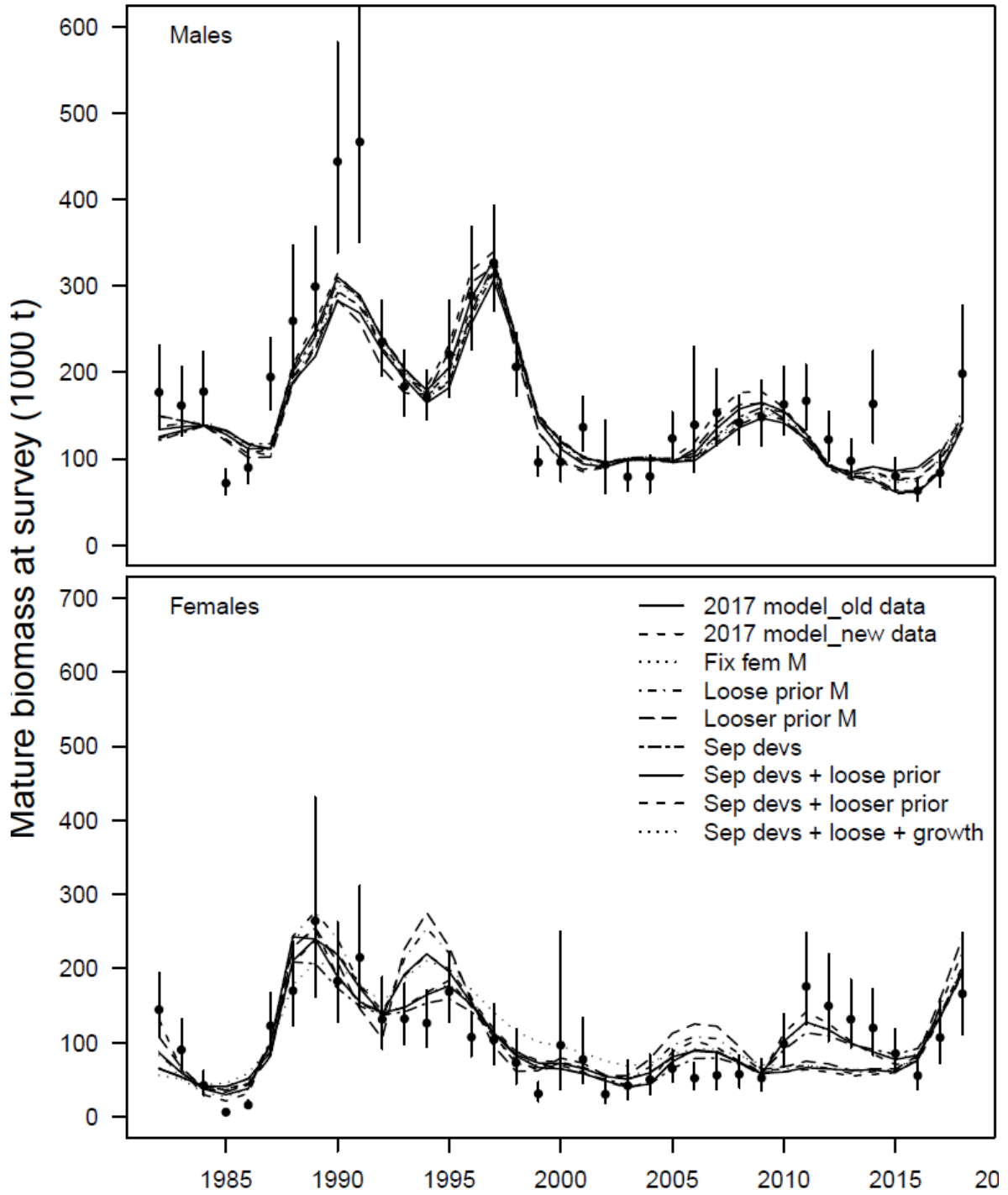


Figure 11. Fits of model prediction to mature biomass for males and females from the 2018 assessment.

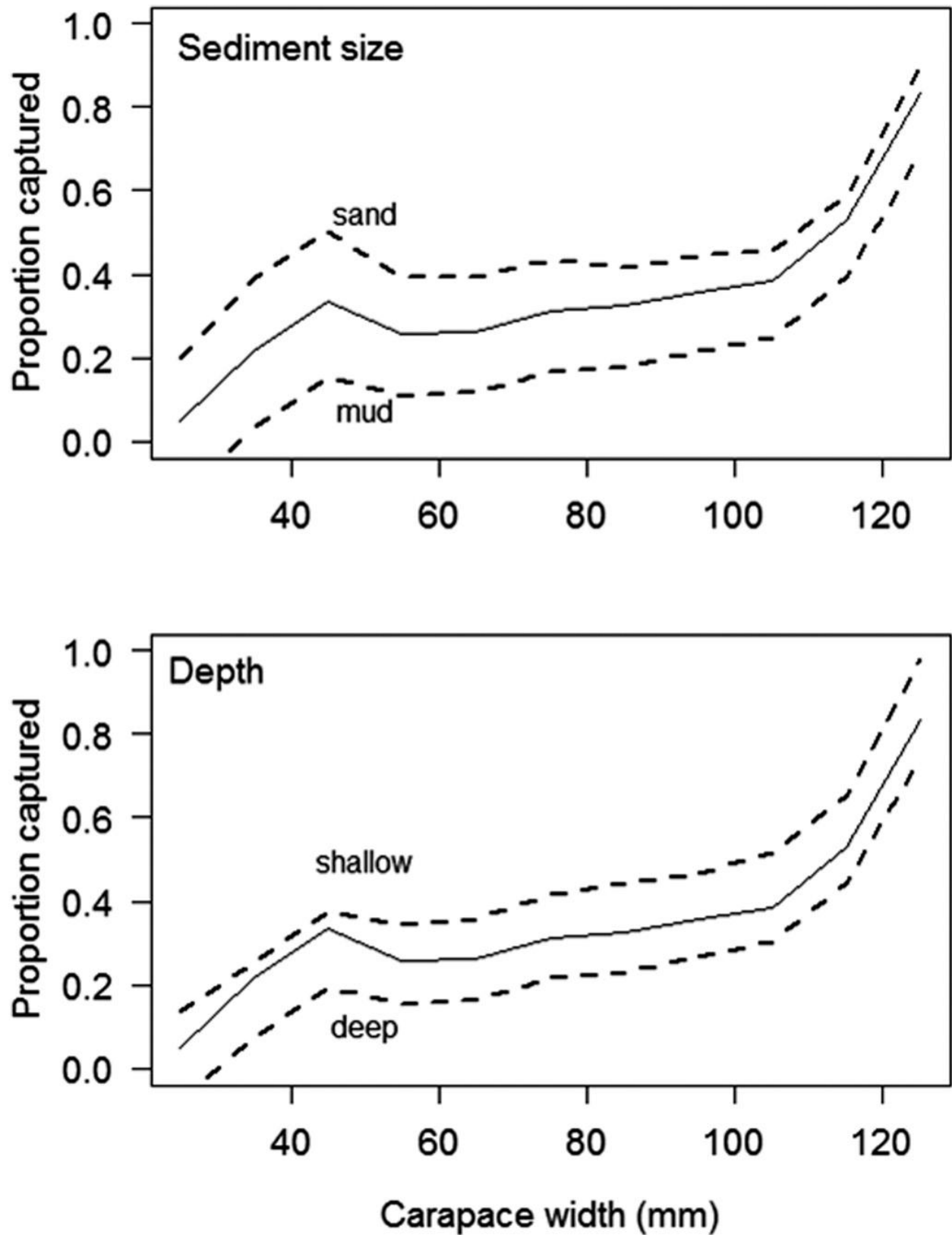


Figure 12. Estimated selectivity from BSFRF selectivity experiments by depth and sediment type.

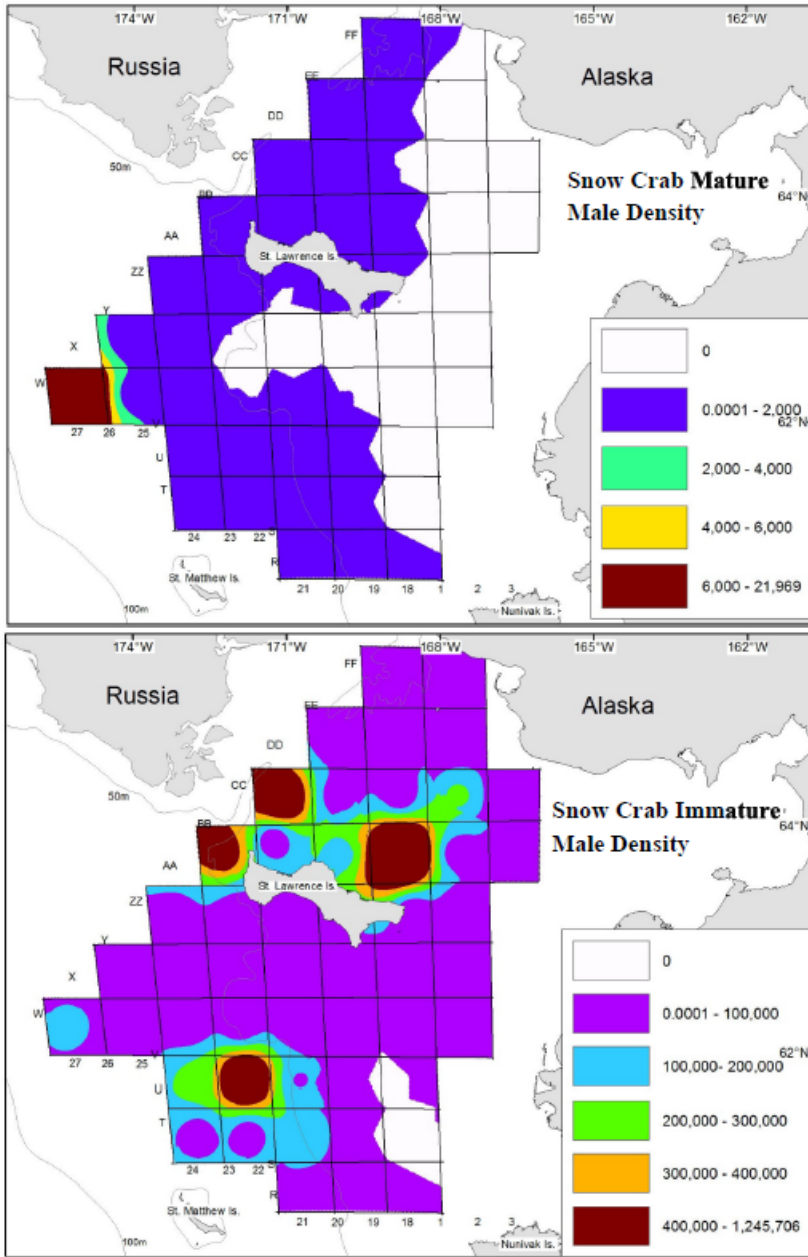


Figure 13. Distribution and density of snow crab in the northern Bering Sea in 2018.

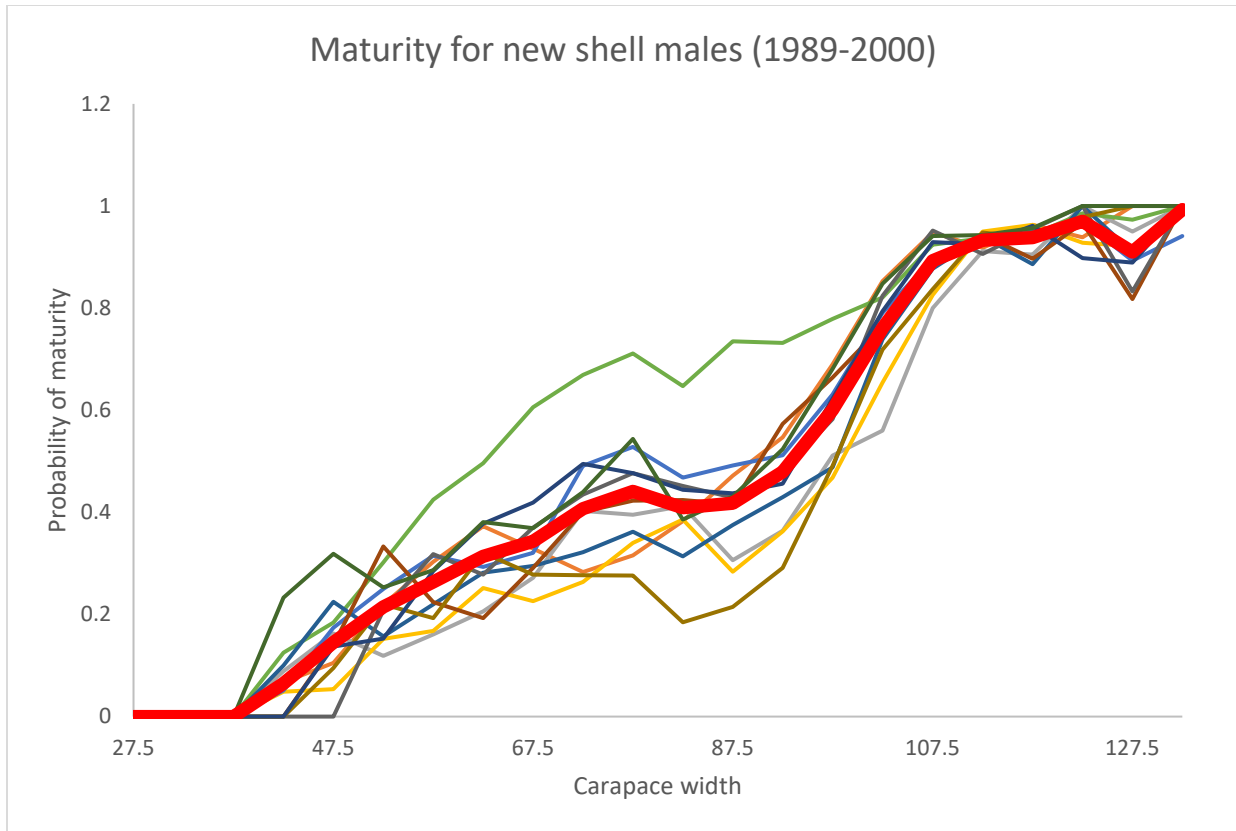


Figure 14. Observed proportion of mature individuals in the NMFS summer survey for new shell males from 1989-2000.

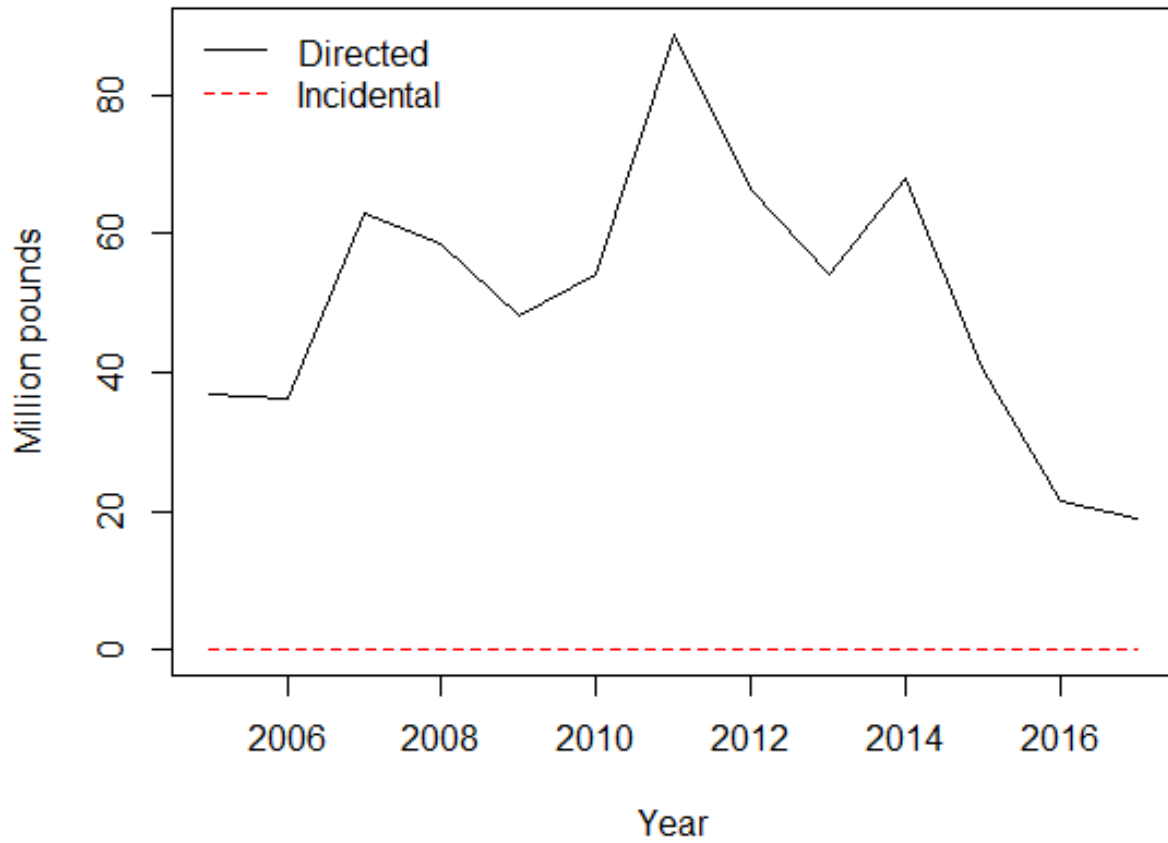


Figure 15. Breakdown of snow crab catch in the eastern Bering Sea according to whether it was caught in the directed fishery or incidentally in other fisheries.

Appendix 1: A summary of model runs requested by the CPT

Cody Szuwalski

April 22, 2019

Contents

CPT recommendations	
Convergence	
Fits to data sources	
Survey biomass data	
Growth data	
Catch data	
Size composition data	
Estimated population processes and derived quantities	
Summary	

Appendix A: Model structure

Population dynamics	
Likelihood components	

CPT recommendations

CPT recommended several runs and lines of research for the next assessment, including:

1. Consider moving to the “GMACS catch equation” as is now the case for the assessment of EBS Tanner crab.
2. Explore parameter correlation matrices to better understand possible reasons for model instability. In addition, examine how the values for each likelihood component change among jittered solutions with similar objective function values.
3. Consider a model in which growth differs for animals that are about to mature.
4. The level of recruitment is likely correlated with immature M. This should be explored in future analyses.
5. Further explore the basis for the existing priors for M; for example, from the estimated ages post terminal molt.
6. Consider including the chela height data in the same manner as for EBS Tanner crab.
7. Explore alternative options for weighting the growth data to achieve a more expected fit to the data (i.e., linear).

Items 2, 3, 4, and 5 are discussed in the main document. Item 1 and 6 were not implemented because the hope is to move to GMACS in the next year (1) and time constraints (6). Item 7 is implemented in two different models below. In addition to the models derived from item 7, a model that places a prior on the sex ratio of recruitment was added, and a model that is fit to VAST estimates of abundance was added. In sum, 5 models are presented:

- 18.1: Accepted model in 2018; fit to 2018 data.
- 19.1: 18.1 + a prior on the sex ratio
- 19.2: 19.1 + fixing growth to a linear relationship fit outside of the model
- 19.3: 19.1 + weighting growth twice as heavily
- 19.4: 19.1 + using VAST survey estimates and CVs

Input data did not change from 2018 (Figures 1-6 and tables 1-5).

Convergence

The accepted model and the model that added a prior on the sex ratio were the only models that produced an invertible Hessian. Both growth models also had gradients much larger than 0 (e.g. 300), but the model fit to VAST estimates of mature biomass had a gradient equal to 0.008. Some parameters (e.g. female catchability in the NMFS survey) were estimated on their bounds, and addressing this may produce invertible Hessians. In general, the fits to the data sources looked passable for all model scenarios.

Fits to data sources

Survey biomass data

Fits to the survey mature male biomass were visually similar for all models (except those fit to VAST estimates) for the majority of years in the time series (Figure 7). The model for which a prior was imposed for the sex ratio between male and female recruitment (prior $N(1,0.5)$) fit the survey data significantly worse than those for which no prior was imposed (Table 6). Estimates of survey MMB in the final year ranged from 72 to 92 kt. All models underestimated the final year of observed survey MMB (198.384 kt), and overestimated the final year of observed survey MFB (165.895 kt). Historical ‘observations’ from the VAST models were generally higher than the designed based estimator and were better fit, given the smaller input CVs. However, because of changes in estimated catchability, the overall biomass levels estimated from the models fit to VAST estimates were lower (Figure 8).

Growth data

Only the model in which growth was fixed at a linear growth model returned a linear relationship between pre- and post-molt lengths (Figure 9). Weighting growth more heavily resulting in a slightly ‘straighter’ growth curve for males, but only pushed the change point higher for females. Likelihood contributions of the growth components are only directly comparable for two models, but in those, the 2018 accepted model fit best (Table 6). Improvements in fits from the kinked growth curve were marginal compared to the linear model, but the parameter cost was relatively high (3 new parameters per sex).

Catch data

Retained catch data were fit by all models well, with no visually discernible differences among models (Figure 10). Female discard data were fit adequately given the specified uncertainty (Figure 10 & Table 6). Male discard data during the period for which data exist (early 1990s to the present) were well fit by every model with little visually discernible difference (Figure 10). Fits to the trawl data were adequate for all models given the uncertainty in the data (Figure 10).

Size composition data

Retained catch size composition data were fit well by all models (Figure 11); total catch size composition data were similarly well fit (Figure 12). Trawl size composition data were generally well fit, with several exceptions in certain years. All models performed similarly in fitting the trawl size composition data (Figure 13 & Table 6). Small differences in fit to the BSFRF size composition data were present among models (Figure 14 & Table 6). The number of males was generally underestimated by the industry survey in 2009 and overestimated by the NMFS survey, while the opposite pattern was seen for females. Fits to the 2010 survey size composition data were better than the 2009 fits. Differences in fits to survey length composition data were small among models, with the model fit to VAST estimates showing occasional departures from the other models (Figure 15 & Figure 16; residuals for 2018 accepted model in Figure 17 & Figure 18).

Estimated population processes and derived quantities

Population processes and derived quantities varied among models. Projected MMB for 2018 ranged from 106.37 to 124.97 kt (Figure 8). In general, estimated fishing mortality from the accepted model from 2018 has been well below $F_{35\%}$ in the recent past, save the years 2012-2015, which exceeded $F_{35\%}$ (Figure 19). Estimated MMB has been less than $B_{35\%}$ since 2010, and estimates from “18.1” suggest that the population may have been overfished in the recent past (Figure 19). Still, the estimated MMB is currently above MSST and is projected to exceed $B_{35\%}$ in the coming years.

Estimates of selectivity and catchability varied among models (Figure 20). Estimated catchability in both eras was lower for males than for females. In era 1 (1982-1988), catchability ranged from 0.52 - 0.79 for males; for females, it ranged from 0.56 - 0.97. In era 2 (1989-present), catchability ranged from 0.74 - 0.99 for males; for females, it ranged from 1 - 1. Estimated size at 50% selection in the survey gear for era 1 ranged from ~38 mm to ~40 mm for both females and males. Size at 50% selection in the survey gear during era 2 ranged from 35 mm to 36 mm for females and 34 mm to 36 mm for males. BSFRF ‘availability’ curves varied widely from 2009 to 2010 and among models, with the availability of crab to the experimental survey generally increasing in 2010 (Figure 21).

The probability of maturing at length for males and females were similar for all models (Figure 22). For all models, the probability of maturing by size for female crab was ~50% at ~47.5 mm and increased to 100% at ~60mm (Figure 22). The probability of maturing for male crab was ~15% to 20% at ~60 mm and increased sharply to 50% at ~97.5mm, and 100% at 107.5 mm.

Estimated fishing mortality in the directed fishery was similar for all models (Figure 23). Total and retained fishery selectivity was very similar for all models because of the weight put on the retained catch and its associated size composition data (Figure 23). Estimated size at 50% selection in the trawl fishery varied more than selectivity in the directed fishery, ranging from 108 - 113 mm (Figure 23). Size at 50% selection for discarded females was similar for all models (Figure 23).

Patterns in recruitment were similar for all models that estimated recruitment similarly (i.e. models with a prior on the sex ratio vs. none). A period of high recruitment was observed in which 3 large cohorts passed through the population during the 1980s and into the early 1990s. Following that, a period of low recruitment persisted from the early 1990s to 2013. All models indicated a large (relative to the past) recruitment to the survey gear occurred in the last few years (Figure 24). Recruitment entering the model was placed primarily in the first three size bins (Figure 24). Stock recruitment relationships were not apparent between the estimates of MMB and recruitment for any model (Figure 24). Relationships were not apparent between mature female biomass and recruitment either (not shown).

Estimated natural mortality ranged from 0.26 to 0.27 for immature crab, 0.26 to 0.26 for mature male crab, and 0.27 to 0.43 for mature females (Table 5).

Summary

The results of this section of the analysis provide little impetus to make large change from the 2018 model for 2019. Modifications to growth produced unviable models, it is unclear what the prior should be for the sex ratio of recruitment, and VAST estimates were different enough to require further consideration and did not return an invertible Hessian.

On a more philosophical note, the benefit of moving to VAST estimates for snow crab is not immediately clear. Depending on the knots specified, VAST essentially adjusts the observed survey data in a given year at a given station based on an estimated spatial correlation matrix. This generally results in bringing low survey values up and high values down, but the changes in the point estimates of the aggregate survey from VAST compared to the designed based estimator are relatively small. However, because of this shrinkage imposed by the use of spatial correlation, smaller CVs are produced. I think there are two potential points for concern with this. First, the observed data are altered, and it is not clear that the alterations are reflective of the underlying population. At least a portion of year-specific effects that might influence the observed density at a station (like fishing mortality and movement) are wrapped up in process error and not represented in the output CVs. Second, if there are underlying processes that systematically vary over time (perhaps similar to catchability, see main document and MMB in 2014) and these are not directly accounted for in the assessment, maintaining the the point estimates but shrinking the CVs around them can introduce conflict in the objective function (and change management quantities) by forcing the model to fit the survey index data more closely than when using a design-based estimator. I look forward to the discussion of this at the CPT.

Appendix A: Model structure

Population dynamics

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

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

Initial numbers at length for males were all assumed to be new shell (this does not affect dynamics because shell conditions are aggregated in the fitting process).

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

The dynamics after the initial year were described by:

$$N_{s,v,m,y+1,l} = \begin{cases} \Omega_{s,l} \kappa_{s,l'} Q_{s,imat,y,l'} X_{s,l',l} & \text{if } v = \text{new}; m = \text{mat} \\ 1 - \Omega_{s,l} \kappa_{s,l'} Q_{s,imat,y,l'} X_{s,l',l} + Rec_y^e Pr_l & \text{if } v = \text{new}; m = \text{imat} \\ Q_{s,mat,y,l'} & \text{if } v = \text{old}; m = \text{mat} \\ (1 - \kappa_{s,l'}) Q_{s,imat,y,l'} & \text{if } v = \text{old}; m = \text{imat} \end{cases} \quad (3)$$

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

$$Q_{s,m,y,l} = \sum_v N_{s,v,m,y,l} e^{Z_{s,v,m,y,l}} \quad (4)$$

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

was estimated subject to constraints (see Table 4; this formulation effectively specified a mean and standard deviation for a prior distribution for M).

$$Z_{s,v,m,y,l} = \gamma_{nat} M_{s,m} + \sum_f S_{s,f,y,l} F_{s,f,y,l} \quad (5)$$

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

$$S_{male,dir,l} = \frac{1}{1 + e^{-S_{slope,m,d}(L_l - S_{50,m,d})}} \quad (6)$$

$$S_{fem,dir,l} = \frac{1}{1 + e^{-S_{slope,f,d}(L_l - S_{50,f,d})}} \quad (7)$$

$$S_{trawl,l} = \frac{1}{1 + e^{-S_{slope,t}(L_l - S_{50,t})}} \quad (8)$$

$$R_{dir,l} = \frac{1}{1 + e^{-S_{slope,m,d}(L_l - S_{50,m,d})}} \quad (9)$$

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

$$C_{male,dir,y} = \sum_l \sum_v \sum_m w_{male,l} \frac{R_l F_{male,dir,y,l}}{F_{male,dir,y,l} + F_{trawl,y,l}} N_{male,v,m,y,l} e^{-\delta_y M_{s,m}} (1 - e^{-(F_{male,dir,y,l} + F_{trawl,y,l})}) \quad (10)$$

$$C_{male,tot,y} = \sum_l \sum_v \sum_m w_{male,l} \frac{F_{male,dir,y,l}}{F_{male,dir,y,l} + F_{trawl,y,l}} N_{male,v,m,y,l} e^{-\delta_y M_{s,m}} (1 - e^{-(F_{male,dir,y,l} + F_{trawl,y,l})}) \quad (11)$$

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

$$C_{m+f,trawl,y} = \sum_s \sum_l \sum_v \sum_m w_{s,l} N_{s,v,m,y,l} e^{-\delta_y M_{s,m}} (1 - e^{-F_{trawl,y,l}}) \quad (13)$$

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

$$F_{f,y} = e^{(F_{avg,f}^{log} + F_{dev,f,y}^{log})} \quad (14)$$

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

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

$$S_{surv,s,l,e} = \frac{q_{s,e}}{1 + e^{-\log(19) \frac{L_l - s_{50,s,e}}{s_{95,s,e} - s_{50,s,e}}}} \quad (15)$$

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

$$S_{ind,s,l,y} = \begin{cases} \frac{q_{ind,s,y}}{1 + e^{-\log(19) \frac{L_l - s_{50,s,y}}{s_{95,s,y} - s_{50,s,y}}}} & \text{if } s = \text{female} \\ q_{ind,s,y} S_y^{free} & \text{if } s = \text{male} \end{cases} \quad (16)$$

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

$$S_{nmfs,s,l,y} = S_{ind,s,l,y} S_{surv,s,l,y} \quad (17)$$

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

$$MMB_y = \sum_{l,v} w_{male,l} N_{male,v,mat,y,l} \quad (18)$$

$$FMB_y = \sum_{l,v} w_{fem,l} N_{fem,v,mat,y,l} \quad (19)$$

$$w_{s,l} = \alpha_{wt,s} L_l^{\beta_{wt,s}} \quad (20)$$

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

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

$$X_{s,l,l'} = \frac{Y_{s,l,l'}}{\sum_{l'} Y_{s,l,l'}} \quad (21)$$

$$Y_{s,l,l'} = (\Delta_{l,l'})^{\frac{L_{s,l} - (\bar{L}_l - 2.5)}{\beta_s}} \quad (22)$$

$$\hat{L}_{s,l}^{post,1} = \alpha_s + \beta_{s,1} L_l \quad (23)$$

$$\hat{L}_{s,l}^{post,2} = \alpha_s + \delta_s(\beta_{s,1} - \beta_{s,2}) + \beta_{s,2}L_l \quad (24)$$

$$\hat{L}_{s,l}^{post} = \hat{L}_{s,l}^{post,1}(1 - \Phi(\frac{L_l - \delta_{a,x}}{stgr})) + \hat{L}_{s,l}^{post,2}(\Phi(\frac{L_l - \delta_{a,x}}{stgr})) \quad (25)$$

$$\Delta_{l,l'} = \bar{L}_{l'} + 2.5 - L_l \quad (26)$$

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

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

$$Rec_y = e^{(Rec_{avg} + Rec_{dev,y})} \quad (27)$$

$$Pr_l = \frac{(\Delta_{1,l})^{\alpha_{rec}/\beta_{rec}} e^{-\Delta_{1,l}/\beta_{rec}}}{\sum_{l'} (\Delta_{1,l'})^{\alpha_{rec}/\beta_{rec}} e^{-\Delta_{1,l'}/\beta_{rec}}} \quad (28)$$

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

Likelihood components

Three general types of likelihood components were used to fit to the available data (Table 8). Multinomial likelihoods were used for size composition data, log-normal likelihoods were used for indices of abundance data, and normal likelihoods were used for catch data, growth data, priors, and penalties. Multinomial likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y N_{x,y}^{eff} \sum_l p_{x,y,l}^{obs} \ln(\hat{p}_{x,y,l}/p_{x,y,l}^{obs}) \quad (29)$$

L_x was the likelihood associated with data component x , where λ_x represented an optional additional weighting factor for the likelihood, $N_{x,y}^{eff}$ was the effective sample sizes for the likelihood, $p_{x,y,l}^{obs}$ was the observed proportion in size bin l during year y for data component x , and $\hat{p}_{x,y,l}$ was the predicted proportion in size bin l during year y for data component x . 10 multinomial likelihood components were included in the assessment (see Table 8 for descriptions, weighting factors, and effective sample sizes).

Log normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y \frac{(\ln(\hat{I}_{x,y}) - \ln(I_{x,y}))^2}{2(\ln(CV_{x,y}^2 + 1))} \quad (30)$$

L_x was the contribution to the objective function of data component x , λ_x was any additional weighting applied to the component, $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y ,

$I_{x,y}$ was the observed value of quantity I from data component x during year y and $CV_{x,y}$ was the coefficient of variation for data component x during year y . 5 log normal likelihood components were included in this assessment (see Table 8 for descriptions, weighting factors, and CVs).

Normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y (\hat{I}_{x,y} - I_{x,y})^2 \quad (31)$$

L_x was the contribution to the objective function of data component x , λ_x was represents the weight applied to the data component (and can be translated to a standard deviation), $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y , $I_{x,y}$ was the observed value of quantity I from data component x during year y . 12 normal likelihood components were included in the base assessment (see Table 8 for descriptions, weighting factors, and translated standard deviations).

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

Table 1: Observed growth increment data by sex

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

Female premolt length (mm)	Female postmolt length (mm)	Male premolt length (mm)	Male postmolt length (mm)
23.09	29.26		
32.8	44.9		
35.3	47.6		
38.3	50.9		
38.9	53		
41	55.8		
42.1	54.6		
44.2	59.5		
44.3	59.3		
44.8	59.7		
45.2	59.6		
46.9	60.4		
47	61.4		
47.9	61.4		
20.6	25.1		
20.8	27.6		
22	28.2		
22.9	28.6		

Table 2: Observed retained catches, discarded catch, and bycatch

Survey year	Retained catch (kt)	Discarded females (kt)	Discarded males (kt)	Trawl bycatch (kt)
1982	11.85	0.02	1.22	0.38
1983	12.16	0.01	1.2	0.49
1984	29.94	0.01	2.67	0.52
1985	44.45	0.01	3.88	0.45
1986	46.22	0.02	4.1	1.91
1987	61.4	0.03	5.34	0.01
1988	67.79	0.04	5.62	0.69
1989	73.4	0.05	6.46	0.8
1990	149.1	0.05	14.71	0.61
1991	143	0.06	11.6	1.88
1992	104.7	0.12	17.06	1.78
1993	67.94	0.08	5.32	1.76
1994	34.13	0.06	4.03	3.54
1995	29.81	0.02	5.75	1.34
1996	54.22	0.07	7.44	0.92
1997	114.4	0.01	5.73	1.47
1998	88.09	0.01	4.67	1.01
1999	15.1	0	0.52	0.61
2000	11.46	0	0.62	0.53
2001	14.8	0	1.89	0.39
2002	12.84	0	1.47	0.23
2003	10.86	0	0.57	0.76
2004	11.29	0	0.51	0.95
2005	16.77	0	1.36	0.36
2006	16.49	0	1.78	0.83
2007	28.59	0.01	2.53	0.43
2008	26.56	0.01	2.06	0.27
2009	21.78	0.01	1.23	0.63
2010	24.61	0.01	0.62	0.17
2011	40.29	0.18	1.69	0.16
2012	30.05	0.03	2.32	0.22
2013	24.49	0.07	3.27	0.12
2014	30.82	0.17	3.52	0.16
2015	18.42	0.07	2.96	0.16
2016	9.67	0.02	1.31	0.08
2017	8.6	0.02	1.93	0.02

Table 3: Observed mature male and female biomass (1000 t) at the time of the survey and coefficients of variation.

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

Table 4: Parameter bounds and symbols

Parameter	Lower	Upper	Symbol
af	-100	5	α_f
am	-50	5	α_m
bf	1	10	$\beta_{f,1}$
bm	1	5	$\beta_{m,1}$
b1	1	1.5	$\beta_{f,2}$
bf1	1	2	$\beta_{m,2}$
deltam	10	50	δ_m
deltaf	5	50	δ_f
st_gr	0.5	0.5	stgr
growth_beta	0.749	0.751	β_g
mateste	-6	-1e-10	$\Omega_{m,l}$
matestfe	-6	-1e-10	$\Omega_{f,l}$
mean_log_rec	“-inf”	Inf	Rec_{avg}
rec_devf	-15	15	$Rec_{f,dev,y}$
alpha1_rec	11.49	11.51	α_{rec}
beta_rec	3.99	4.01	β_{rec}
mnatlen_styr	-3	15	$\lambda_{male,v,l}$
fnatlen_styr	-10	15	$\lambda_{fem,v,l}$
log_avg_fmort	“-inf”	Inf	$F_{avg,dir}^{log}$
fmort_dev	-5	5	$F_{dev,dir,y}^{log}$
log_avg_fmortdf	-8	-1e-04	$F_{avg,disc}^{log}$
fmortdf_dev	-15	15	$F_{dev,disc,y}^{log}$
log_avg_fmortt	-8	-1e-04	$F_{avg,trawl}^{log}$
fmortt_dev_era1	-15	15	$F_{dev,trawl,era1}^{log}$
fmortt_dev_era2	-15	15	$F_{dev,trawl,era2}^{log}$
log_avg_sel50_mn	4	5	$S_{50,new,dir}$
log_avg_sel50_mo	4	5	$S_{50,old,dir}$
fish_slope_mn	0.1	0.5	$S_{slope,m,d}$
fish_fit_slope_mn	0.05	0.5	$S_{slope,m,d}$
fish_fit_sel50_mn	85	120	$S_{50,old,dir}$
fish_slope_mo2	1.9	2	$S_{slope,m,d}$
fish_sel50_mo2	159	160	$S_{50,old,dir}$
fish_slope_mn2	0.01	2	$S_{slope,m,d}$
fish_sel50_mn2	100	160	$S_{50,old,dir}$
fish_disc_slope_f	0.1	0.7	$S_{slope,m,d}$
fish_disc_sel50_f	1	5	$S_{50,old,dir}$
fish_disc_slope_tf	0.01	0.3	$S_{slope,trawl}$
fish_disc_sel50_tf	30	120	$S_{50,trawl}$
srv1_q	0.2	1	$q_{m,era1,surv}$
srv1_q_f	0.2	1	$q_{f,era1,surv}$
srv1_sel95	30	150	$S_{95,era1,surv}$
srv1_sel50	0	150	$S_{50,era1,surv}$
srv2_q	0.2	1	$q_{m,era2,surv}$
srv2_q_f	0.2	1	$q_{f,era2,surv}$
srv2_sel95	50	160	$S_{95,era2,surv}$
srv2_sel50	0	80	$S_{50,era2,surv}$
srv3_q	0.2	1	$q_{m,era3,surv}$
srv3_sel95	40	200	$S_{95,m,era2,surv}$
srv3_sel50	25	90	$S_{50,m,era2,surv}$

Parameter	Lower	Upper	Symbol
srv3_q_f	0.2	1	$q_{f,era3,surv}$
srv3_sel95_f	40	150	$S_{95,f,era2,surv}$
srv3_sel50_f	0	90	$S_{50,f,era2,surv}$
srvind_q	0.1	1	$q_{m,09,ind}$
srvind_q_f	0.01	1	$q_{f,09,ind}$
srvind_sel95_f	55	120	$S_{95,f,09,ind}$
srvind_sel50_f	-50	110	$S_{50,f,09,ind}$
srv10in_q	0.1	1	$q_{m,10,ind}$
srv10ind_q_f	0.01	1	$q_{f,10,ind}$
selsmo10ind	-4	-0.001	SelVecMaleInd09
selsmo09ind	-4	-0.001	SelVecMaleInd10
Mmult_imat	0.2	2	$\gamma_{natM,imm}$
Mmult	0.2	2	$\gamma_{natM,mat,m}$
Mmultf	0.2	2	$\gamma_{natM,mat,f}$
cpueq	0.0000877	0.00877	q_{cpue}

Table 5: Maximum likelihood estimates of parameter values by scenario

Parameter	18.1	19.1	19.2	19.3	19.4
af	-1.46	-1.45	-1.15	-1.15	-1.52
am	-0.78	-0.98	2.05	1.31	-0.94
bf	1.35	1.35	1.34	1.34	1.35
bm	1.36	1.37	1.23	1.26	1.37
b1	1.17	1.16	1.16	1.2	1.17
bf1	1.04	1.04	1.04	1	1.05
deltam	32.53	32.52	200	42.86	32.57
deltaf	41.1	41.11	200	44.44	41.09
mateste	vector	vector	vector	vector	vector
matestfe	vector	vector	vector	vector	vector
rec_devf	vector	vector	vector	vector	vector
mnatlen_styr	vector	vector	vector	vector	vector
fnatlen_styr	vector	vector	vector	vector	vector
log_avg_fmort	-0.17	-0.23	-0.17	-0.2	-0.07
fmort_dev	vector	vector	vector	vector	vector
log_avg_fmortdf	-5.62	-5.65	-6.01	-5.67	-5.38
fmortdf_dev	vector	vector	vector	vector	vector
log_avg_fmortt	-4.62	-4.62	-4.59	-4.63	-4.63
fmortt_dev_era1	vector	vector	vector	vector	vector
fmortt_dev_era2	vector	vector	vector	vector	vector
log_avg_sel50_mn	4.66	4.66	4.66	4.66	4.66
fish_slope_mn	0.19	0.19	0.19	0.19	0.2
fish_fit_slope_mn	0.43	0.44	0.45	0.44	0.44
fish_fit_sel50_mn	96.14	96.12	96.01	96.08	96.11
fish_disc_slope_f	0.26	0.26	0.26	0.25	0.26
fish_disc_sel50_f	4.25	4.25	4.23	4.25	4.26
fish_disc_slope_tf	0.08	0.08	0.08	0.08	0.08
fish_disc_sel50_tf	110.18	111.47	111.2	110.52	108.59
srv2_q	0.52	0.47	0.48	0.49	0.79
srv2_q_f	0.75	0.56	0.59	0.56	0.97
srv2_sel95	58.85	57.7	59.4	58.69	55.32
srv2_sel50	39.99	39.03	40.23	39.6	38.64
srv3_q	0.78	0.74	0.75	0.75	0.99
srv3_sel95	49.04	48.99	52.03	50.94	50.51
srv3_sel50	34.94	34.9	36.1	35.8	35.6
srv3_q_f	1	1	1	1	1
srv3_sel95_f	47.2	46.66	46.53	46.81	48.17
srv3_sel50_f	36.1	35.82	35.72	35.91	36.79
srvind_q	1	0.29	1	0.29	1
srvind_q_f	0.16	0.12	0.12	0.12	0.15
srvind_sel95_f	54.56	43.09	43.33	43.31	47.69
srvind_sel50_f	49.79	43.07	43.23	43.31	47.56
srv10ind_q_f	1	1	1	1	0.75
selsmo10ind	vector	vector	vector	vector	vector
selsmo09ind	vector	vector	vector	vector	vector
Mmult_imat	1.18	1.2	1.19	1.2	1.15
Mmult	1.14	1.16	1.17	1.17	1.16
Mmultf	1.57	1.52	1.51	1.52	1.88
cpueq	0	0	0	0	0

Table 6: Contribution to the objective function by individual likelihood component by modeling scenario. Values in columns after Model 0 are the likelihood contribution of Model 0 minus the likelihood contribution of the model in the column. Positive values represent improvements in fit. Note that some of the model scenarios involve changing the weightings of data sources which invalidate the comparison of likelihoods for a data source among models.

Likelihood component	18.1	19.1	19.2	19.3	19.4
Recruitment deviations	70.18	69.79	71.1	70.32	79.93
Initial numbers old shell males small length bins	4.62	4.66	4.83	4.74	4.69
ret fishery length	320.96	327.54	350.27	340.69	320.94
total fish length (ret + disc)	920.93	925.48	941.45	935.53	921.02
female fish length	241.32	239.81	237.05	240.88	235.45
survey length	4293.05	4299.14	4406.17	4327.54	4408.28
trawl length	300.15	286.75	286.84	284.51	310.15
2009 BSFRF length	-92.24	-82.15	-86.22	-82.61	-87.38
2009 NMFS study area length	-75.15	-65.09	-63.92	-64.48	-72.81
M multiplier prior	77.61	73.83	72.03	76.33	152.52
maturity smooth	43.65	43.05	61.91	55.56	44.37
growth males	140.07	142.35	0	1166.28	140.32
growth females	394.96	396.02	0	700.28	387.76
2009 BSFRF biomass	0.47	0.25	0.37	0.26	0.9
2009 NMFS study area biomass	0.22	0.3	0.21	0.3	0.57
cpue q	0.21	0.21	0.21	0.2	0.25
retained catch	3.65	3.96	4.8	4.61	4.55
discard catch	116.77	137.25	170.25	161.31	117.17
trawl catch	6.95	7.12	7.1	6.84	9.18
female discard catch	4.17	4.49	6.05	4.53	3.53
survey biomass	207.32	226.46	235.3	231.24	604.09
F penalty	23.51	23.91	26.77	25.14	24.04
2010 BSFRF Biomass	9.58	11.26	8.75	11.28	10.71
2010 NMFS Biomass	3.44	2.57	4.17	2.58	6.01
Extra weight survey lengths	547.47	551.79	640.07	548.89	669.91
first year					
2010 BSFRF length	-51.66	-51.63	-47.16	-49.73	-50.08
2010 NMFS length	-64.14	-64.63	-59.16	-63.13	-66.59

Likelihood component	18.1	19.1	19.2	19.3	19.4
smooth selectivity	2.44	0.73	2.04	0.69	2.42
smooth female selectivity	0	0	0	0	0
init nos smooth constraint	43.32	43.9	37.17	44.9	37.02
Total	7493.83	7559.12	7318.45	8985.48	8218.92

Table 7: Changes in management quantities for each scenario considered.

Model	MMB	B35	F35	FOFL	OFL
18.1	85.84	142.8	1.22	1.04	29.74
19.1	94.64	141.2	1.32	1.15	34.12
19.2	92.23	137.8	1.36	1.17	33.77
19.3	93.58	141	1.34	1.16	34.15
19.4	72.86	129.9	1.12	0.9	24.6

Table 8: Likelihoods form and weighting for each likelihood component for models in the analysis (continued below)

Likelihood component	Form	18.1	19.1
Recruitment deviations	normal	0.71	0.71
Initial numbers old shell males small length bins	normal	707.1	707.1
ret fishery length	multinomial	200	200
total fish length (ret + disc)	multinomial	200	200
female fish length	multinomial	200	200
survey length	multinomial	NA	NA
trawl length	multinomial	200	200
2009 BSFRF length	multinomial	200	200
2009 NMFS study area length	multinomial	200	200
M multiplier prior	normal	0.23	0.23
maturity smooth	normal	3.16	3.16
growth males	normal	0.71	0.71
growth females	normal	0.32	0.32
2009 BSFRF biomass	lognormal	NA	NA
2009 NMFS study area biomass	lognormal	NA	NA
cpue q	normal	0.32	0.32
retained catch	normal	0.22	0.22
discard catch	normal	3	3
trawl catch	normal	0.22	0.22
female discard catch	normal	17	17
survey biomass	lognormal	NA	NA
F penalty	normal	0.5	0.5
2010 BSFRF Biomass	lognormal	NA	NA
2010 NMFS Biomass	lognormal	NA	NA
Extra weight survey lengths	multinomial	200	200
first year 2010 BSFRF length	multinomial	200	200
2010 NMFS length	multinomial	200	200
smooth selectivity	norm2(firstdiff(firstDiff))	2	2
smooth female selectivity	norm2(firstdiff(firstDiff))	3	3
init nos smooth constraint	norm2(firstdifference)	1	1

19.2	19.3	19.4
0.71	0.71	0.71
707.1	707.1	707.1
200	200	200
200	200	200
200	200	200
NA	NA	NA
200	200	200
200	200	200
200	200	200
0.23	0.23	0.23
3.16	3.16	3.16
0.22	0.22	0.71
0.22	0.22	0.32
NA	NA	NA
NA	NA	NA
0.32	0.32	0.32
0.22	0.22	0.22
3	3	3
0.22	0.22	0.22
17	17	17
NA	NA	NA
0.5	0.5	0.5
NA	NA	NA
NA	NA	NA
200	200	200
200	200	200
200	200	200
2	2	2
3	3	3
1	1	1

Table 10: Predicted mature male (MMB), mature female (FMB), and males >101mm biomass (1000 t) and numbers (in millions) at the time of the survey from the chosen model. Columns 2-5 are subject to survey selectivity; columns 6-9 are the population values (i.e. the numbers at length are not modified by multiplying them by a selectivity curve—they are estimates of the underlying population). These are based on maximum likelihood estimates of parameter values.

Survey year	FMB	MMB	Male >101 biomass	Male >101 (millions)	FMB	MMB	Male >101 biomass	Male >101 (millions)
1982	65.22	121.3	28.61	54.27	97.17	233.3	47.68	90.46
1983	53.85	129.7	49.22	87.75	79.3	249.4	82.03	146.3
1984	40.52	137.9	67.47	115.7	59.72	265.5	112.5	192.8
1985	35.97	132.3	68.73	116.1	53.31	255.2	114.6	193.5
1986	44.37	117.1	46.27	78.04	66.26	226.5	88.72	149.6
1987	102.1	117.3	39.84	69.39	154.1	228	76.38	133
1988	208.7	200.6	44.35	77.37	212.5	257.3	85.02	148.3
1989	206.5	241	54.94	95.78	209.8	309.1	105.3	183.6
1990	173.4	305.6	84.45	146.3	176	391.7	161.9	280.5
1991	149.2	287.4	77.77	134.5	151.6	368.2	149.1	257.9
1992	137.4	240.6	62.78	109.2	139.7	308.2	120.4	209.3
1993	141.3	205.5	80.92	136.7	143.8	263.7	103.5	174.9
1994	153.3	173.9	48.61	80.82	156	223.2	62.16	103.3
1995	158.9	189.8	45	79.3	161.6	243.5	57.55	101.4
1996	141.5	269.2	110.5	193.8	143.7	344.9	141.3	247.9
1997	112.9	326	180.2	302	114.6	417.4	230.5	386.2
1998	88.28	241.7	125.4	207.2	89.62	309.5	160.4	265
1999	72.15	148.8	60.42	101.2	73.27	190.7	77.26	129.4
2000	64.82	119.2	45.48	75.83	65.88	152.8	58.15	96.97
2001	58.26	100.6	34.35	58.05	59.19	128.9	43.92	74.24
2002	50.27	94.79	33.17	57.46	51.06	121.5	42.42	73.47
2003	42.78	100.9	44.33	75.4	43.46	129.3	56.69	96.42
2004	43.96	102.2	49.31	81.88	44.74	130.9	63.06	104.7
2005	65.11	98.39	43.69	72.36	66.39	126.2	55.87	92.53
2006	78.43	102.9	40.37	68.68	79.8	131.9	51.63	87.83
2007	79.32	127.1	55.28	94.8	80.64	162.9	70.69	121.2
2008	70.46	148.3	72.96	124	71.57	189.9	93.3	158.5
2009	59.91	159.2	86.96	145.4	60.84	203.8	111.2	185.9
2010	90.23	153.8	88.53	146.3	92.06	196.9	113.2	187.1
2011	113.2	131.2	72.91	119.8	115.2	168	93.24	153.2
2012	109.2	94.29	40.92	68.91	110.9	120.8	52.33	88.12
2013	97.49	80.31	30.53	53.32	99.06	102.9	39.04	68.18
2014	90.7	77.83	32.68	55.97	92.2	99.75	41.79	71.57
2015	84.1	63.68	22.77	38.76	85.47	81.67	29.12	49.57
2016	91.97	62.65	19.14	32.81	93.61	80.46	24.48	41.95
2017	137.8	86.73	27.04	46.46	140.5	111.6	34.58	59.41
2018	198.3	139.4	45.7	78.1	202.1	179.1	58.44	99.87

Table 11: Maximum likelihood estimates of predicted mature male biomass at mating, mature female biomass at mating (in 1000 t), recruitment (millions) from the chosen model, and estimated fully-selected total fishing mortality.

Survey year	Mature male biomass	Mature female biomass	Recruits	Fishing mortality
1982	184.6	77.48	162.5	0.42
1983	198.6	63.23	463.6	0.24
1984	194.1	47.61	1087	0.46
1985	170.6	42.5	4557	0.74
1986	143.3	52.81	1517	1.12
1987	131.1	122.9	842.9	2.28
1988	150.9	169.4	373.6	2.26
1989	190.4	167.3	942.3	1.72
1990	187	140.3	891.8	3.32
1991	171.3	120.8	1444	3.86
1992	158.4	111.3	1484	2.83
1993	154.8	114.6	1179	1.65
1994	152	124.2	267.8	1.23
1995	176.6	128.8	208.4	1.04
1996	239.7	114.5	240.2	0.73
1997	239.8	91.36	308.9	1.06
1998	172.2	71.45	454	1.24
1999	145.8	58.41	243.1	0.32
2000	117.3	52.52	194.5	0.33
2001	93.65	47.19	180.1	0.63
2002	89.93	40.7	545.8	0.54
2003	98.38	34.64	1326	0.32
2004	99.05	35.66	536.7	0.3
2005	89.72	52.94	527.1	0.54
2006	94.97	63.61	206.8	0.58
2007	109.8	64.29	257.8	0.78
2008	134.7	57.06	2277	0.5
2009	150.8	48.51	749.4	0.33
2010	142.2	73.41	432.3	0.37
2011	101.3	91.71	532.4	0.87
2012	71.49	88.42	643	1.32
2013	62.54	78.96	446.3	1.48
2014	53.47	73.41	1225	2.04
2015	50.22	68.13	2765	1.55
2016	58.33	74.64	2847	0.76
2017	85.84	112	600	0.44

Table 12: Maximum likelihood estimates of predicted total numbers (billions), not subject to survey selectivity at the time of the survey.

Survey year	Total numbers
1982	3.994
1983	4.322
1984	4.829
1985	6.057
1986	12.26
1987	11.9
1988	12.29
1989	9.464
1990	8.136
1991	6.922
1992	10.36
1993	9.797
1994	8.803
1995	6.856
1996	5.271
1997	4.108
1998	3.709
1999	3.546
2000	3.008
2001	2.549
2002	2.502
2003	3.277
2004	4.705
2005	4.701
2006	4.466
2007	3.599
2008	3
2009	5.112
2010	4.852
2011	4.221
2012	3.747
2013	3.83
2014	3.731
2015	5.34
2016	10.17
2017	12.96
2018	10.65

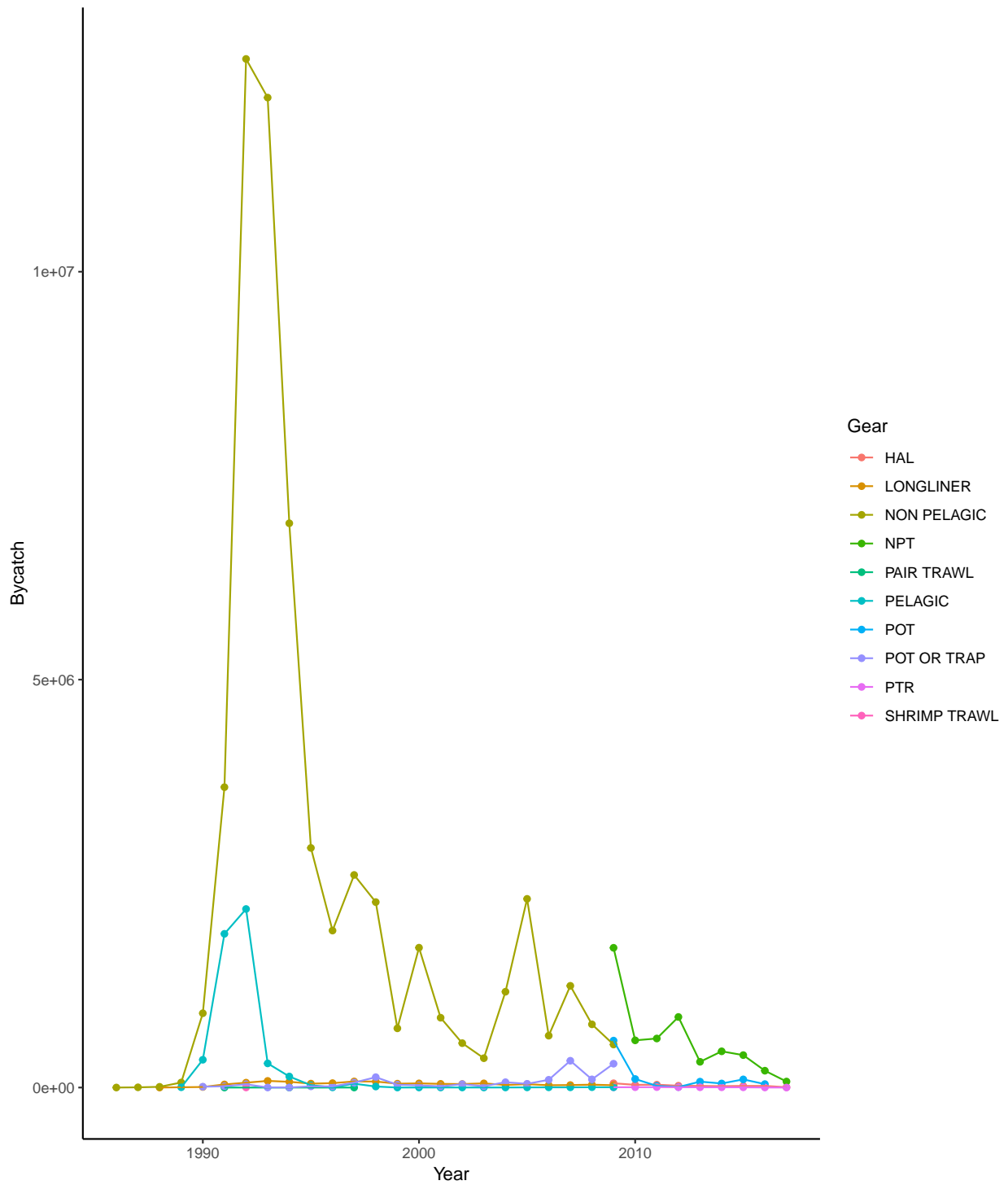


Figure 1: Bycatches in other fishing fleets.

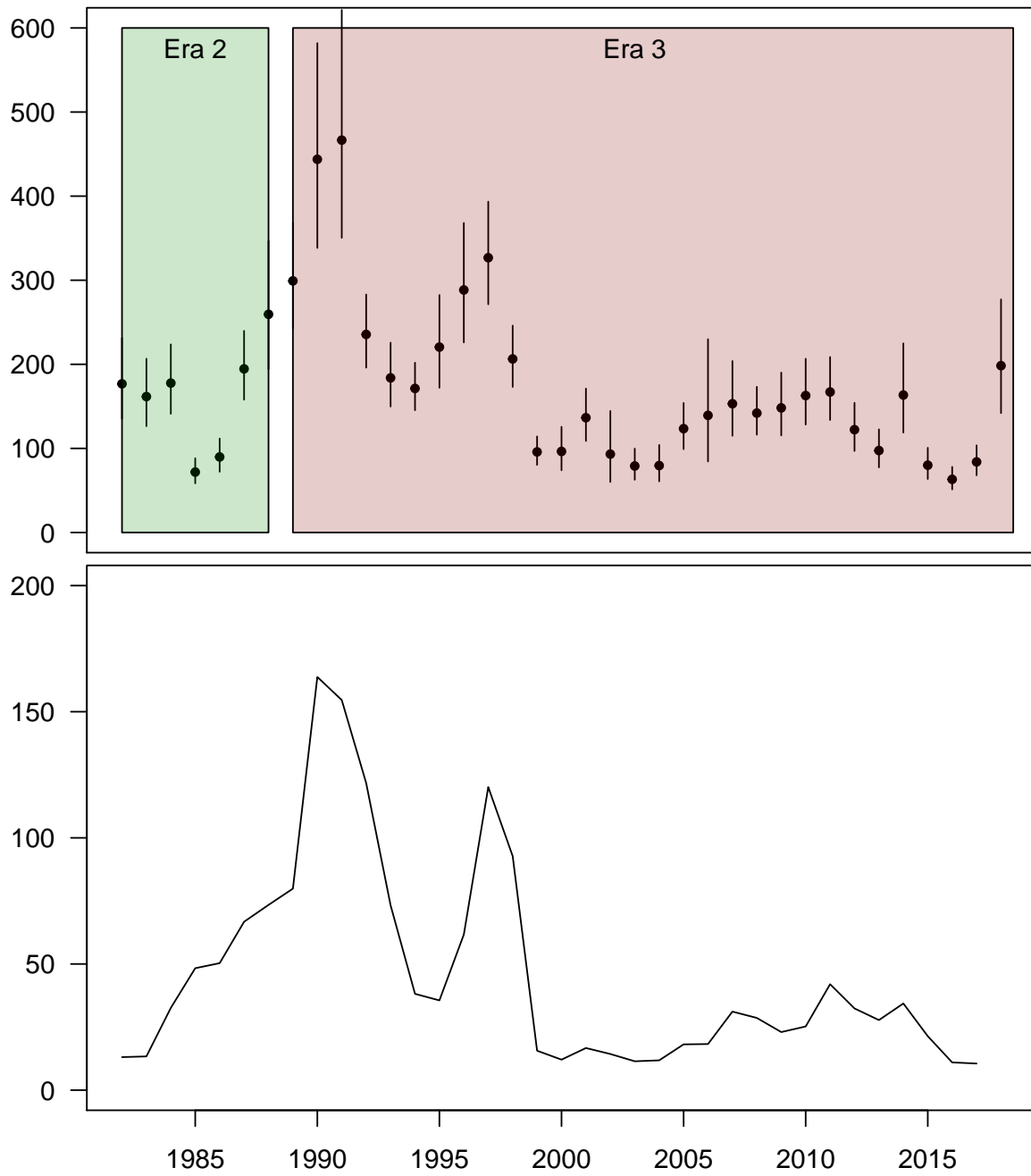


Figure 2: Divisions of survey data for estimation of q (MMB shown for reference; top) and total catches (bottom)

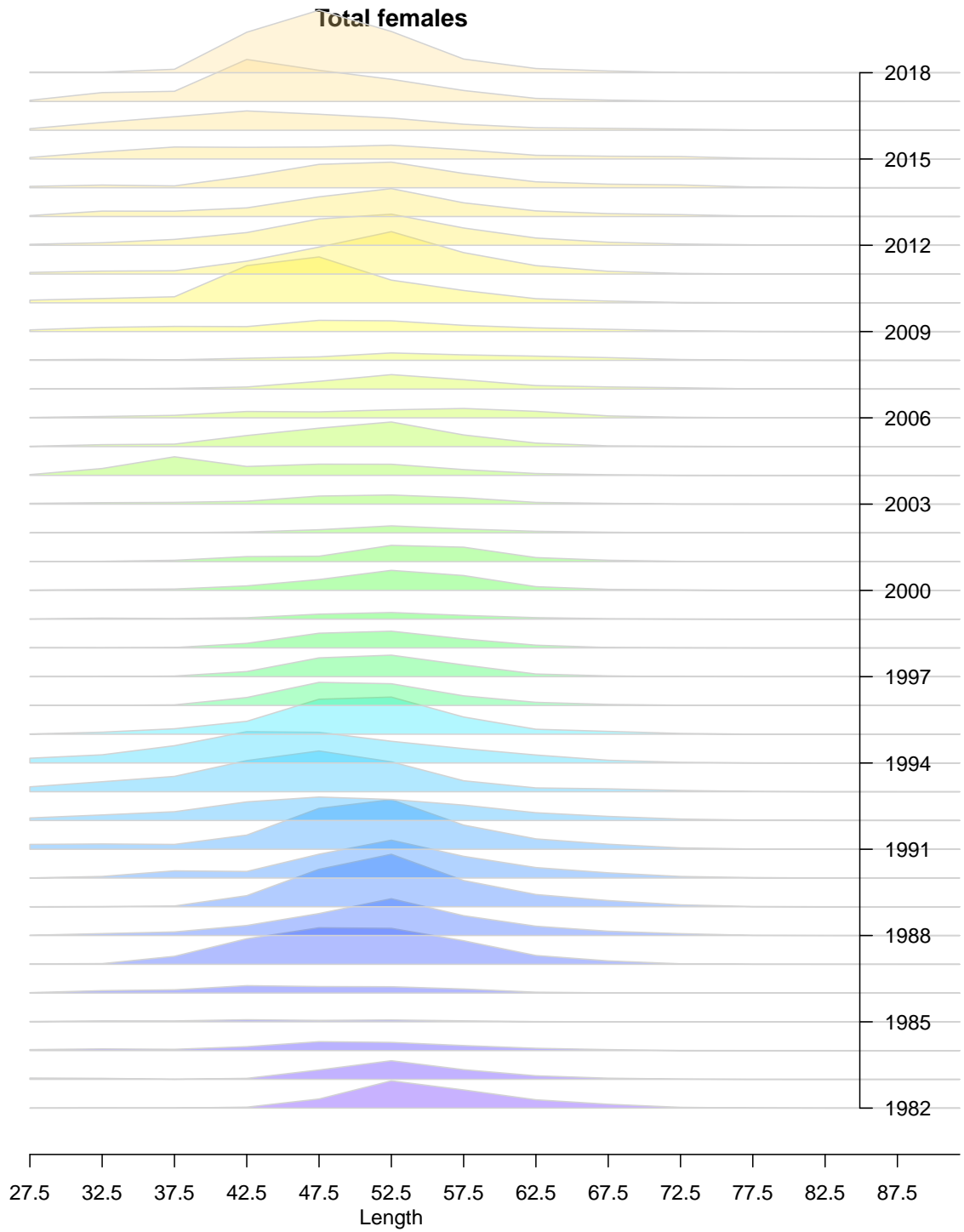


Figure 3: Observed relative numbers at length at the time of the survey

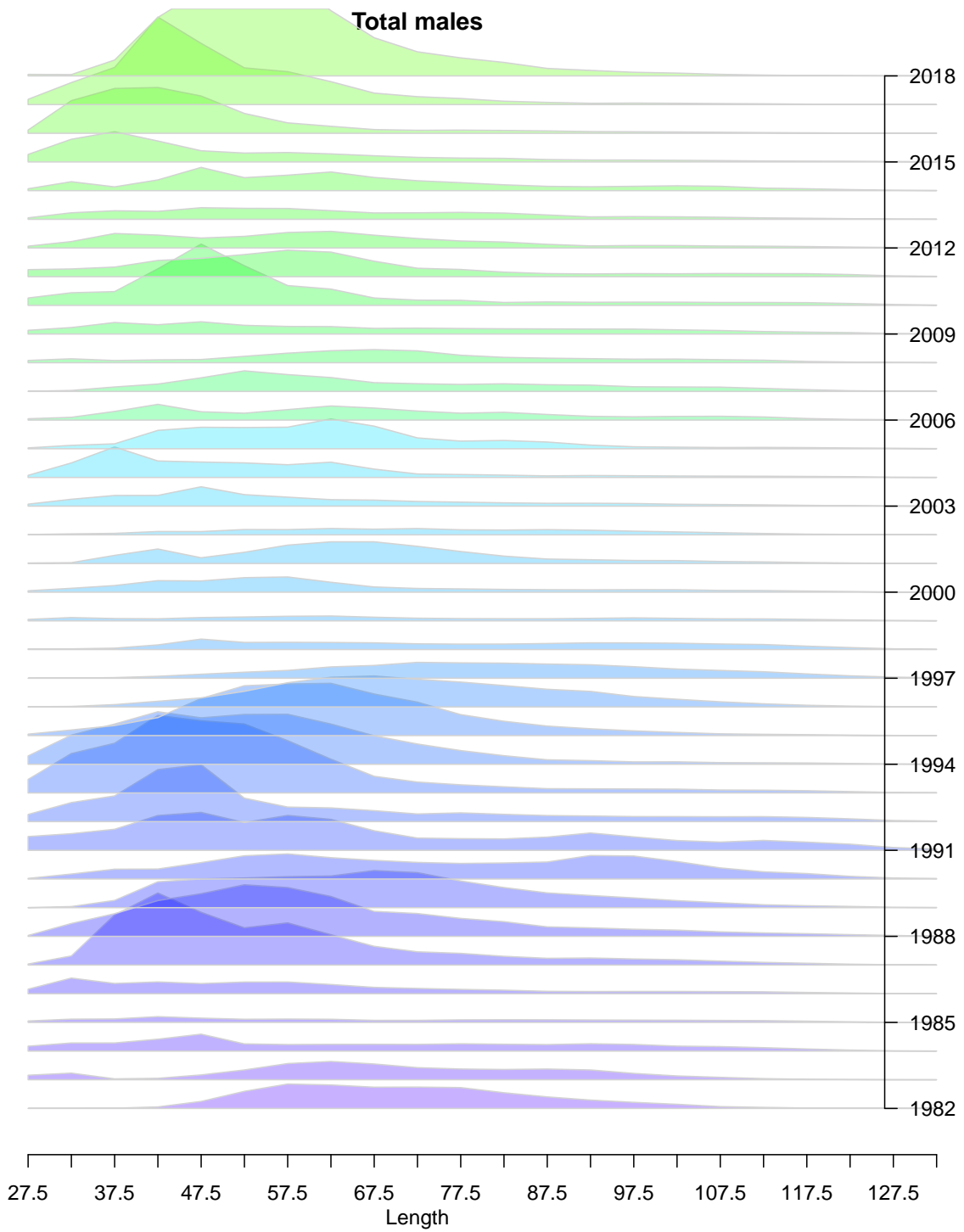


Figure 4: Observed relative numbers at length at the time of the survey

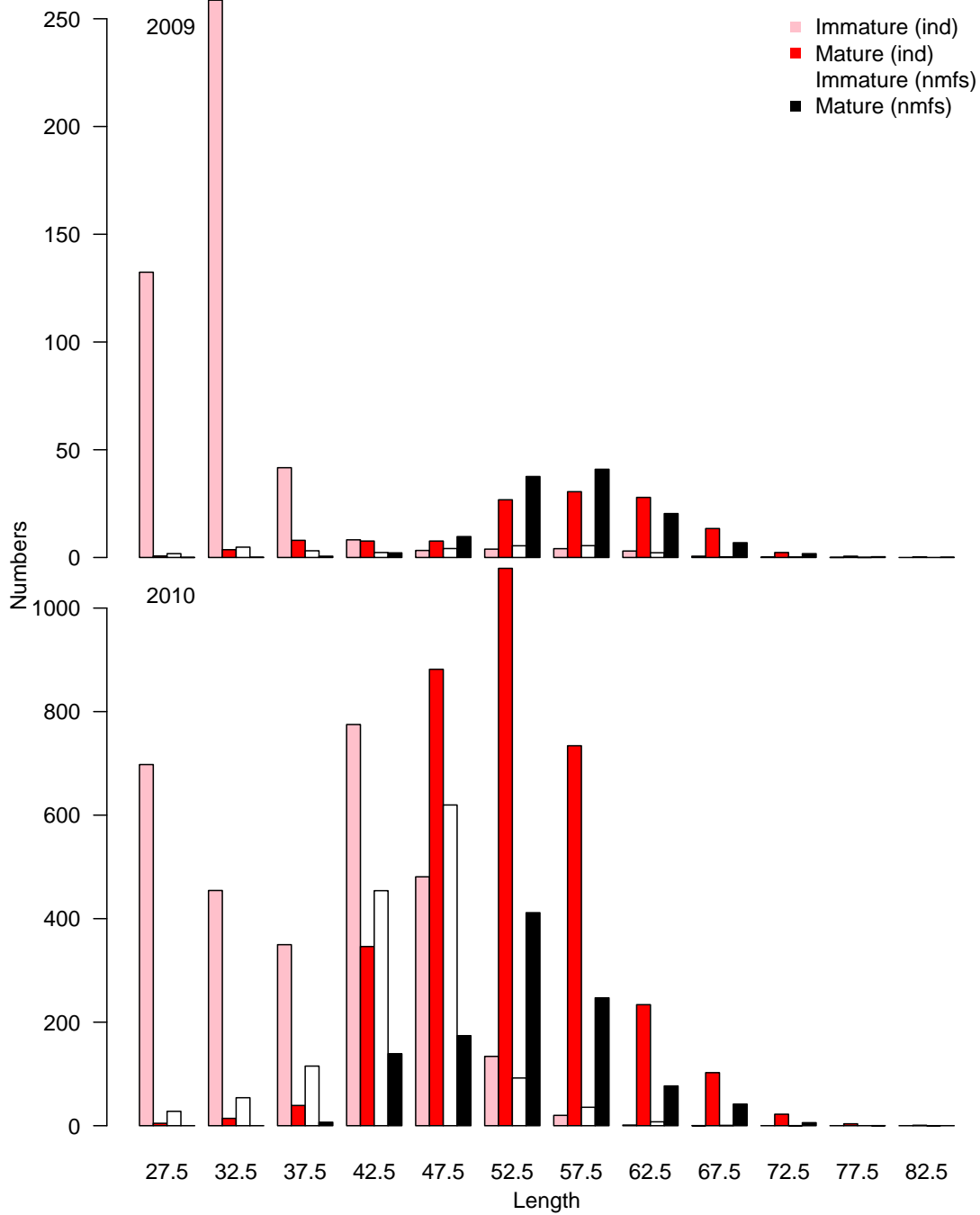


Figure 5: Raw female numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale on the y-axis from 2009 to 2010

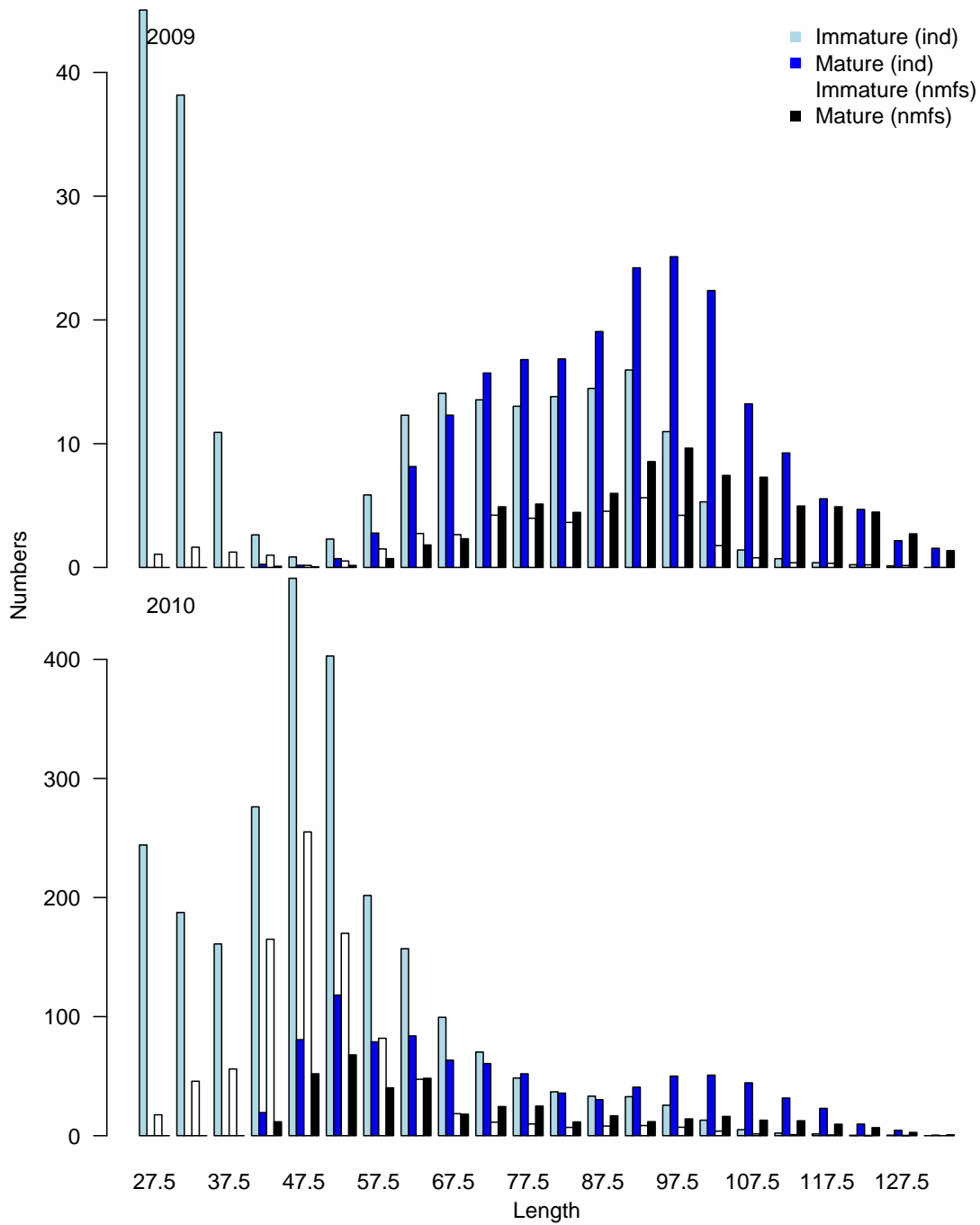


Figure 6: Raw male numbers from BSFRF survey selectivity experiments (2009 & 2010). Note a change in scale from 2009 to 2010 on the y-axis.

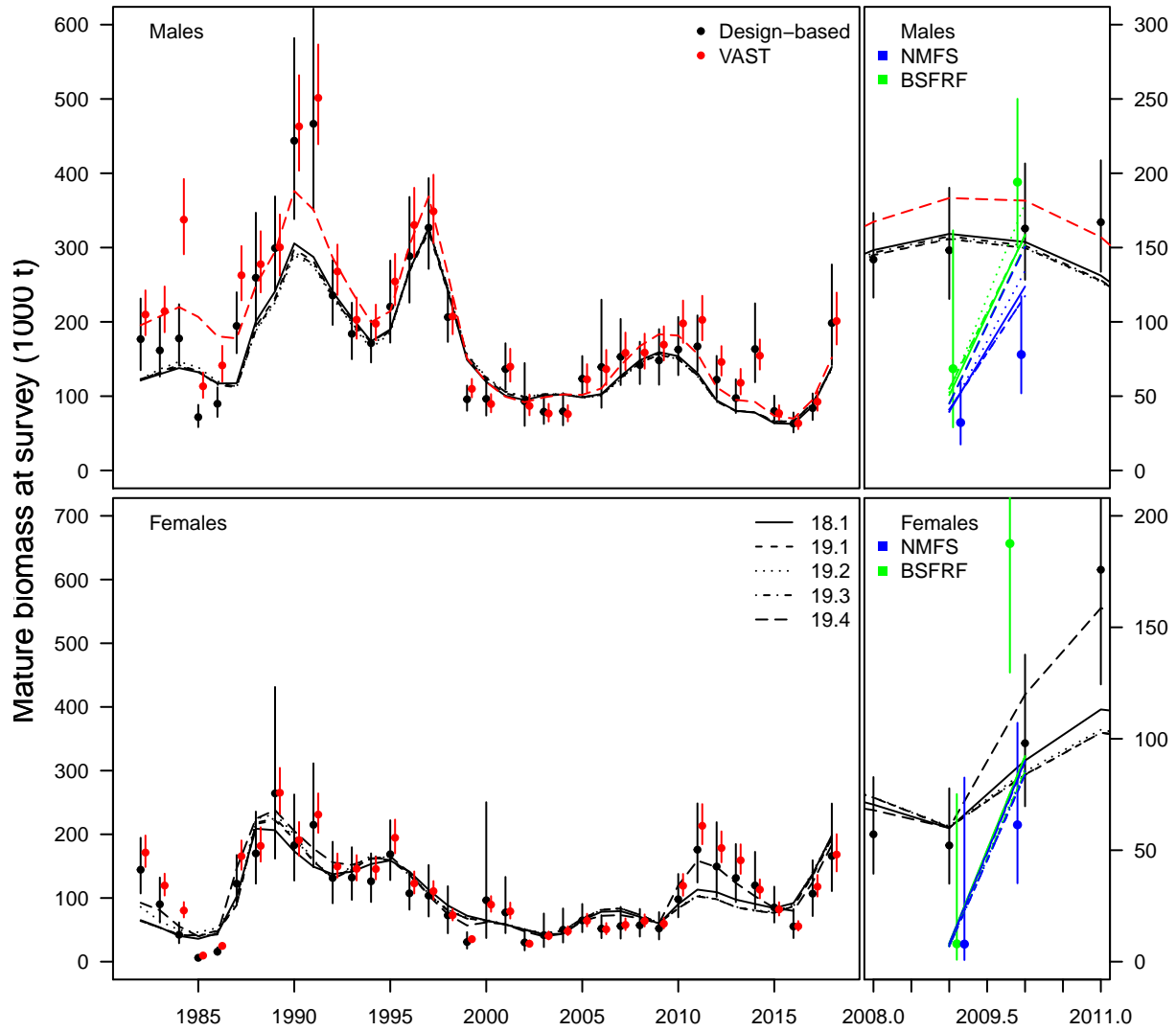


Figure 7: Model fits to the observed mature biomass at survey

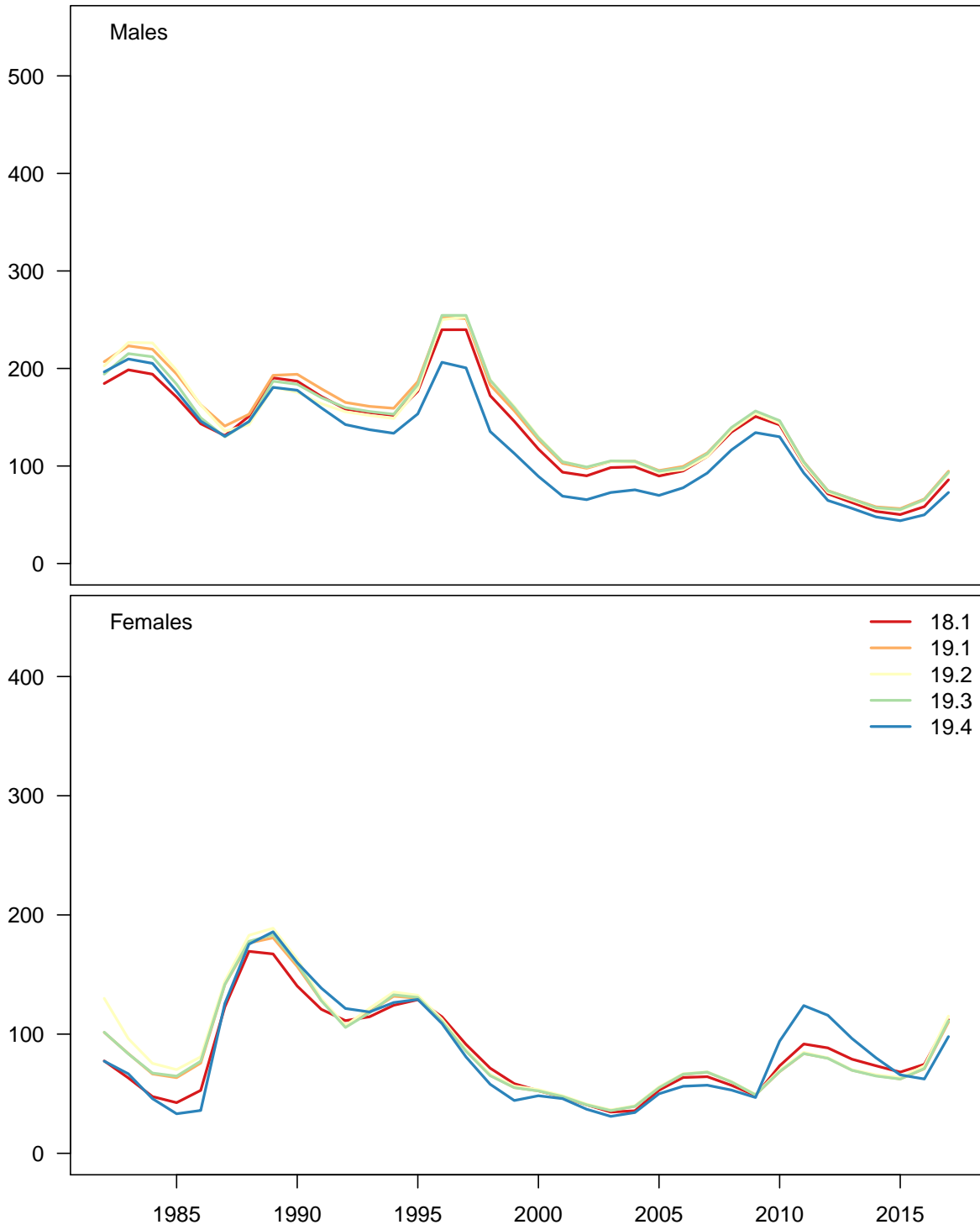


Figure 8: Model predicted mature biomass at mating time

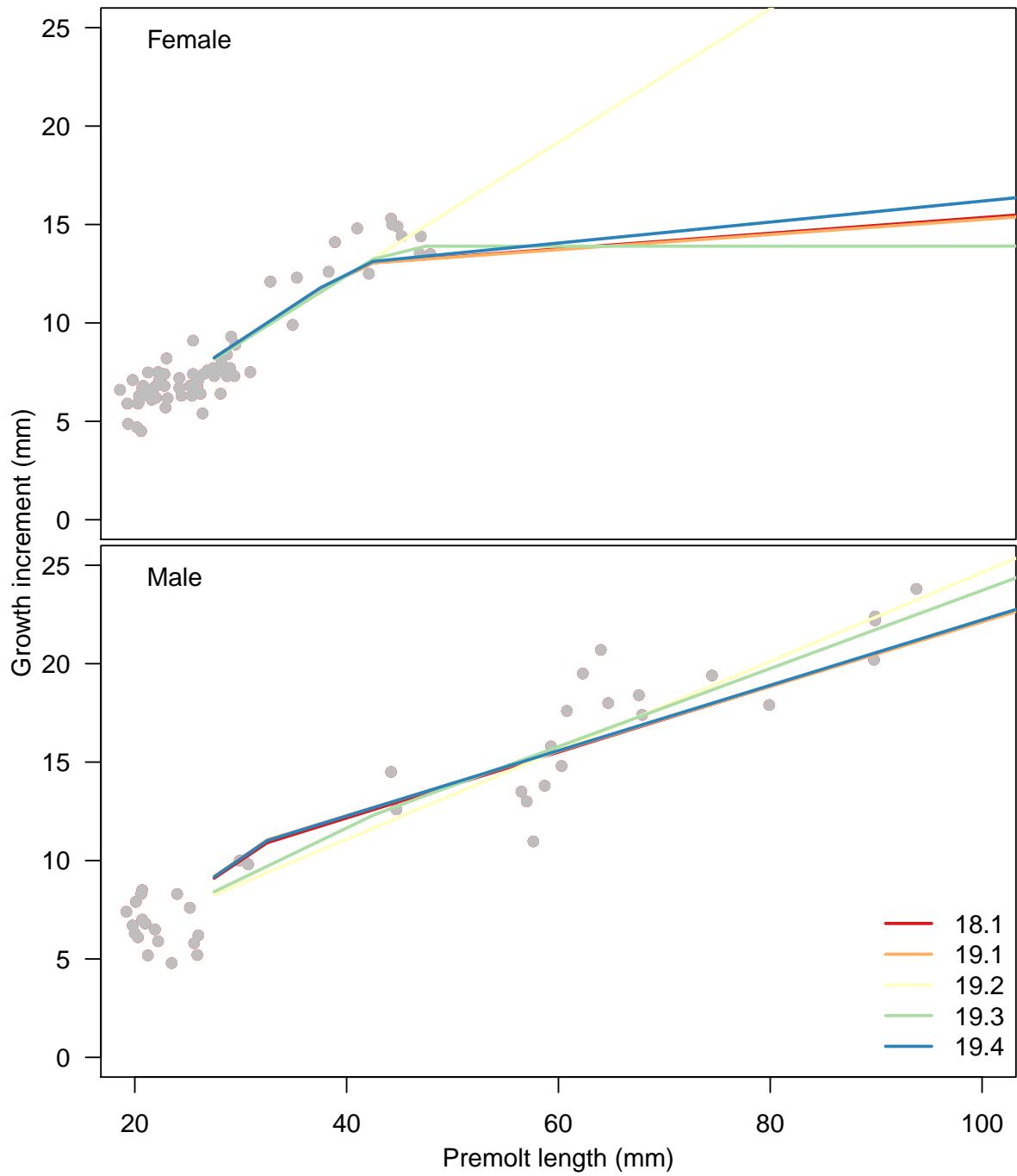


Figure 9: Model fits to the growth data

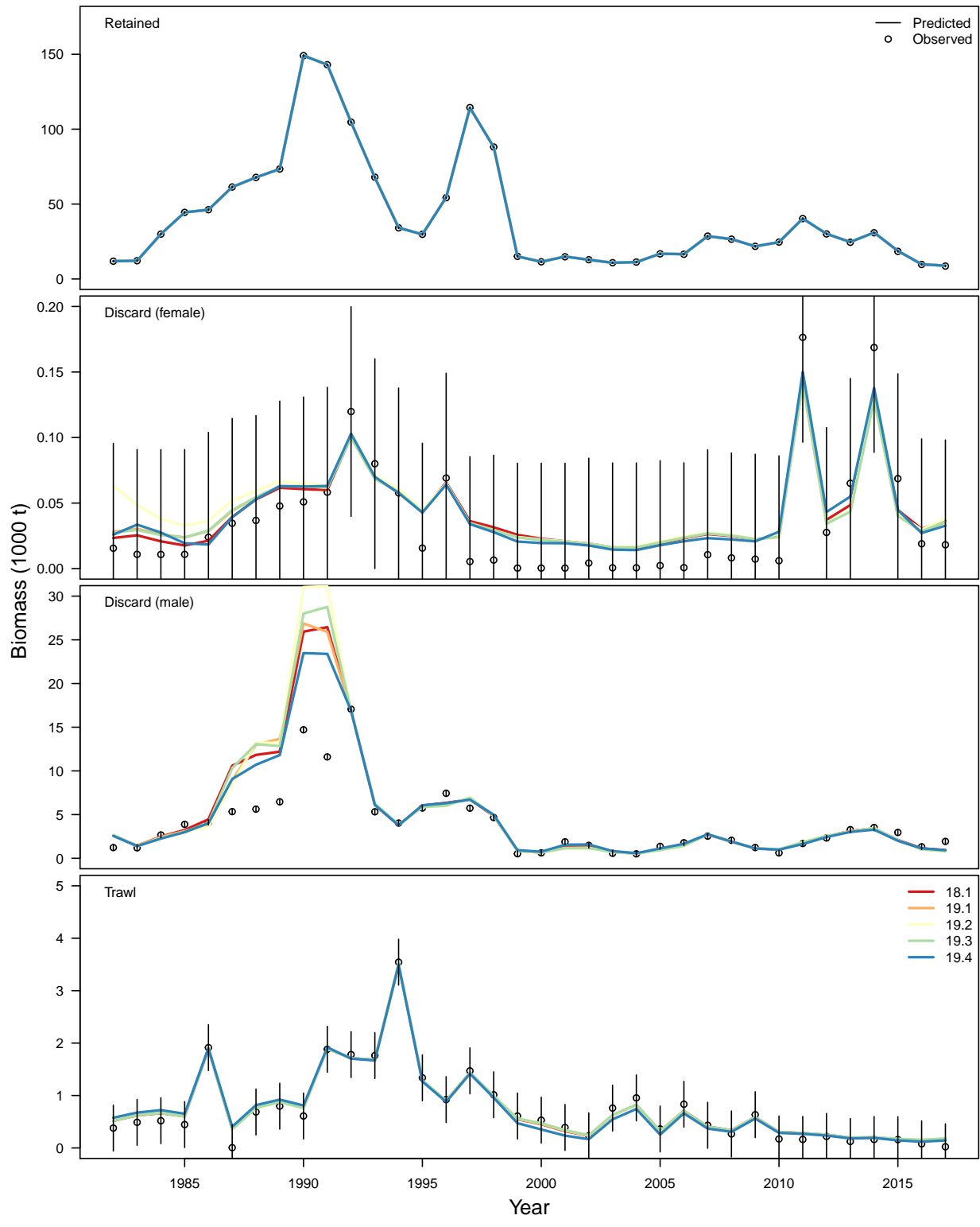


Figure 10: Model fits to catch data

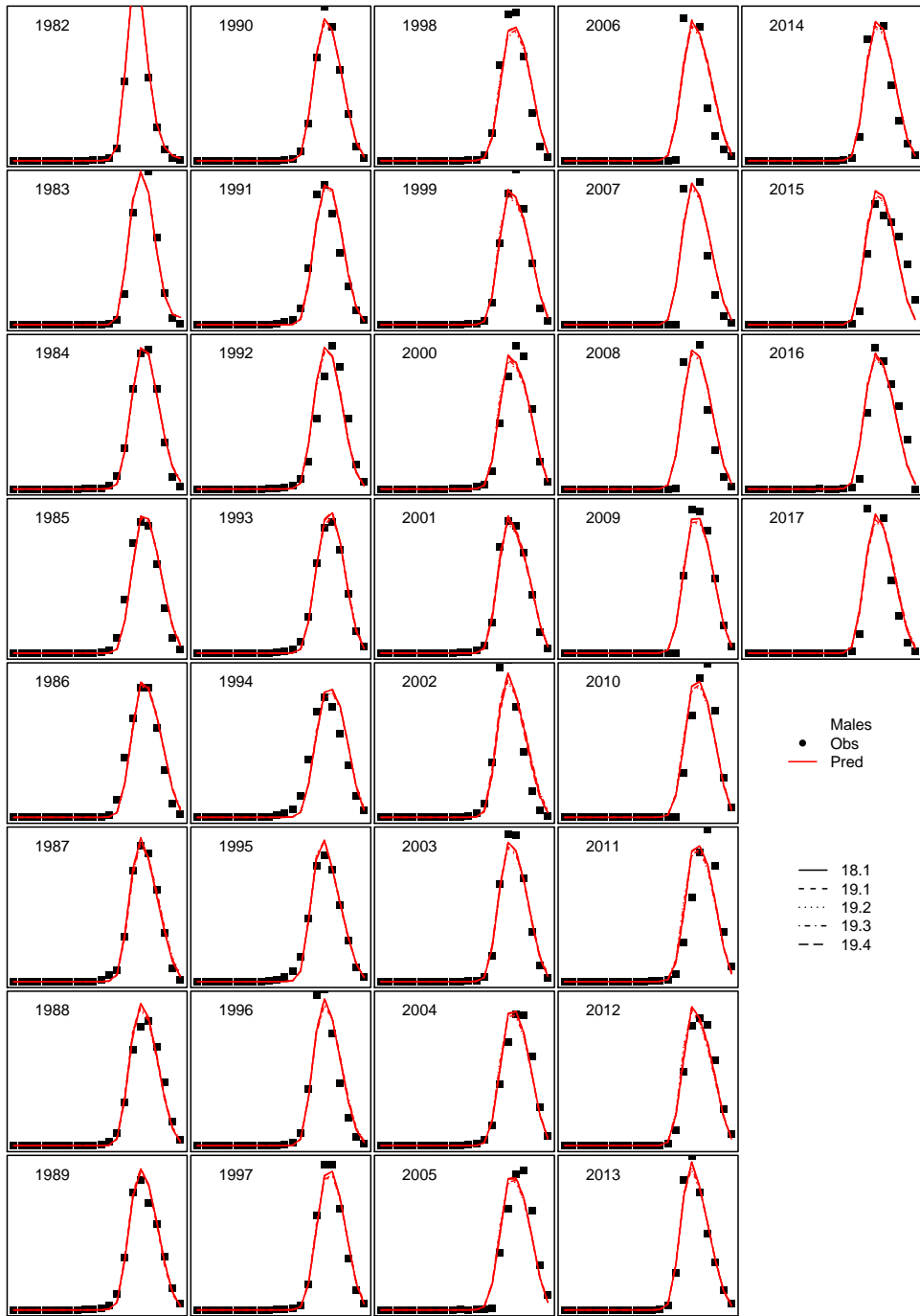


Figure 11: Model fits to retained catch size composition data

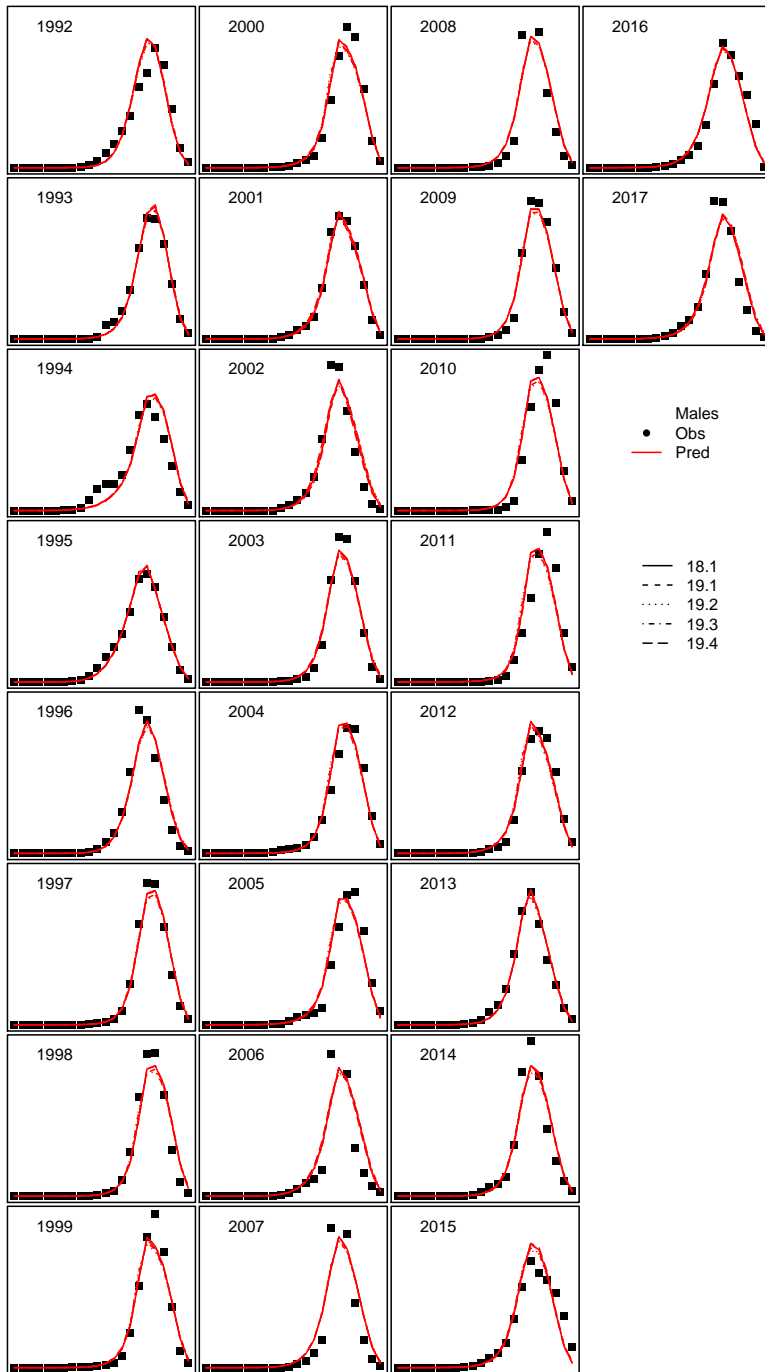


Figure 12: Model fits to total catch size composition data

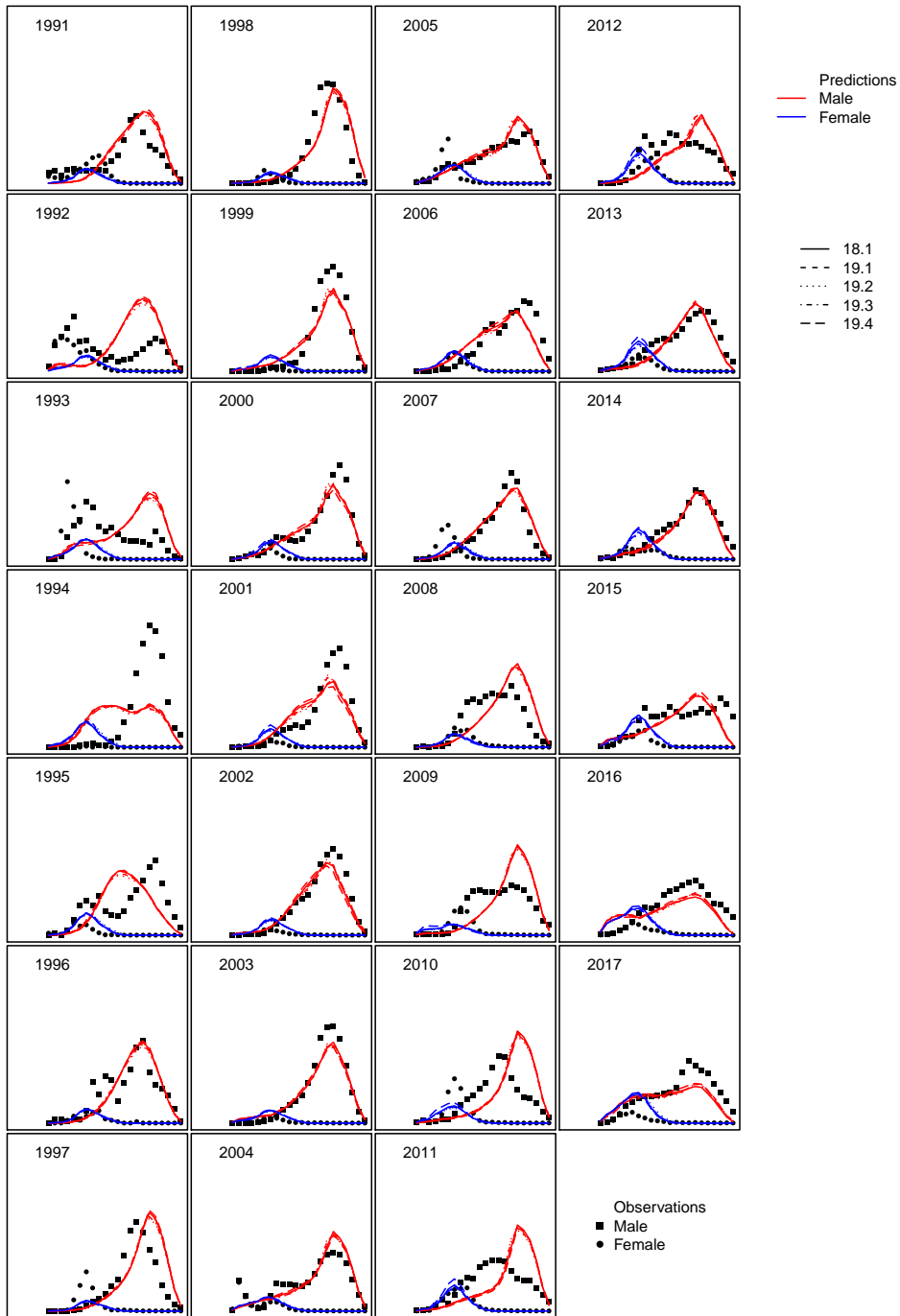


Figure 13: Model fits to trawl catch size composition data

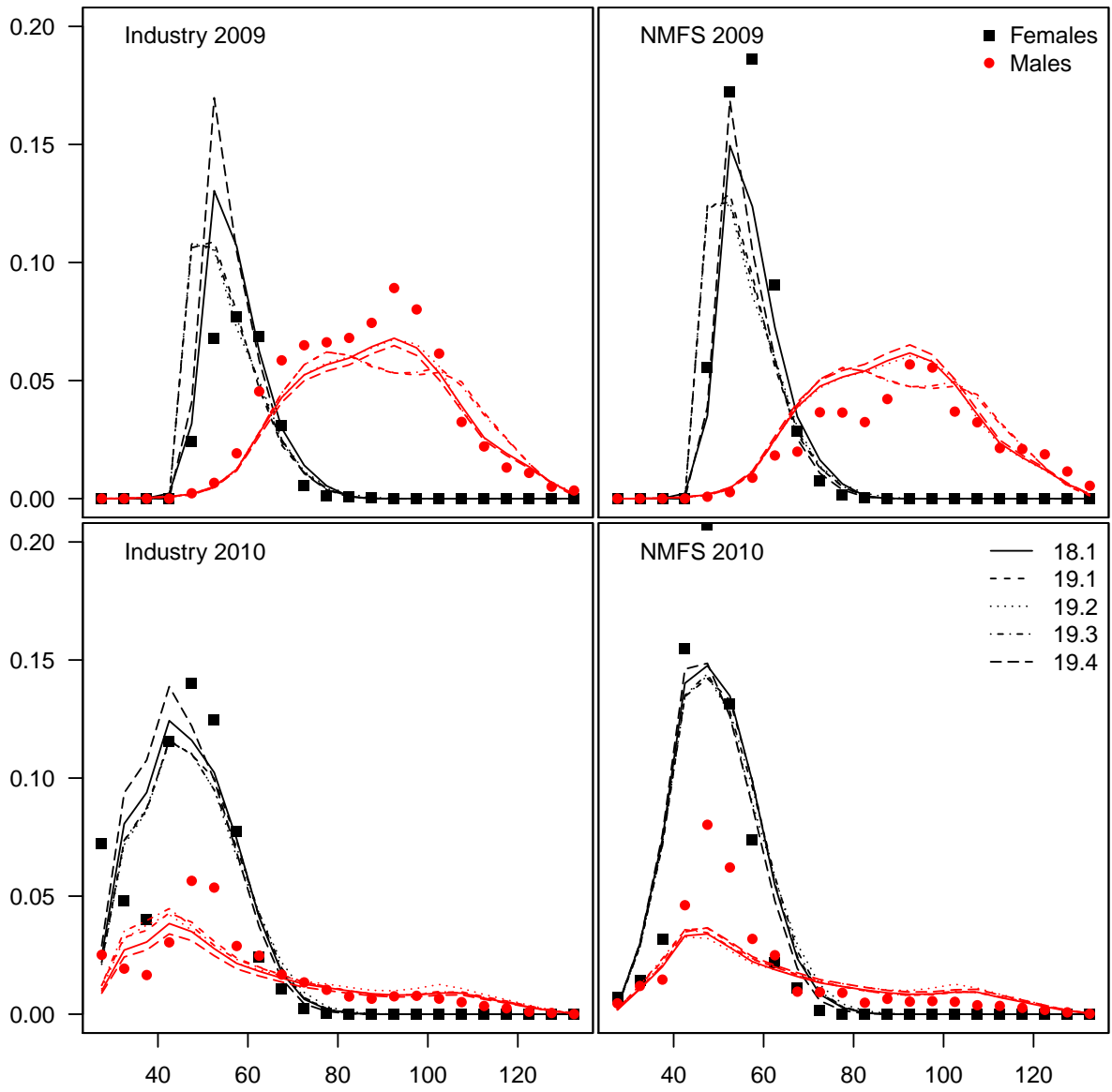


Figure 14: Model fits to size composition data from summer survey experiments (2009 & 2010)

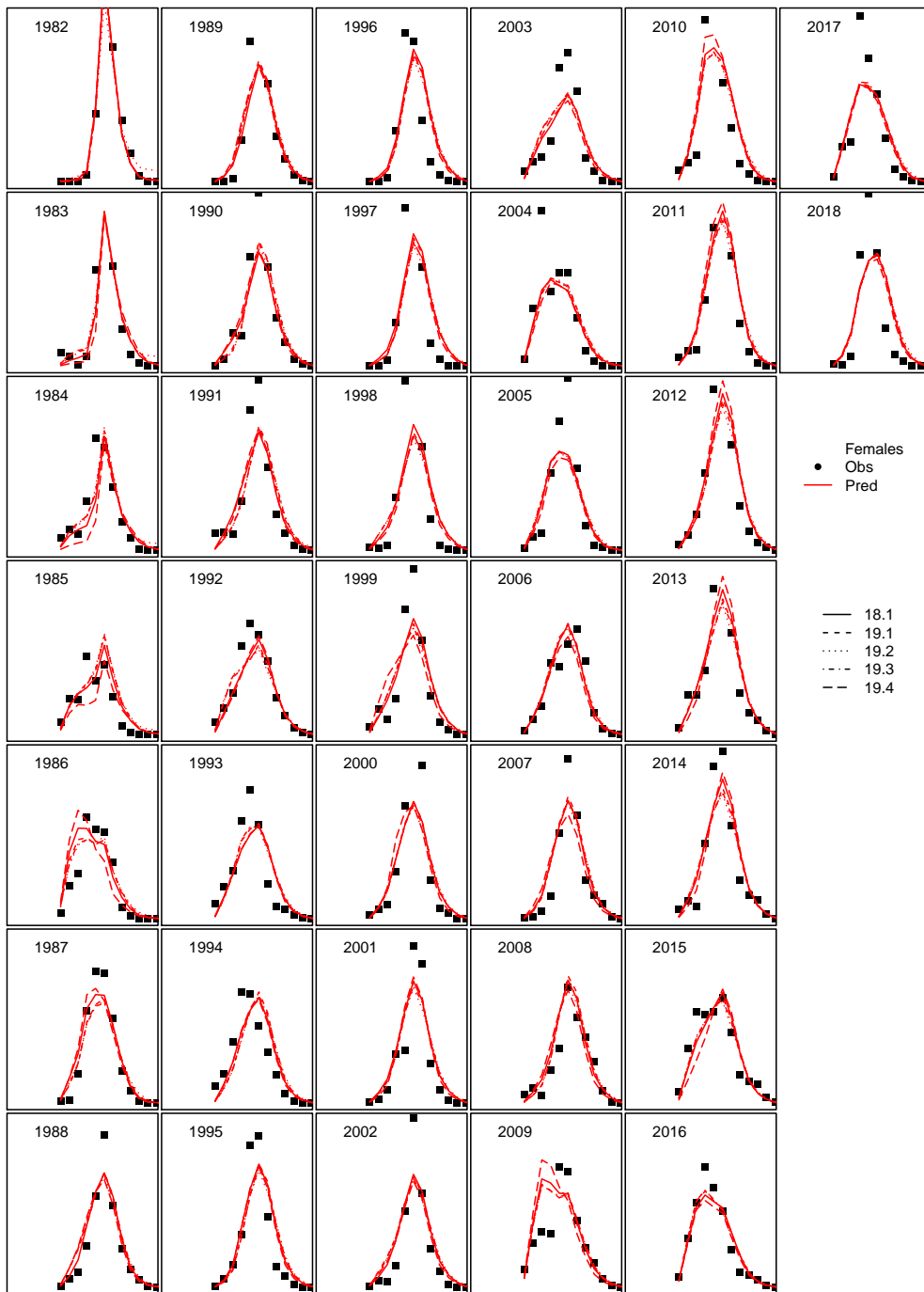


Figure 15: Model fits to female survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

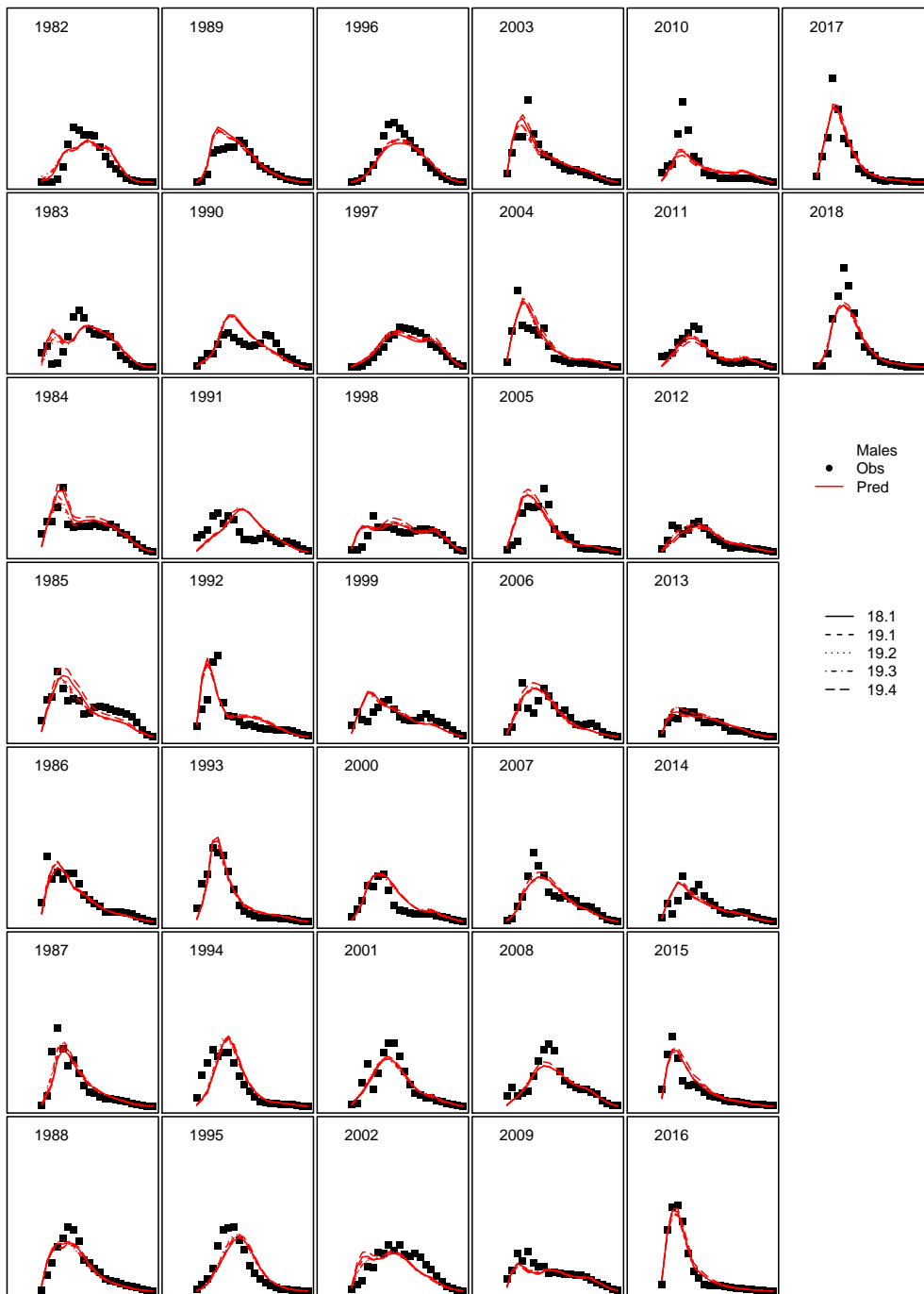


Figure 16: Model fits to male survey size composition data. Note that male and female survey selectivity proportions at length in a given year sum to 1. Consequently, the integral of predicted length compositions may appear to be different than the integral of the observed length composition data.

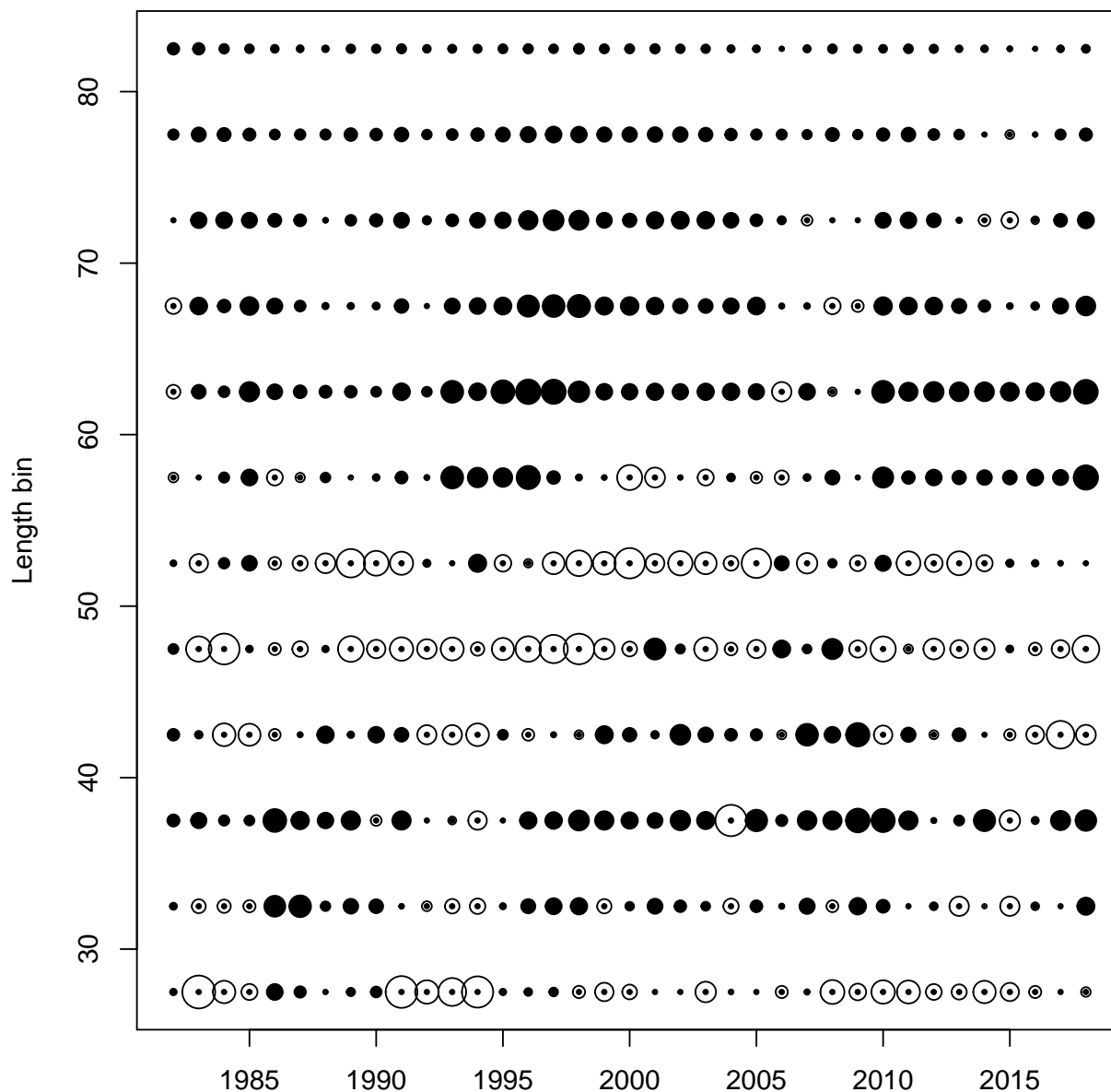


Figure 17: Residuals for female survey length proportion data for the author's preferred model (3b). Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual. Stars are residuals > 5 .

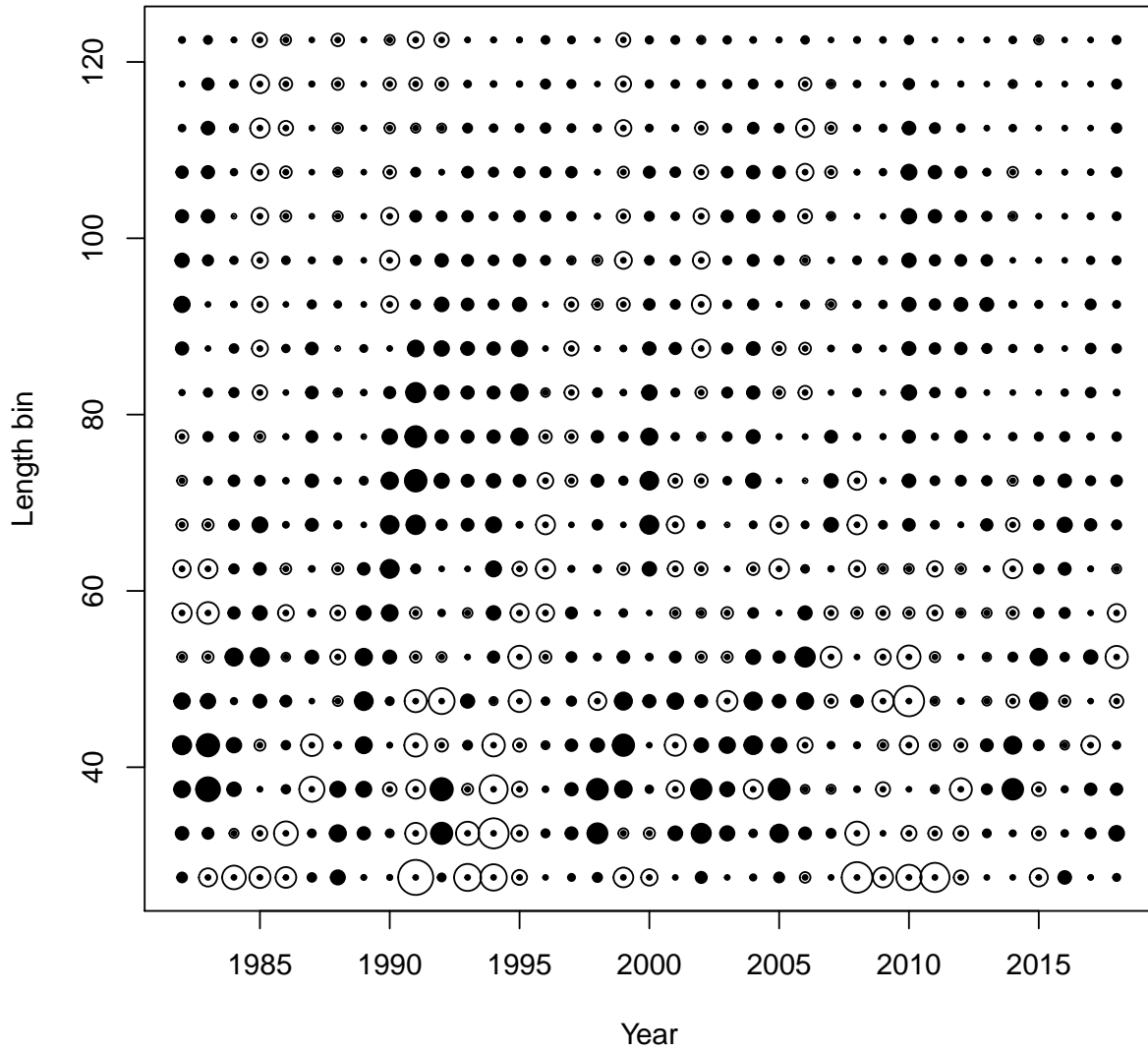


Figure 18: Residuals for male survey length proportion data for the author's preferred model (3b). Open circles are positive residuals, filled are negative, and the size of the circle is proportional to the magnitude of the residual. Stars are residuals > 5 .

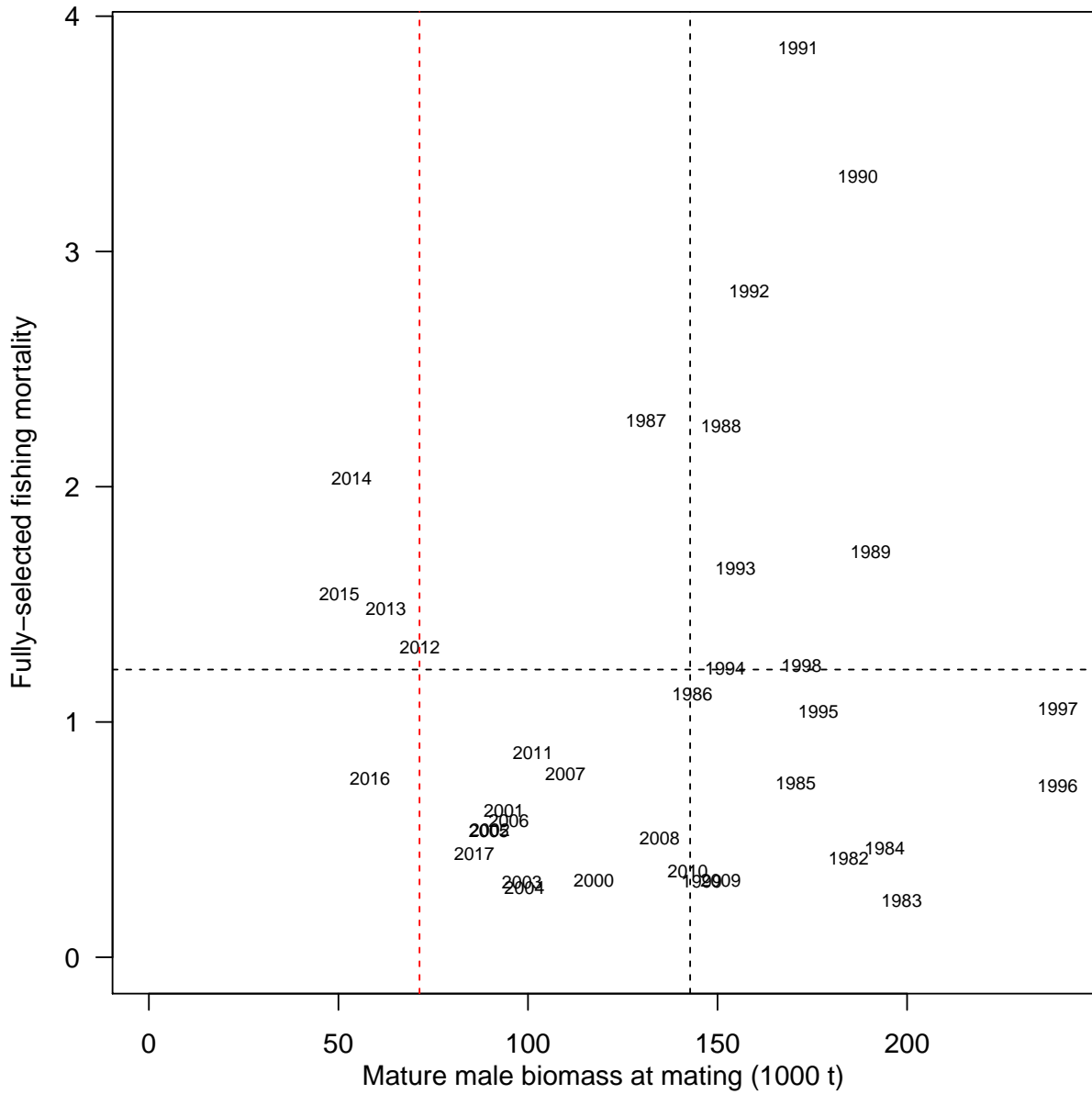


Figure 19: Kobe plot for the chosen model. Vertical dashed black line represents the median posterior value for B35; Vertical dashed red line represents the overfished level, horizontal dashed black line represents F35

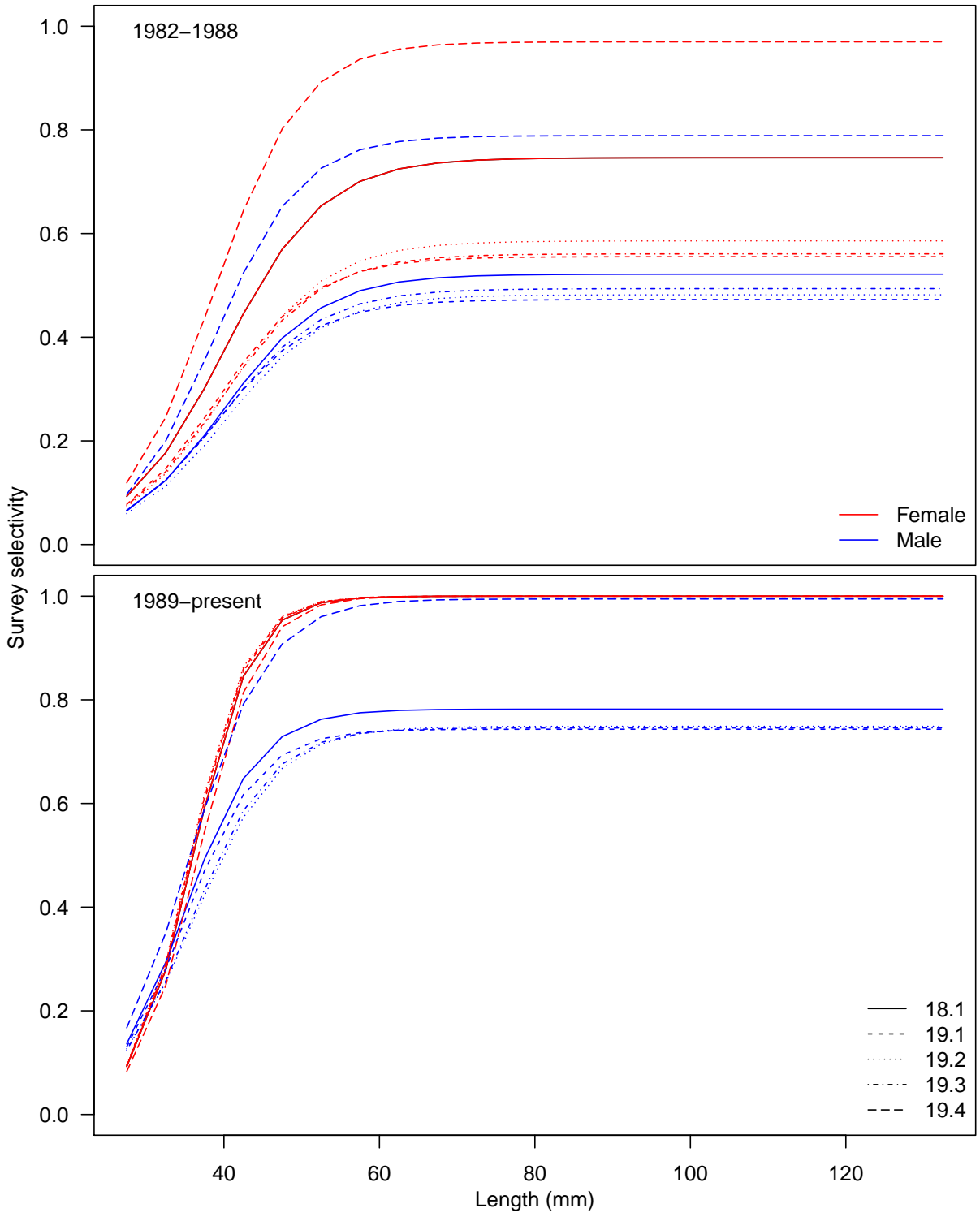


Figure 20: Estimated survey selectivity

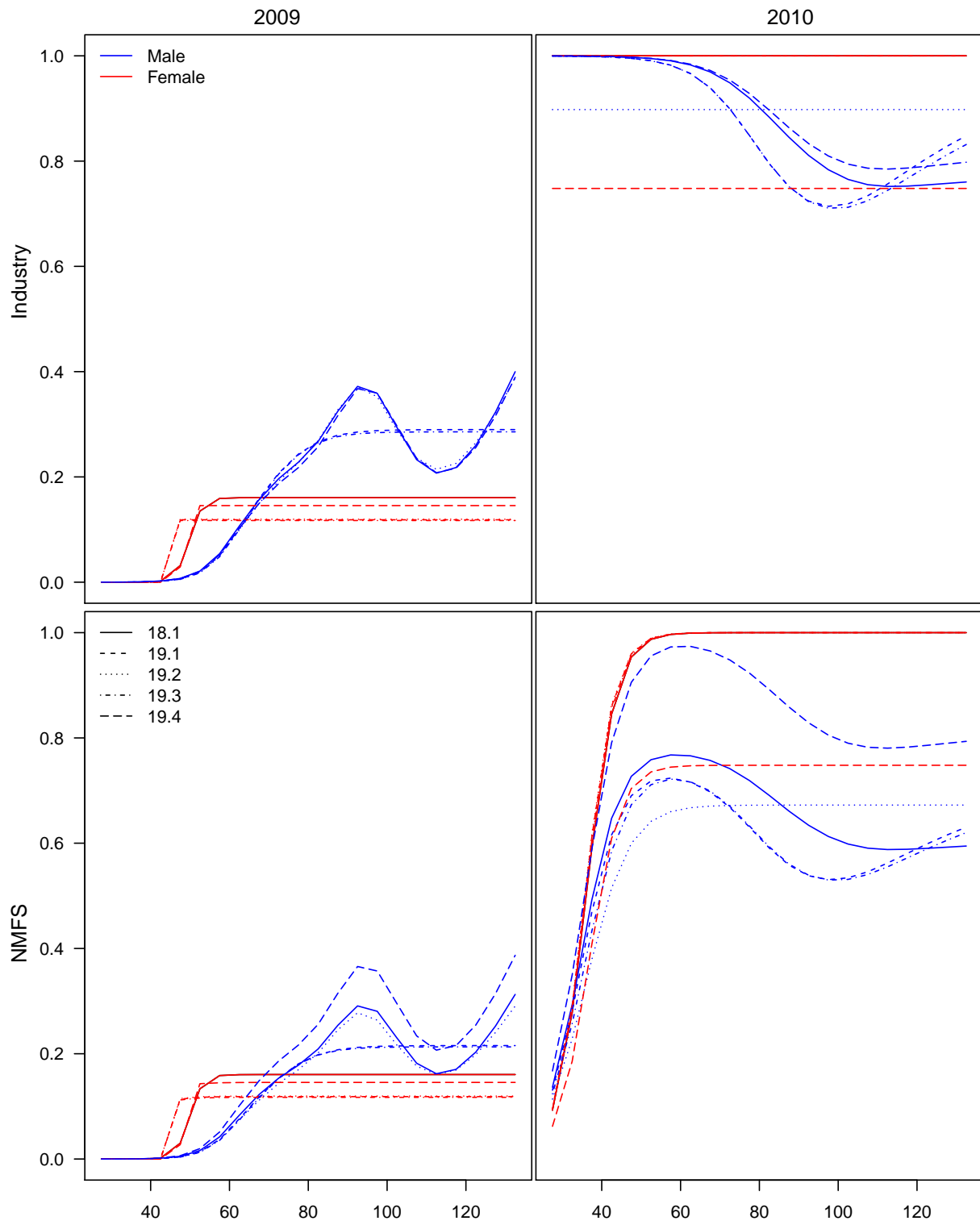


Figure 21: Estimated experimental survey selectivity (availability * survey selectivity)

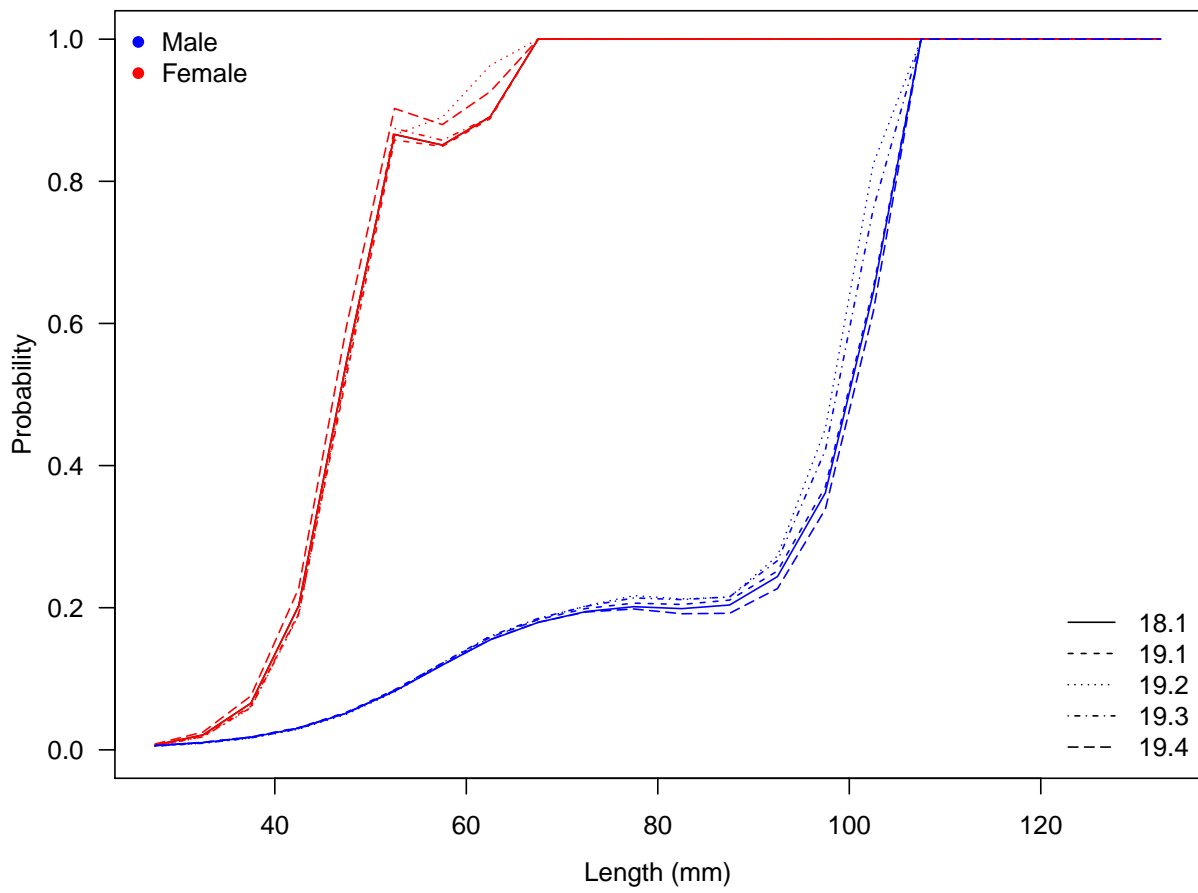


Figure 22: Estimated probability of maturing

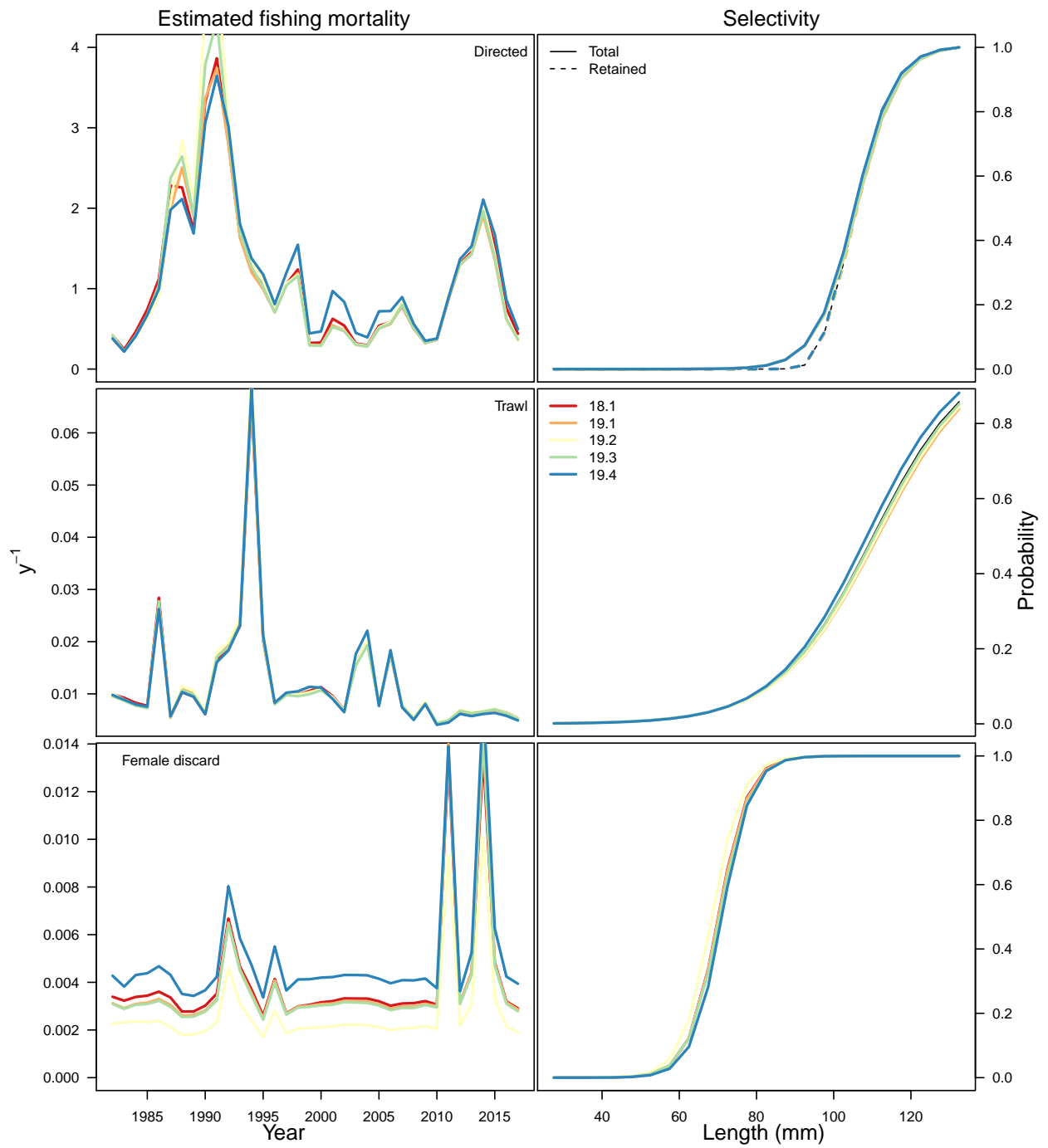


Figure 23: Model predicted fishing mortalities and selectivities for all sources of mortality

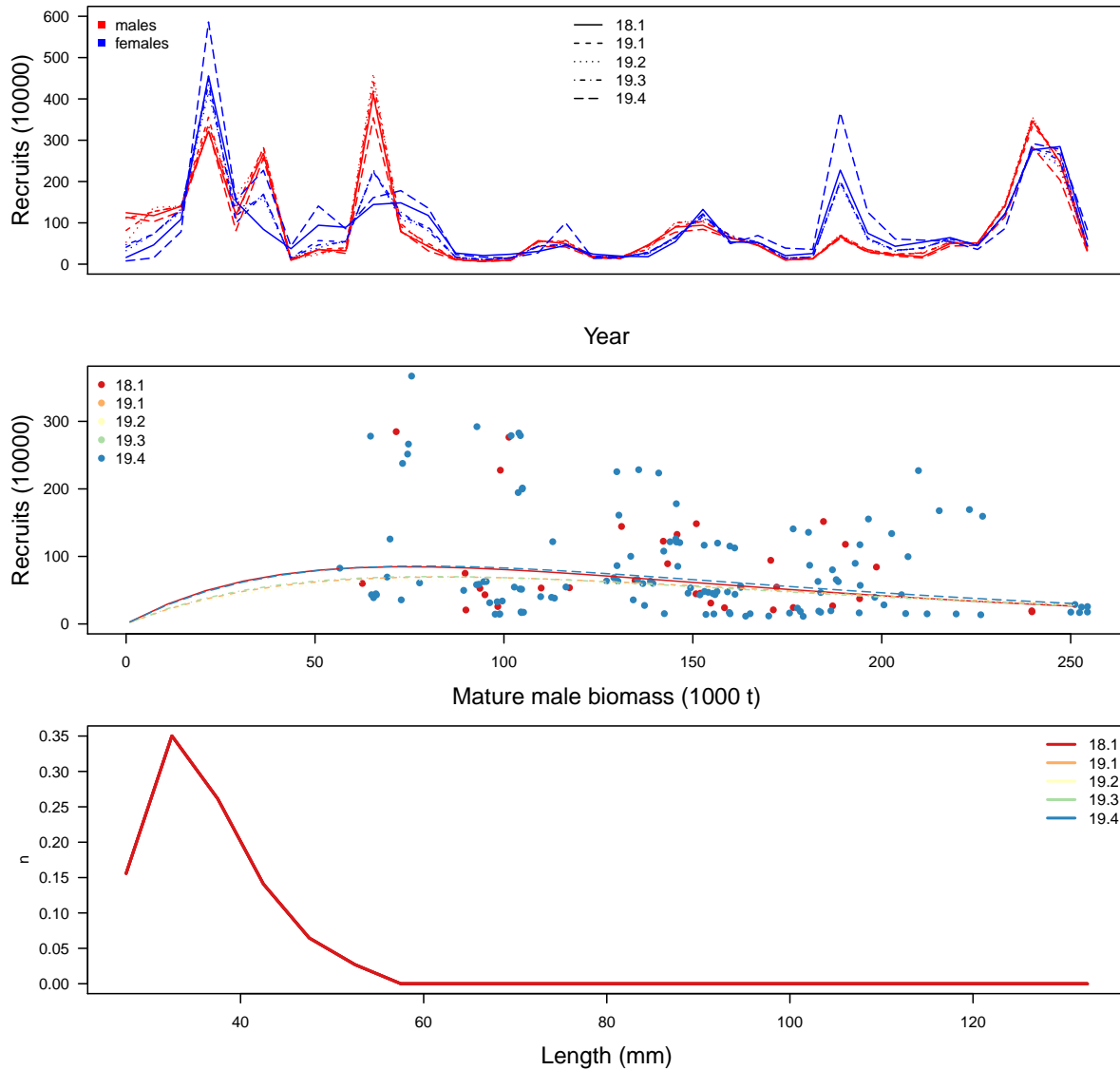


Figure 24: Estimated recruitment, fits to stock recruit curve (MMB lagged 5 years), and proportions recruiting to length bin

Appendix 2: A description and preliminary model runs of a simplified snow crab assessment model

Cody Szuwalski

April 22, 2019

Contents

Motivation for a simple model

Model performance	
Fits to data	
Survey biomass data	
Growth data	
Catch data	
Size composition data	
Estimated population processes and derived quantities	
Jittering	
Summary and next steps	

Appendix A: Model structure

Population dynamics	
Likelihood components	

Motivation for a simple model

The main document provided for this CPT meeting (May 2019) outlines differing estimates of parameters that determine population processes in the literature. Many of these processes are confounded in the assessment and some are more strongly informed by data than others. Differences among population processes appear to exist for females and males, and some of these differences contribute to model instability. It is not immediately clear why there are differences in processes like recruitment between the sexes; nor is it clear precisely from where the instability arises. Instability has historically been expressed in the kinked growth curve, but this may be related to the weighting of the model. The goal in simplifying the assessment model and then building complexity is to attempt to identify how, where, and why model instability occurs. This process will inform what data are entered into GMACS when it has been modified for use with terminally molting species.

This document presents preliminary analyses with a simple model that excludes females, shell condition, the kinked growth curve, and the BSFRF data. The exclusion of females is a large step, and, in the long term, it is desirable to keep females within the assessment model. However, the largest issues related to model stability appear to stem from female processes and measures of female biomass play a small role in the harvest control rule for snow crab. A very small fraction of the OFL is devoted to female mortality associated with discard from the directed and trawl fisheries. Discarded female catch is 2% (on average) of the total discards in numbers—even less in biomass. In addition to removing females and the kinked growth curve, all of the extra weighting factors applied in the likelihood were removed from the assessment. Now lognormal and normal likelihoods are weighted by their CVs in the code (rather than inferred CVs from weightings applied to them). Multinomial likelihoods still use an input sample size as weighting in the objective function. The initial model also excludes BSFRF data to attempt to establish a baseline to which increases in complexity can be compared.

The increases in complexity presented in this preliminary analysis are simple and intended to give a flavor of future analysis. Discussion among the plan team on a ‘plan of attack’ for this exercise will be welcomed. Six basic models are presented:

- 19s.1: Males tracked by maturity state, no kinked growth curve, no BSFRF data.
- 19s.2: Same as 19s.1, but weighting increased on survey MMB by multiplying likelihood by 10.
- 19s.3: Same as 19s.1, but samples sizes for all length comps were input as 40 instead of 200.
- 19s.4: Males tracked by maturity state, no kinked growth curve, BSFRF data included.
- 19s.5: Same as 19s.4, but weighting increased on survey MMB by multiplying likelihood by 10.
- 19s.6: Same as 19s.4, but samples sizes for all length comps were input as 40 instead of 200.

Model performance

All models returned small gradients (though including the BSFRF data increased the gradients slightly) and positive definite Hessians.

Fits to data

Survey biomass data

Fits to the survey mature male biomass varied widely among different models (Figure 1). Even within models fitting to the same data, there were large differences when weightings changed. Survey MMB is much more poorly fit when the BSFRF data were incorporated into the model (Table 5). Interestingly, even though catchability was affected by incorporating the BSFRF data, recruitment was strongly affected as well. In 2010, the BSFRF estimate of numbers was nearly 3 times that of the NMFS estimates. To reach these estimates, the model added a large recruitment that appears in 2003 to boost the population to reach those numbers. Estimates of survey MMB in the final year ranged from 85.84 to 141.6 kt. All models underestimated the final year of observed survey MMB.

Growth data

All models estimated growth similarly, with slight variations in slope and intercept (Figure 2 & Table 5). Models in which BSFRF data were fit to had poorer fits to the growth data.

Catch data

Estimates of retained catch data all had similar trends, but some models missed the CIs in years of high catches (Figure 3). Discard numbers were fit adequately given the specified uncertainty (Figure 3 & Table 5) and trawl numbers were fit similarly in recent years for which length data were available for all models.

Size composition data

Retained catch size composition data were fit adequately by most models (Figure 4); discard catch size composition data were similarly well fit (Figure 5). Trawl size composition data were generally well fit, with several exceptions in certain years. Most models performed similarly in fitting the trawl size composition data (Figure 6 & Table 5). Models in which length composition sample sizes were downweighted had a higher frequency of oddly fitting predictions in the survey composition data (particularly when the BSFRF data were incorporated into the model; Figure 7 and Figure 8).

Fits to the BSFRF length composition data were passable for immature crab, but fits to mature crab data were overestimated in the largest size bins and underestimated in the other size classes (Figure 9). The number of males was generally underestimated by the industry survey in 2009 and overestimated by the NMFS survey, while the opposite pattern was seen for females.

Estimated population processes and derived quantities

Population processes and derived quantities varied among models, sometimes widely. Projected MMB for 2018 ranged from 192.57 to 572.97 kt (Figure 10). Estimates of selectivity and catchability varied among models (Figure 11). Estimated catchability in era 2 was generally lower than in era 3. Estimated size at 50% selection in the survey gear for era 2 ranged from ~38 mm to ~47 mm. Size at 50% selection in the survey gear during era 3 ranged from 35 mm to 41 mm. BSFRF ‘availability’ curves varied from 2009 to 2010, but were consistent in their shape among models within a year (Figure 12).

The probability of maturing by size had the same general shape for all models, but some were smoother than others (Figure 13). The probability of maturing for crab was ~15% to 20% at ~60 mm and increased sharply to 50% at ~97.5mm. The region from 60 mm to 110 mm carapace width displayed the largest differences in estimates of the probability of maturing among models.

Estimated fully selected fishing mortality in the directed fishery had similar trends for all models, but the scaling changed among models (Figure 14). A fair amount of variability in total directed fishery selectivity occurred among models, but the retention ogive was consistently estimated. Large differences existed among the models for estimated trawl selectivity and associated mortality (Figure 14).

Patterns in recruitment were similar for all models that didn’t fit to the BSFRF data (Figure 15). For models that fit to the BSFRF data, a large recruitment event was estimated to allow fits to the large observed BSFRF numbers in 2010. Stock recruitment relationships were not apparent between the estimates of MMB and recruitment for any model (Figure 15).

Estimated natural mortality ranged from 0.17 to 0.35 for immature crab and 0.26 to 0.35 for mature male crab (Table 4).

Jittering

All models were ran 100 times with a .PIN file that was jittered from the MLE values with a CV of 0.10. Models in which the BSFRF data were not fit all converged to the same likelihood (Figure 16). Models in which the BSFRF data were fit had less success in convergence (up to 24% of models did not converge) and displayed some instability in estimated management quantities (Figure 16). As few as 1% (and as much as 70%) of jittered models ended at the observed minimum likelihood over the jittered runs within a scenario that incorporated the BSFRF data.

Summary and next steps

First, I want to reiterate that these are preliminary results and should not be considered for management. The primary goal of this document is to lay out a framework for understanding the sources of instability in the assessment model and the information content of the data. A few interesting points came from this exercise. First, the male data can be fit with a linear growth curve and converge—something that has not been possible with the current assessment method that incorporates females. Further, a stable model is possible when excluding females and the BSFRF data, as seen through the jittering analysis.

Incorporating the BSFRF data presented some challenges. Including the BSFRF data did result in lower estimated of survey catchability in the third survey era (unless the survey MMB was more heavily weighted), but the model also inserted large recruitments to attempt to fit the numbers reported in the BSFRF survey. There are a few possible explanations for this. First, it could be a bug in the scaling of the BSFRF data. However, the estimated recruitment could also reflect a conflict in the data and an imbalance in the weighting of different data sources. More time will be needed to understand this result, but these are the sorts of problems the simple model is designed to understand. Hopefully, this will be a successful platform to explore the instability and information content in the data to inform what data should be used when moving to GMACS.

Appendix A: Model structure

Population dynamics

Numbers of males in maturity state m at length l in the initial year of the assessment, $N_{m,y=1,l}$, were estimated as a vector of numbers at length l and maturity state m , $\lambda_{m,l}$.

$$N_{m,y=1,l} = \begin{cases} \lambda_{s,1,l} & \text{if } m = \text{mat} \\ \lambda_{s,2,l} & \text{if } m = \text{imat} \end{cases} \quad (1)$$

The dynamics after the initial year were described by:

$$N_{m,y+1,l} = \begin{cases} \Omega_l \kappa_{l'} Q_{imat,y,l'} X_{l',l} & \text{if } m = \text{mat} \\ 1 - \Omega_l \kappa_{l'} Q_{imat,y,l'} X_{l',l} + Rec_y^\epsilon Pr_l & \text{if } m = \text{imat} \end{cases} \quad (2)$$

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

$$Q_{m,y,l} = \sum_v N_{m,y,l} e^{Z_{m,y,l}} \quad (3)$$

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

$$Z_{m,y,l} = \gamma_{natM,m} M_m + \sum_f S_{f,y,l} F_{f,y,l} \quad (4)$$

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

$$S_{tot,l} = \frac{1}{1 + e^{-S_{slope,f}(L_l - S_{50})}} \quad (5)$$

$$S_{trawl,l} = \frac{1}{1 + e^{-S_{slope,f}(L_l - S_{50})}} \quad (6)$$

$$R_{ret,l} = \frac{1}{1 + e^{-S_{slope,f}(L_l - S_{50})}} \quad (7)$$

Where $S_{slope,f}$ was the slope of the logistic curve in fishery f and $S_{50,f}$ was the length at 50% selection in fishery f . Catches for all fisheries were modeled as pulse fisheries in which all catch was removed instantaneously

(i.e. no natural mortality occurred during the fishery). Catch in fishery f during year y was calculated as the fraction of the total fishing mortality, $F_{f,y,l}$, applied in a fishery f times the biomass removed by all fisheries.

$$C_{ret,y} = \sum_l \sum_m w_l \frac{R_l F_{tot,y,l}}{F_{tot,y,l} + F_{trawl,y,l}} N_{m,y,l} e^{-\delta_y M_m} (1 - e^{-(F_{dir,y,l} + F_{trawl,y,l})}) \quad (8)$$

$$C_{trawl,y} = \sum_l \sum_m \frac{F_{trawl,y,l}}{F_{tot,y,l} + F_{trawl,y,l}} N_{m,y,l} e^{-\delta_y M_m} (1 - e^{-F_{trawl,y,l}}) \quad (9)$$

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

$$F_{f,y} = e^{(F_{avg,f}^{log} + F_{dev,f,y}^{log})} \quad (10)$$

Selectivity for the survey was estimated for 2 eras in the base model: 1982-1988 and 1989-present. Selectivity was assumed to be logistic and separate parameters representing the length at which selection probability equal 50% and 95% ($s_{50,e}$ and $s_{95,e}$, respectively) were estimated in the third era (1989-present). Separate catchability coefficients ($q_{s,e}$) were estimated for both eras.

$$S_{surv,l,e} = \frac{q_e}{1 + e^{-\log(19) \frac{L_l - s_{50,e}}{s_{95,e} - s_{50,e}}}} \quad (11)$$

Survey selectivity was informed by experimental surveys during the years 2009 and 2010. A portion of the NMFS summer survey tows were accompanied by an industry vessel using nephrops trawls with an assumed selectivity of 1 for all size classes. To represent the proportion of the population covered by the experiment, a vector was freely estimated in inverse logit space, S_y^{free} .

$$S_{ind,l,y} = \frac{1}{1 + e^{-S_y^{free}}} \quad (12)$$

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

$$S_{nmfs,l,y} = S_{ind,l,y} S_{surv,l,y} \quad (13)$$

Mature male biomass (MMB) were fitted in the objective function and were the product of mature numbers at length during year y and the weight at length, w_l :

$$MMB_y = \sum_l w_l N_{mat,y,l} \quad (14)$$

$$w_l = \alpha_{wt} L_l^{\beta_{wt}} \quad (15)$$

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

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

$$X_{l,l'} = \frac{Y_{l,l'}}{\sum_{l'} Y_{l,l'}} \quad (16)$$

$$Y_{l,l'} = (\Delta_{l,l'})^{\frac{\bar{L}_l - (\bar{L}_l - 2.5)}{\beta}} \quad (17)$$

$$\hat{L}_l^{post} = \alpha + \beta L_l^{pre} \quad (18)$$

$$\Delta_{l,l'} = \bar{L}_{l'} + 2.5 - L_l \quad (19)$$

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

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

$$Rec_y = e^{(Rec_{avg} + Rec_{dev,y})} \quad (20)$$

$$Pr_l = \frac{(\Delta_{1,l})^{\alpha_{rec}/\beta_{rec}} e^{-\Delta_{1,l}/\beta_{rec}}}{\sum_{l'} (\Delta_{1,l'})^{\alpha_{rec}/\beta_{rec}} e^{-\Delta_{1,l'}/\beta_{rec}}} \quad (21)$$

Recruitment deviation and fishing mortality vectors were subject to a smoothing penalty.

Likelihood components

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

$$L_x = \sum_y N_{x,y}^{eff} \sum_l p_{x,y,l}^{obs} \ln(\hat{p}_{x,y,l}/p_{x,y,l}^{obs}) \quad (22)$$

L_x was the likelihood associated with data component x , where $N_{x,y}^{eff}$ was the effective sample sizes for the likelihood, $p_{x,y,l}^{obs}$ was the observed proportion in size bin l during year y for data component x , and $\hat{p}_{x,y,l}$ was the predicted proportion in size bin l during year y for data component x . \mathbf{r} multinomial likelihood components were included in the assessment.

Log normal likelihoods were implemented in the form:

$$L_x = \sum_y \frac{(\ln(\hat{I}_{x,y}) - \ln(I_{x,y}))^2}{2(\ln(CV_{x,y}^2 + 1))} \quad (23)$$

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

Normal likelihoods were implemented in the form:

$$L_x = \lambda_x \sum_y \frac{(\hat{I}_{x,y} - I_{x,y})^2}{\sigma_x^2} \quad (24)$$

L_x was the contribution to the objective function of data component x , λ_x was represents the weight applied to the data component (and can be translated to a standard deviation), $\hat{I}_{x,y}$ was the predicted value of quantity I from data component x during year y , $I_{x,y}$ was the observed value of quantity I from data component x during year y . \mathbf{r} normal likelihood components were included in the base assessment (see ?? for descriptions, weighting factors, and translated standard deviations).

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

Table 1: Observed growth increment data

Male premolt length (mm)	Male postmolt length (mm)
57.63	68.6
20.6	28.9
25.6	31.4
25.9	31.1
20	26.3
25.2	32.8
21	27.8
20.3	26.4
21.9	28.4
20.7	27.7
20.1	28
19.8	26.5
26	32.2
62.3	81.8
56.5	70
57	70
58.7	72.5
60.8	78.4
59.3	75.1
64	84.7
60.3	75.1
20.7	29.2
24	32.3
16.1	23
19.2	26.6
21.23	26.41
22.2	28.1
23.48	28.27
29.9	39.9
30.3	40.3
30.7	40.5
44.2	58.7
44.7	57.3
64.7	82.7
67.6	86
67.9	85.3
74.5	93.9
79.9	97.8
89.8	110
89.9	112.1
89.9	112.3
93.8	117.6
20	26.3

Table 2: Observed retained catches, discarded catch, and bycatch

Survey year	Retained catch (kt)	Discarded males (numbers)	Trawl bycatch (numbers)
1982	11.85	5549	1136
1983	12.16	3131	1464
1984	29.94	8938	1555
1985	44.45	14637	1335
1986	46.22	14099	5735
1987	61.4	18510	16.81
1988	67.79	15266	2057
1989	73.4	19037	2388
1990	149.1	137819	1826
1991	143	48075	7039
1992	104.7	159673	8806
1993	67.94	51899	9319
1994	34.13	47880	5799
1995	29.81	56339	4461
1996	54.22	73983	3069
1997	114.4	51590	4907
1998	88.09	41570	2399
1999	15.1	4743	1475
2000	11.46	5204	1496
2001	14.8	15740	980.6
2002	12.84	14009	635.2
2003	10.86	4877	2061
2004	11.29	5506	3370
2005	16.77	11248	1154
2006	16.49	16303	1885
2007	28.59	22370	1433
2008	26.56	17709	909.5
2009	21.78	10657	2032
2010	24.61	4884	599.8
2011	40.29	13393	503.6
2012	30.05	19067	738.6
2013	24.49	33091	344.8
2014	30.82	33430	451.3
2015	18.42	25774	456.6
2016	9.67	11616	239
2017	8.6	17977	70.54

Table 3: Observed mature male biomass (1000 t) at the time of the survey and coefficients of variation.

Survey year	Mature male biomass	CV
1982	171.6	0.14
1983	156.4	0.13
1984	172.5	0.12
1985	70.3	0.11
1986	87.11	0.11
1987	189.4	0.11
1988	254.3	0.15
1989	290.2	0.11
1990	436.5	0.14
1991	457.5	0.15
1992	228.5	0.09
1993	178.8	0.1
1994	164.8	0.08
1995	212.6	0.13
1996	281.5	0.12
1997	317.6	0.1
1998	200.7	0.09
1999	90.79	0.09
2000	90.36	0.14
2001	130.3	0.12
2002	89.87	0.23
2003	76.25	0.12
2004	76.34	0.14
2005	119.8	0.11
2006	135.7	0.26
2007	149.3	0.15
2008	137.8	0.1
2009	142.8	0.13
2010	157.1	0.12
2011	167.1	0.11
2012	122.2	0.12
2013	97.46	0.12
2014	163.5	0.16
2015	80.04	0.12
2016	63.21	0.11
2017	83.96	0.11
2018	198.4	0.17

Table 4: Maximu likelihood estimates of parameter values by scenario.

Parameter	19s.1	19s.2	19s.3	19s.4	19s.5	19s.6
am:	2.7	2.86	2.33	1.44	1.78	0.89
bm:	1.21	1.21	1.22	1.25	1.26	1.27
st_gr:	0.5	0.5	0.5	0.5	0.5	0.5
growth_beta:	0.75	0.75	0.75	0.75	0.75	0.75
mateste:	vector	vector	vector	vector	vector	vector
mean_log_rec:	13.29	13.36	13.21	13.74	13.27	13.4
rec_dev:	vector	vector	vector	vector	vector	vector
alpha1_rec:	11.5	11.5	11.5	11.5	11.5	11.5
beta_rec:	4	4	4	4	4	4
mnatlen_styr:	vector	vector	vector	vector	vector	vector
log_avg_fmort:	-1.33	-1.1	-1.34	-2.21	-1.38	-2.37
fmort_dev:	vector	vector	vector	vector	vector	vector
log_avg_fmortt:	-4.82	-4.63	-4.97	-6.42	-5.39	-6.72
fmortt_dev_era1:	vector	vector	vector	vector	vector	vector
fmortt_dev_era2:	vector	vector	vector	vector	vector	vector
fish_slope_ret:	0.27	0.27	0.27	0.26	0.25	0.25
fish_sel50_ret:	99.9	99.9	99.84	100.32	100.04	101.07
fish_slope_tot:	0.19	0.2	0.2	0.21	0.21	0.22
fish_sel50_tot:	96.64	96.83	95.64	92.96	93.63	89.49
trawl_slope:	0.07	0.07	0.07	0.09	0.09	0.1
trawl_sel50:	108.77	108.45	104.85	89.75	92.13	79.51
srv2_q:	0.38	0.75	0.57	0.37	1	0.88
srv2_sel95:	80.21	70.32	71.77	83.93	59.08	74.17
srv2_sel50:	46.3	46.77	45.81	49.93	37.62	48.49
srv3_q:	0.94	1	1	0.66	1	0.83
srv3_sel95:	56.81	52.41	52.41	62.89	51.35	61.93
srv3_sel50:	37.24	36.33	35.6	41.09	36.06	41.35
selsmo10ind:	vector	vector	vector	vector	vector	vector
selsmo09ind:	vector	vector	vector	vector	vector	vector
Mmult_imat:	1.04	1.32	1.04	0.87	1.54	0.75
Mmult:	1.2	1.52	1.14	1.14	1.54	1.12

Table 5: Contribution to the objective function by individual likelihood component by modeling scenario. Note that some of the model scenarios involve changing the weightings of data sources which invalidate the comparison of likelihoods for a data source among models.

Likelihood component	19s.1	19s.2	19s.3	19s.4	19s.5	19s.6
Smoothness for recruitment	189.35	240.79	135.54	189.91	435.81	178.82
Constraint on initial numbers	0	0	0	0	0	0
Retained length comp	13592.7	13616.5	2729.74	13975.9	14114.7	2983.93
Discard length comp	10649	10672.3	2127.85	10543.2	10628.8	2103.35
Trawl length comp	15073.5	15113	3016.75	15336.8	15350.9	3155.41
Survey immature length comp	18408.5	18531.9	3707.28	18546.3	18891.1	3809.6
Survey mature length comp	20240.6	20282.8	4070.29	20515.5	20686.6	4262.45
BSFRF length comp 2009	0	0	0	1123.47	1143.68	231.44
NMFS length comp 2009	0	0	0	1148.41	1155.32	231.42
BSFRF length comp 2010	0	0	0	1060.28	1121.88	224.94
NMFS length comp 2010	0	0	0	1215.94	1271.43	247.3
Survey MMB 2009	198.21	925.87	174	596.41	1369.89	610.03
BSFRFnumbers 2009 NMFS numbers	0	0	0	189.71	258.22	137.56
2010 BSFRF numbers	0	0	0	302.89	387.32	196.5
2010 NMFS numbers	0	0	0	3271.26	4231.28	2501.95
Retained catch	10.39	40	6.37	9.69	206.96	8.79
Discard catch	67	75.89	71.45	72.34	85.23	92.67
Trawl catch	0	0	0	0	0	0
Initial length comp smoothness	63.74	59.7	23.72	57.62	61.49	18.25
smoothness on availability 10	0	0	0	7.81	7.27	4.89
smoothness on availability 09	0	0	0	3.12	3.45	1.7
natural mortality prior mature	7.13	46.52	3.24	3.39	50.63	2.32
natural mortality prior immature	7.44	64.04	3.56	6.47	99.94	12.94
smoothness on maturity	8.07	8.46	4.53	10.71	11.86	14.5

Likelihood component	19s.1	19s.2	19s.3	19s.4	19s.5	19s.6
growth	123.49	124.17	117.74	147.28	206.68	186.07
fishing mortality	34.02	39.5	36.09	51.23	44.21	57.03

Table 6: Changes in management quantities for each scenario presented.

Model	MMB	B35	F35	FOFL	OFL
19s.1	235.8	171.4	1.06	1.06	114.3
19s.2	192.6	139.7	1.12	1.12	105.7
19s.3	218.1	165.8	0.83	0.83	105.2
19s.4	573	334.1	0.87	0.87	290.5
19s.5	220.1	159	0.76	0.76	116.6
19s.6	519.3	343.5	0.52	0.52	235

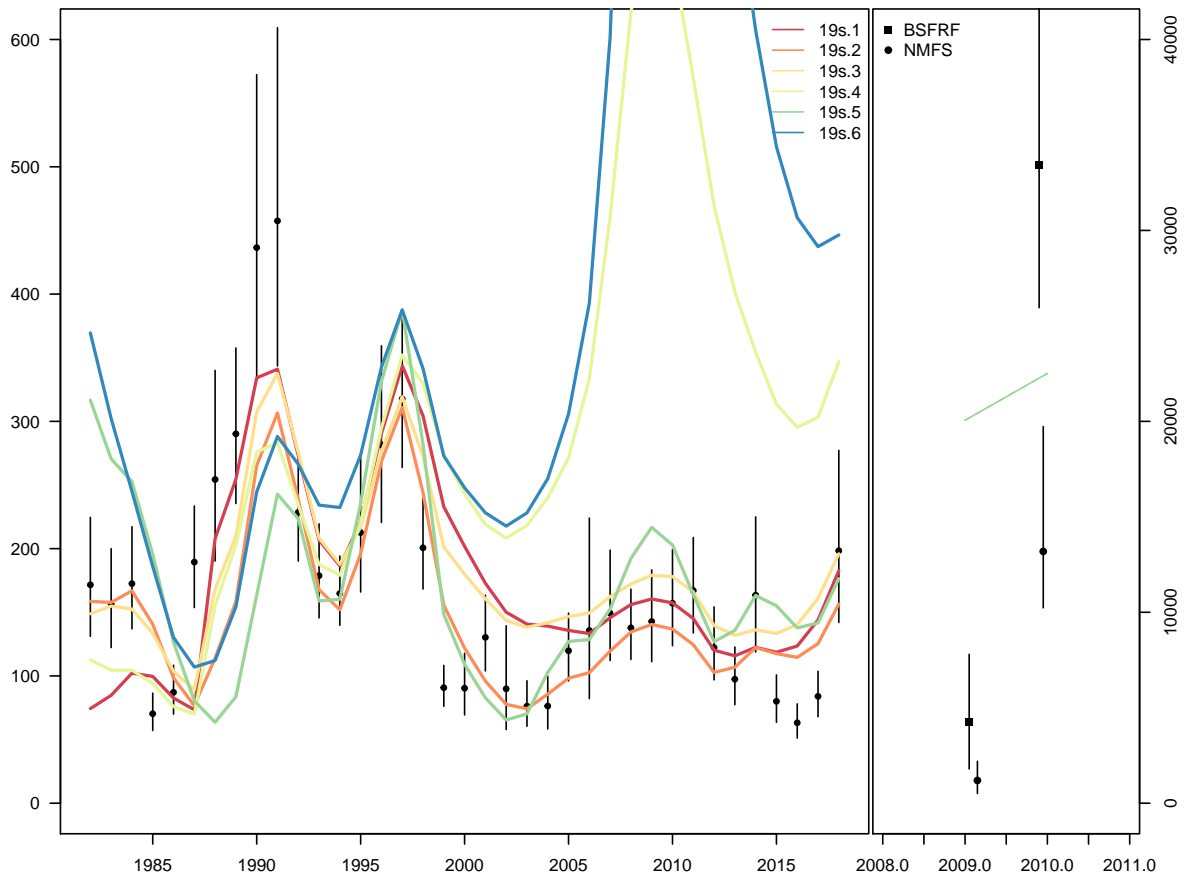


Figure 1: Model fits to the observed mature biomass at survey

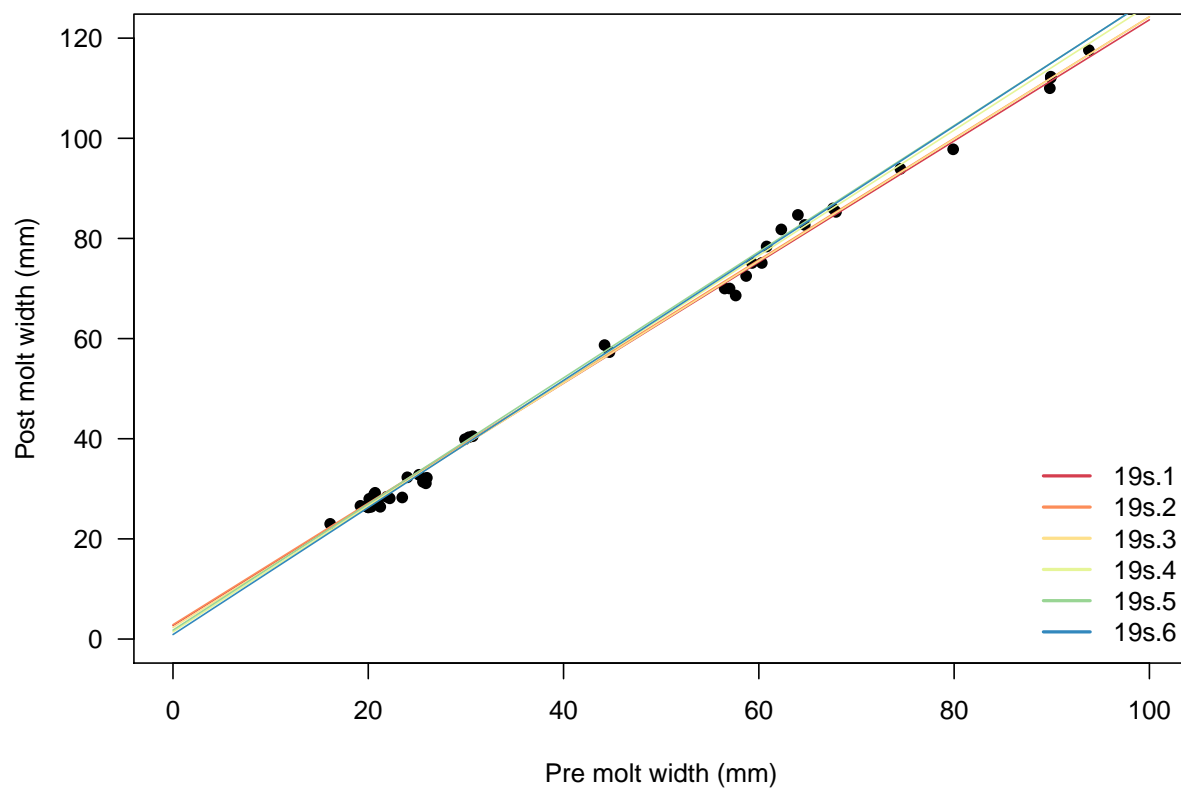


Figure 2: Model fits to the growth data

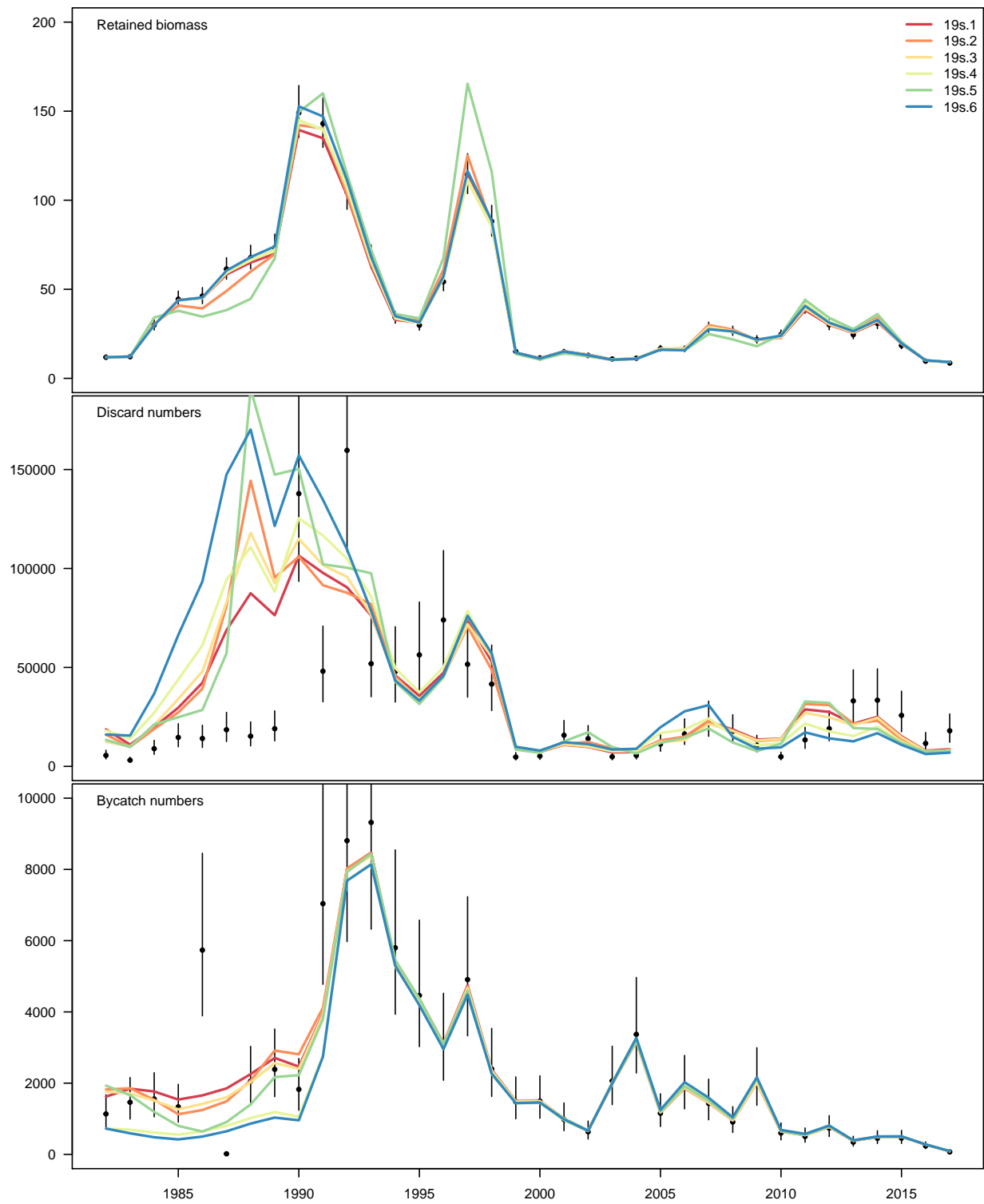


Figure 3: Model fits to catch data

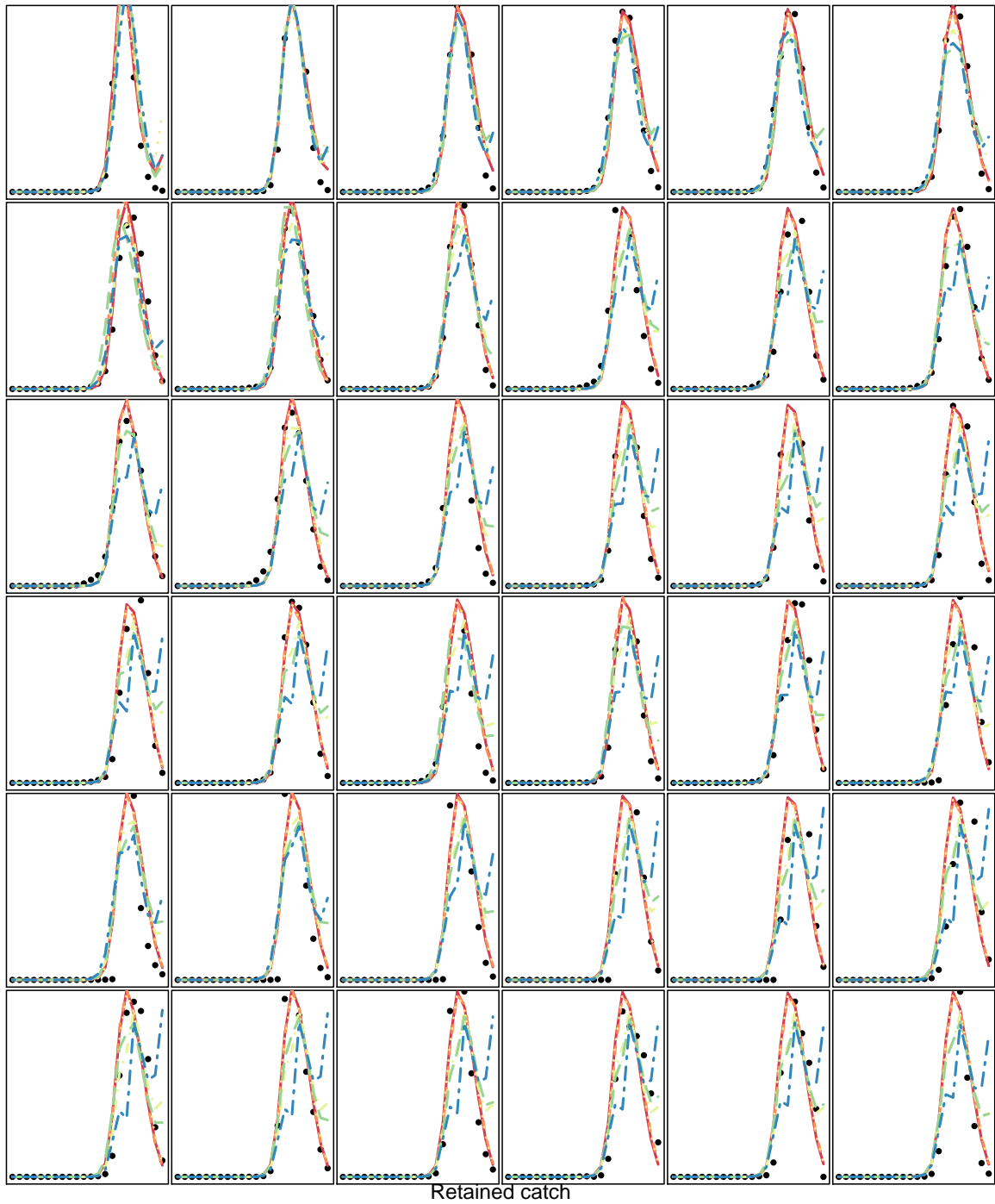
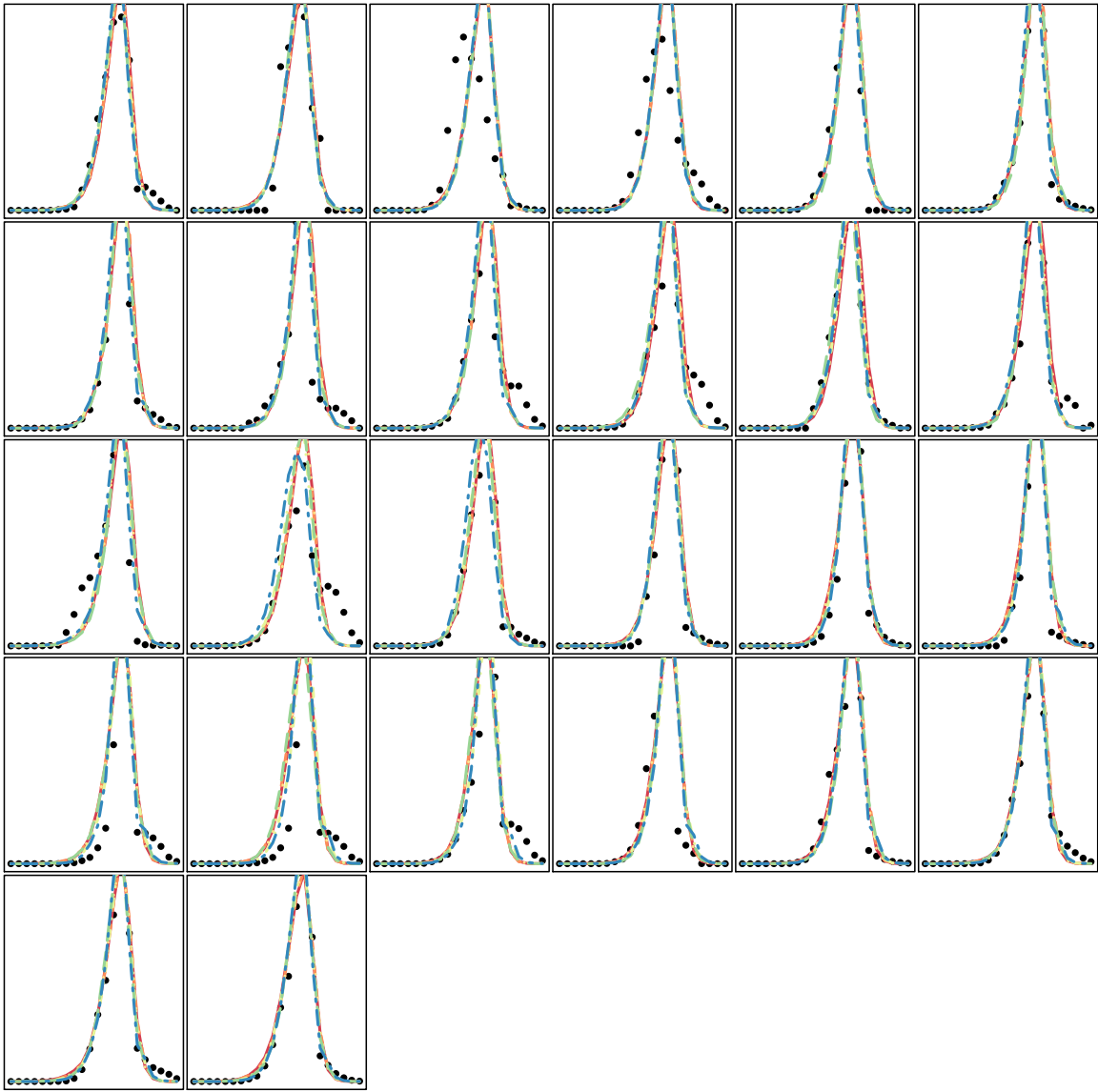


Figure 4: Model fits to retained catch size composition data



Discard catch

Figure 5: Model fits to discard catch size composition data

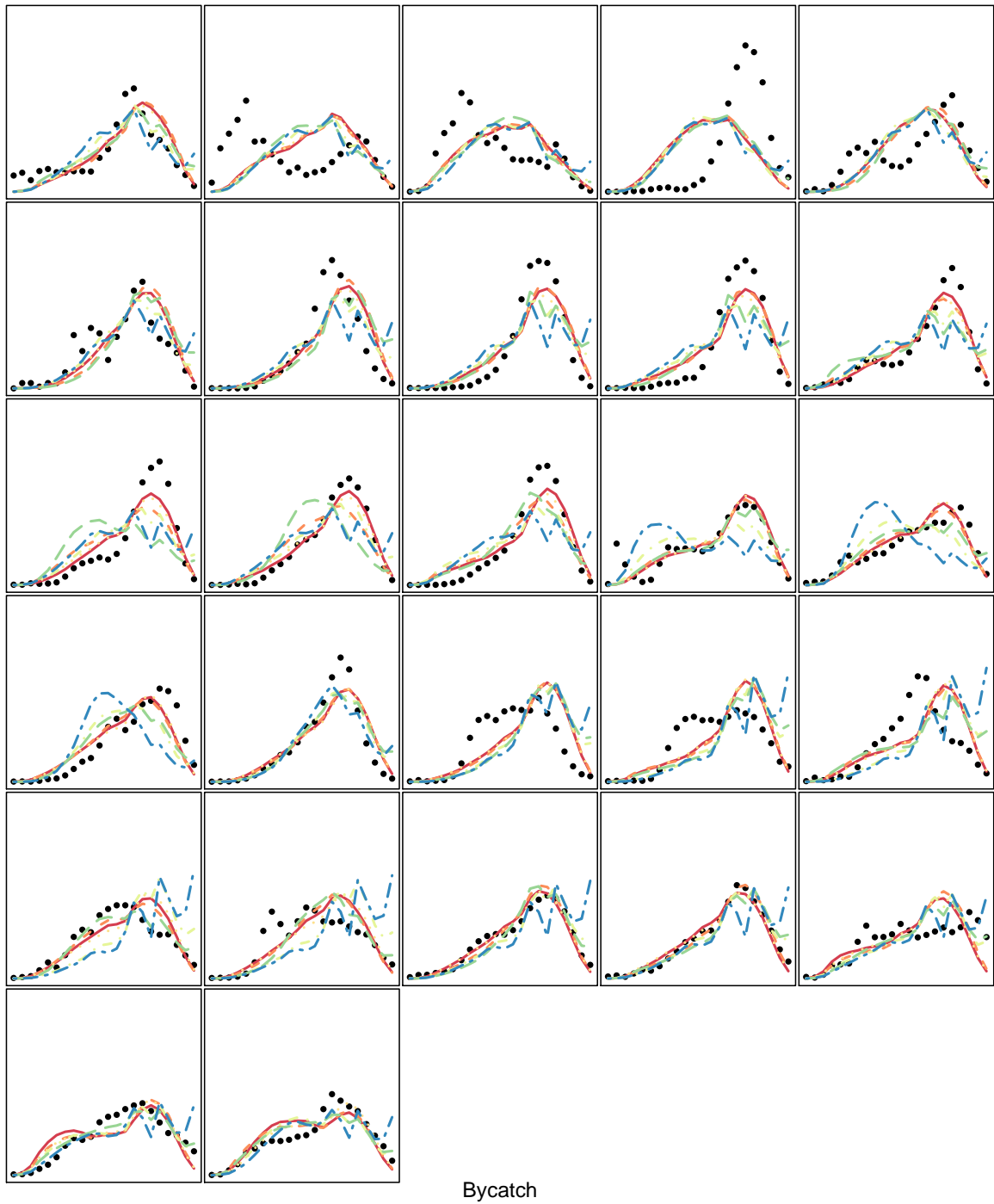
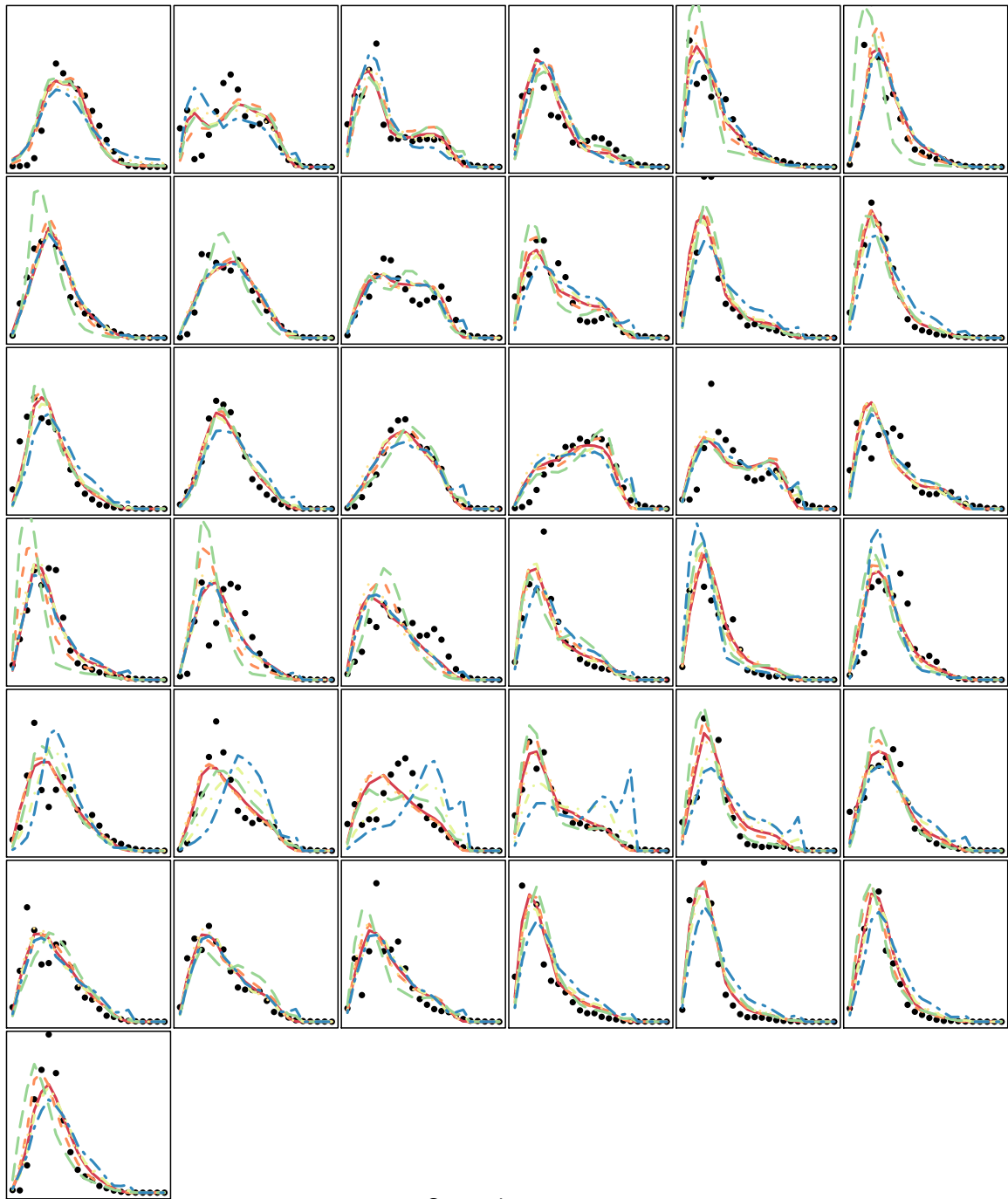
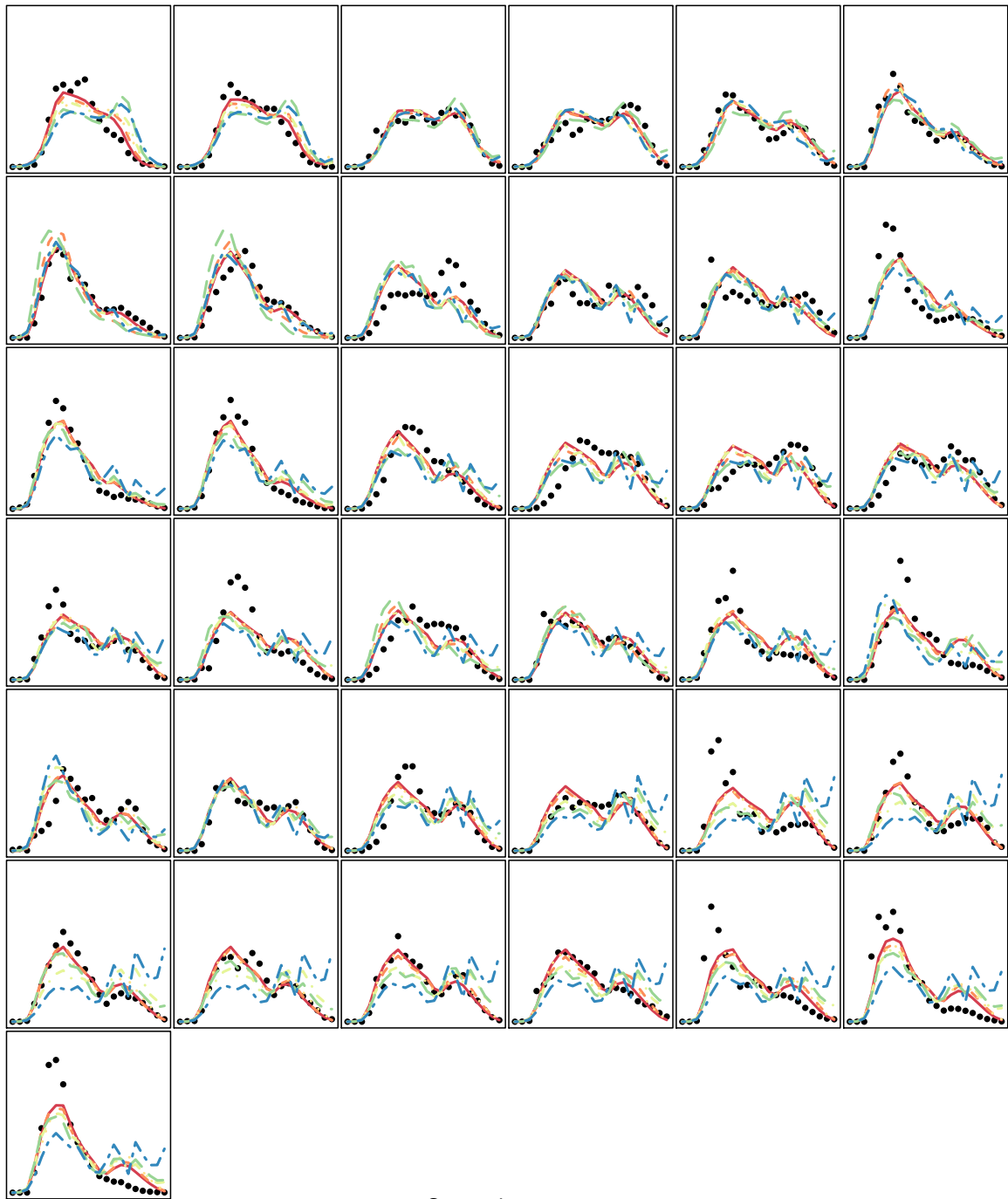


Figure 6: Model fits to trawl catch size composition data



Survey immature

Figure 7: Model fits to immature survey size composition data



Survey immature

Figure 8: Model fits to mature survey size composition data

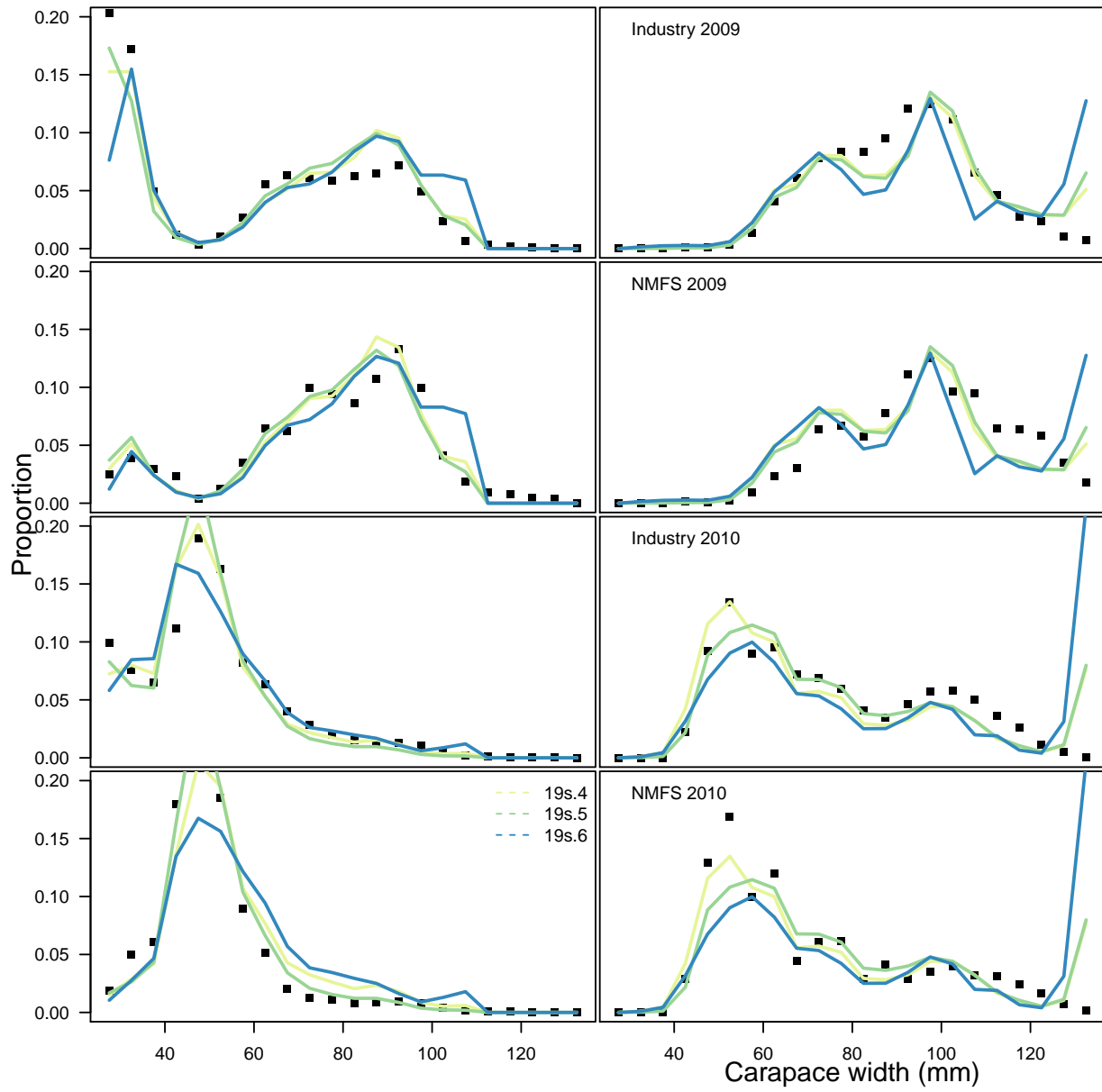


Figure 9: Model fits to size composition data from summer survey experiments (2009 & 2010)

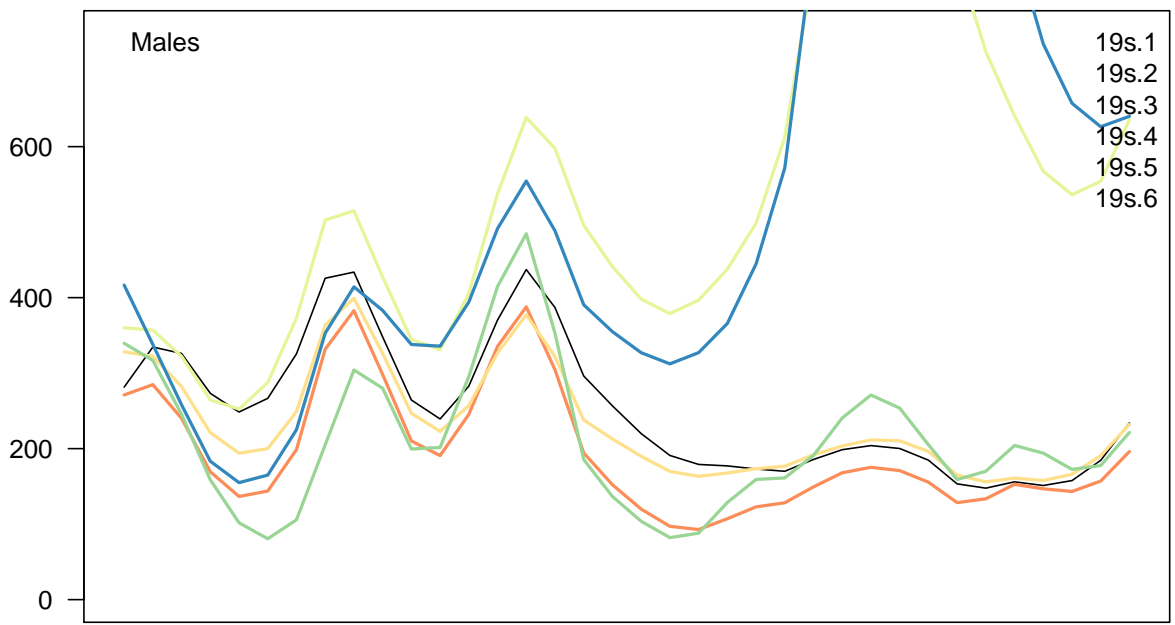


Figure 10: Model predicted mature male biomass at mating time

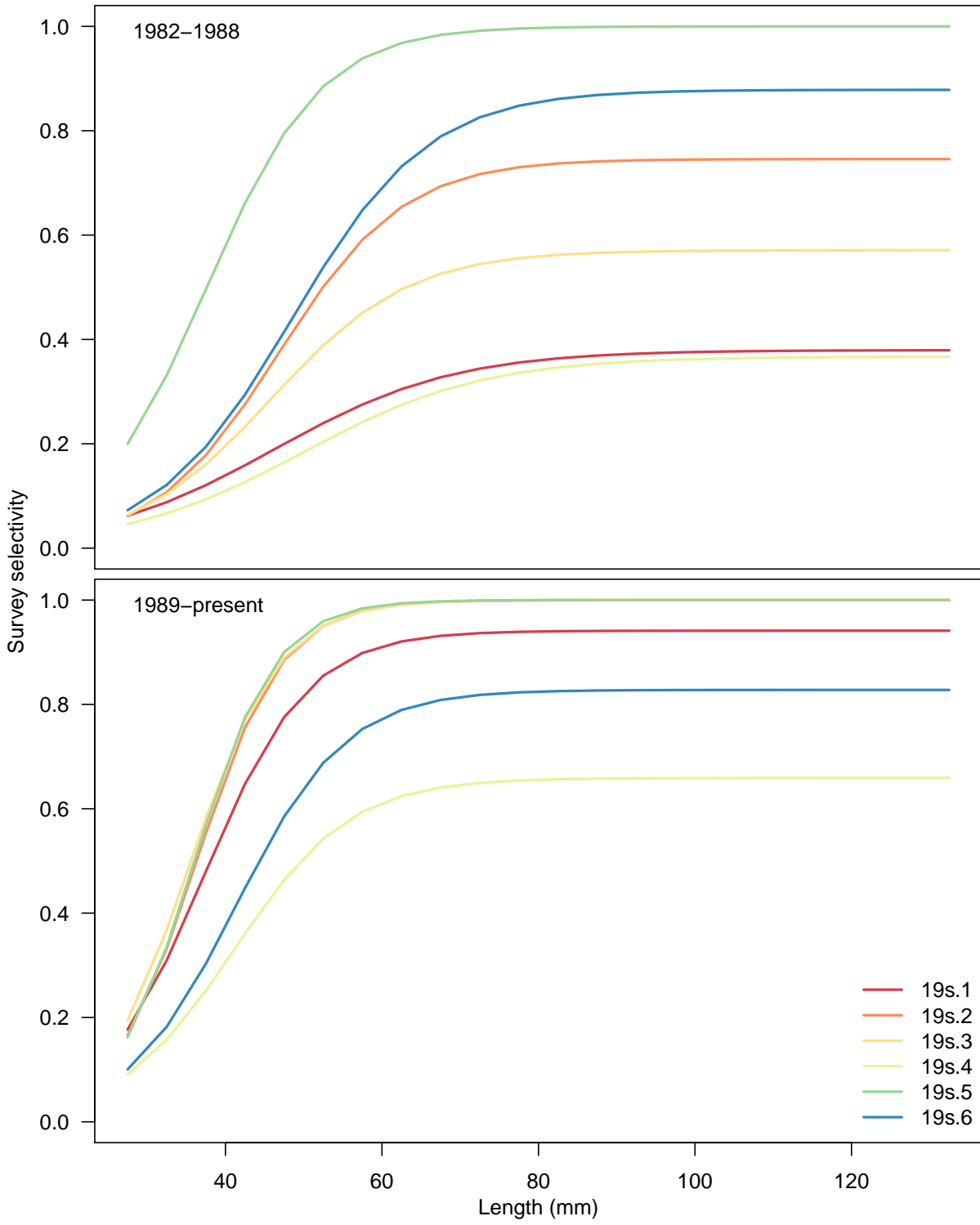


Figure 11: Estimated survey selectivity

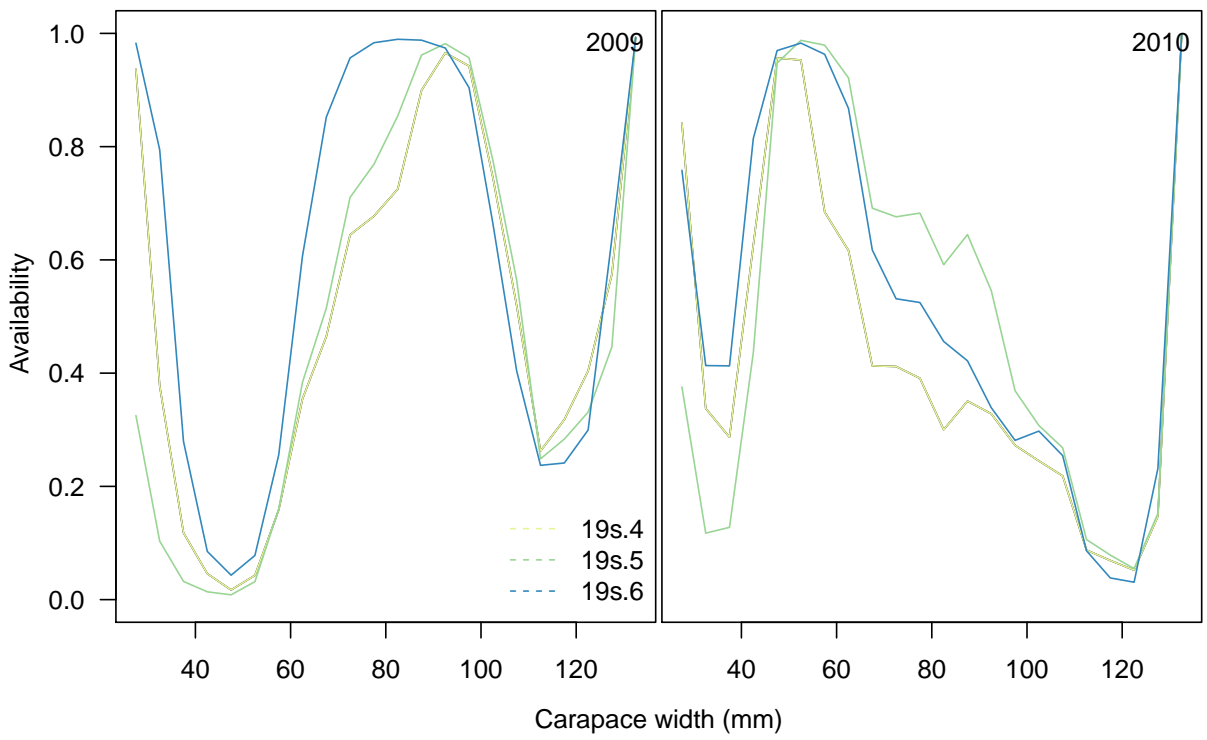


Figure 12: Estimated experimental survey availability

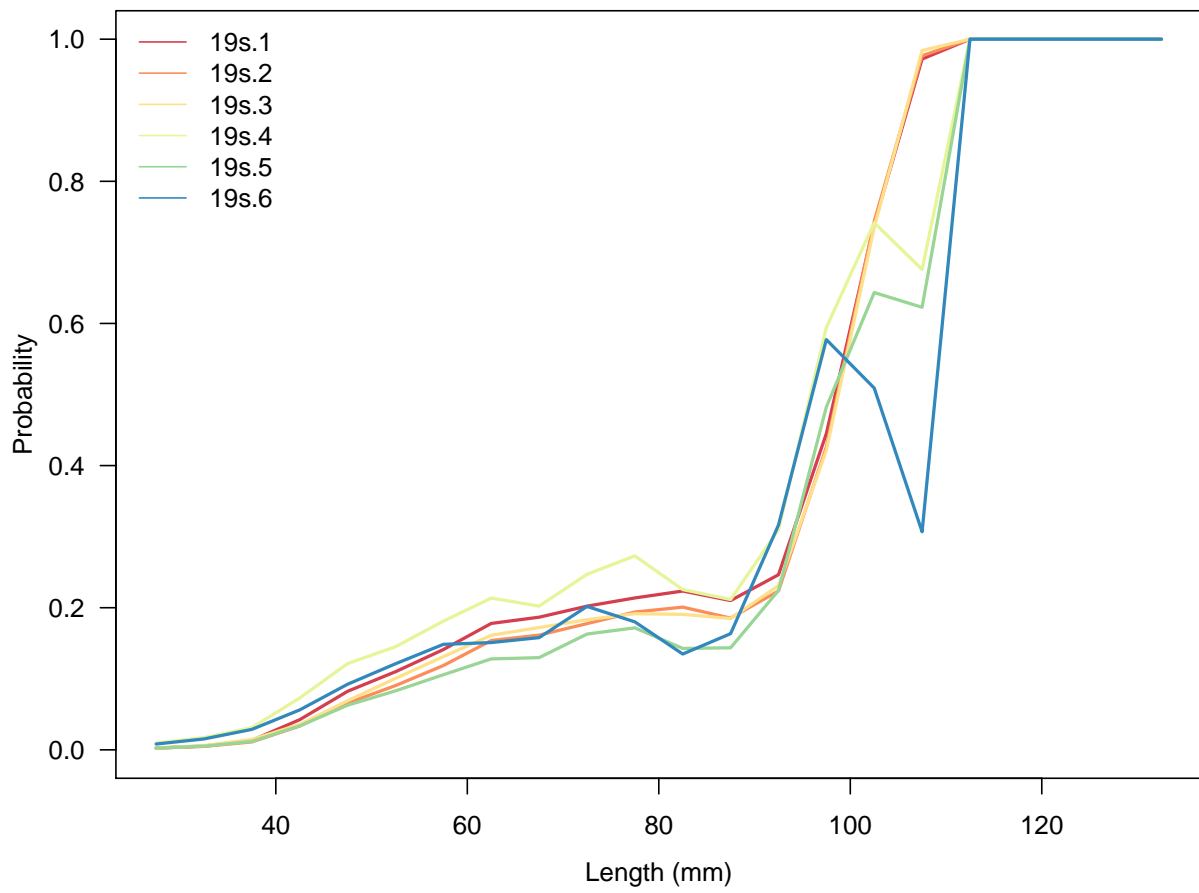


Figure 13: Estimated probability of maturing

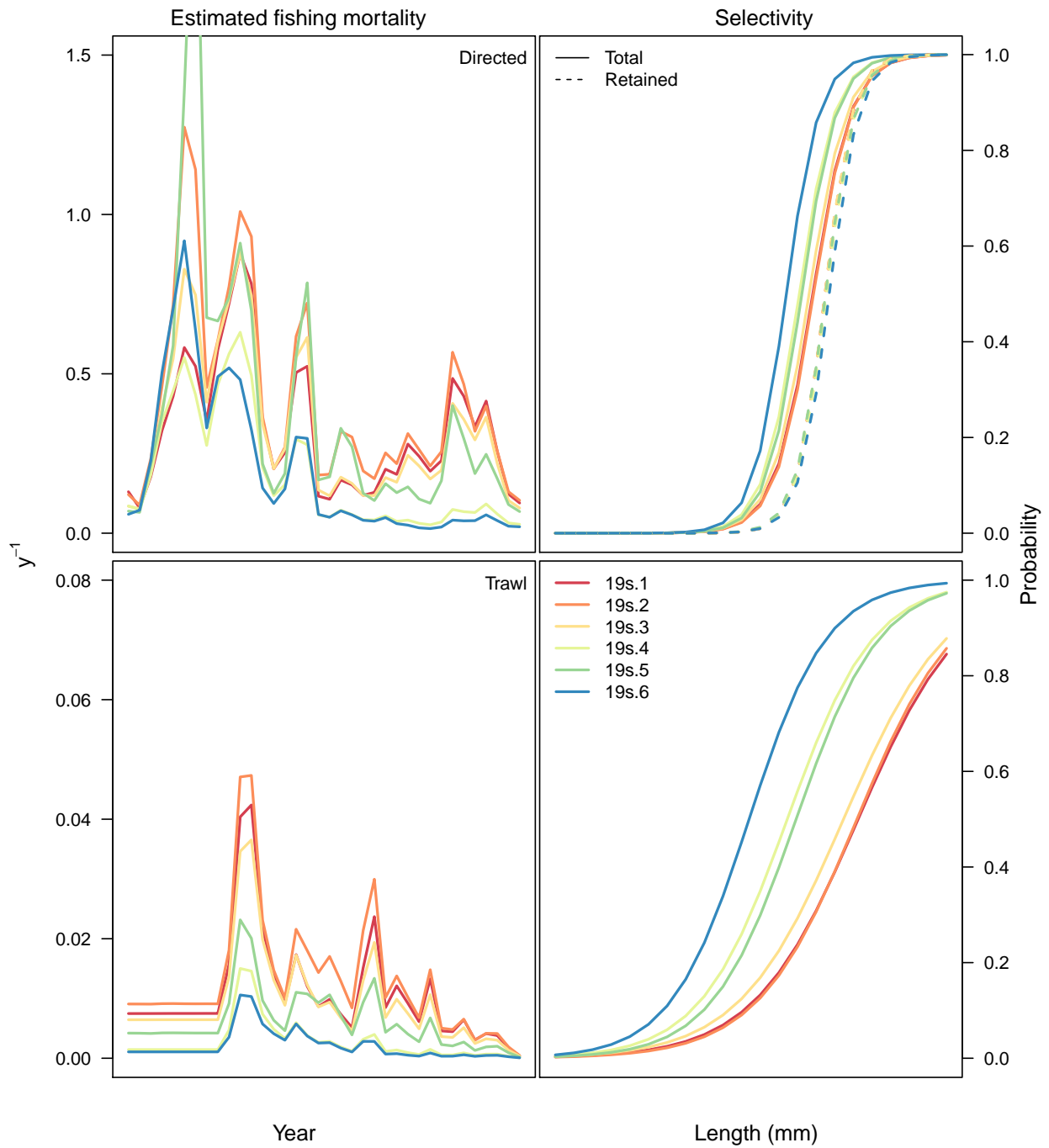


Figure 14: Model predicted fishing mortalities and selectivities for all sources of mortality

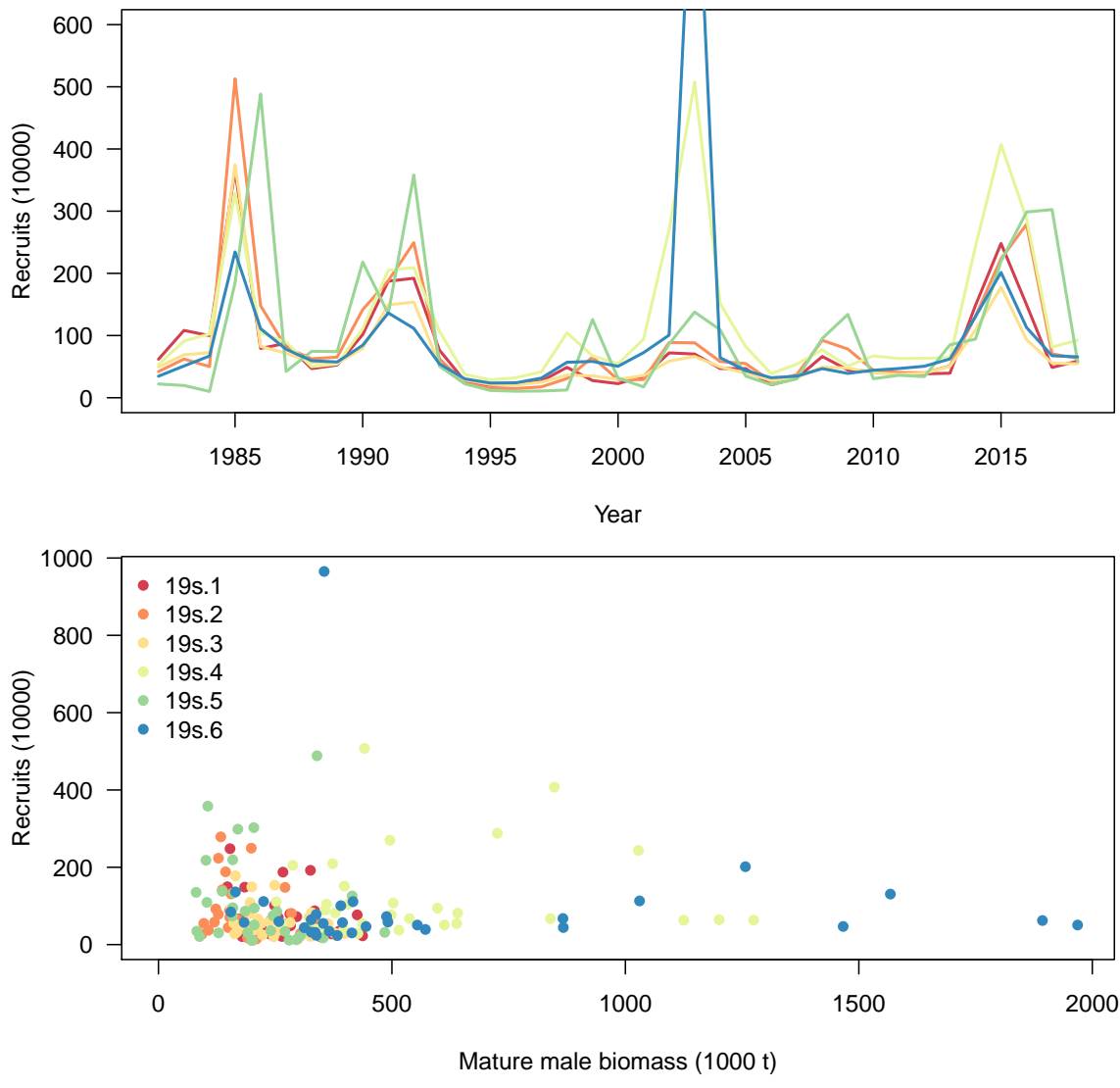


Figure 15: Estimated recruitment and stock recruit scatter plot (MMB lagged 5 years)

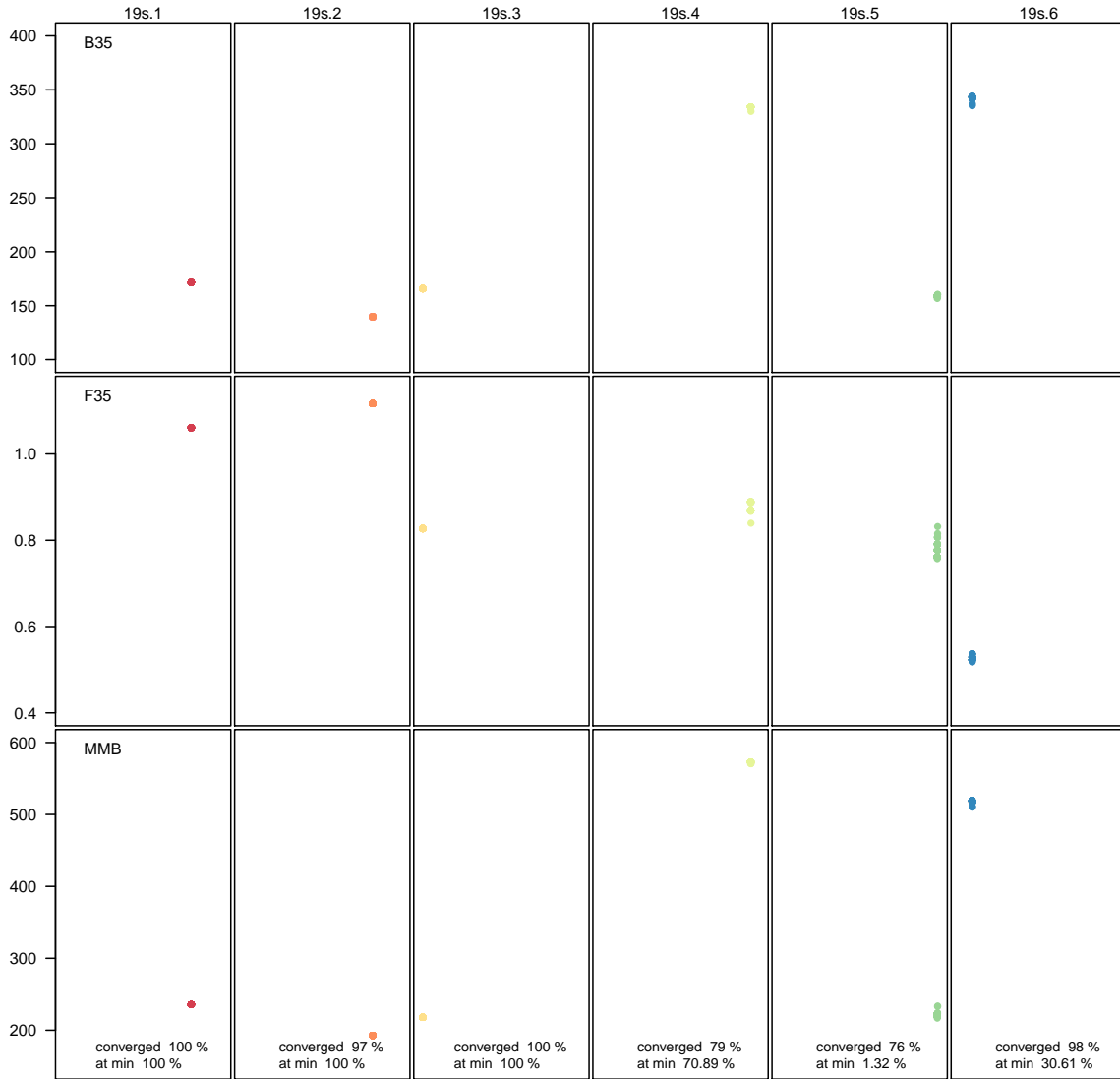


Figure 16: Management quantities after jittering selected models. Converged % indicates the % of jittered models that had a maximum gradient component < 0.005 . at min % indicates the number of runs that converged to the minimum observed negative log likelihood