Atlantic States Marine Fisheries Commission

2018 Northern Shrimp Benchmark Stock Assessment and Peer Review Report

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Sustainably Managing Atlantic Coastal Fisheries

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ACRONYMS

ASAP	Age-Structured Assessment Program
CSA	Catch Survey Analysis
CV	Coefficient of Variation
GOM	Gulf of Maine
M	Natural Mortality
MSY	Maximum Sustainable Yield
NEFSC	Northeast Fisheries Science Center
PPI	Predator-Prey Index
RSA	Research Set-Aside
SSB	Spawning Stock Biomass
TOR	Term of Reference
UME	University of Maine

PREFACE

The 2018 Northern Shrimp Benchmark Stock Assessment occurred through an Atlantic States Marine Fisheries Commission (ASMFC) external peer review process. ASMFC organized and held a Data Workshop on April 5-7, 2017 and an Assessment Workshop on April 10-12, 2018. In addition, the University of Maine held a Modeling Workshop on July 17-19, 2017. Participants of the Workshops included the ASMFC Northern Shrimp Stock Assessment Subcommittee and Technical Committee. ASMFC coordinated a Peer Review Workshop for the Northern Shrimp Assessment on August 14-16, 2018. Participants included members of the Northern Shrimp Stock Assessment Subcommittee and a Review Panel consisting of three reviewers appointed by ASMFC.

Section A – 2018 Northern Shrimp Stock Assessment Peer Review Report (PDF pages 5-29)
The Peer Review Report provides a detailed evaluation of how each Term of Reference was addressed by the Stock Assessment Subcommittee, including the Panel's findings on stock status and future research recommendations.

Section B – 2018 Northern Shrimp Stock Assessment Report for Peer Review (PDF pages 30-291)
This report describes the background information on data used, and analysis for the assessment submitted by the Stock Assessment Subcommittee to the Review Panel.

Section C – Addendum to the Northern Shrimp Stock Assessment Report (PDF pages 292-356)
This addendum describes the revision that was made to the base run of the stock assessment as recommended by the peer review panel at the Review Workshop, and presents the results of the new base run of the assessment.

Atlantic States Marine Fisheries Commission

2018 Northern Shrimp Benchmark Stock Assessment Peer Review Report

Conducted on
August 14-16, 2018
Portland, Maine

Prepared by the
ASMFC Northern Shrimp Stock Assessment Review Panel

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EXECUTIVE SUMMARY

The northern shrimp (*Pandalus borealis*) is a broadly distributed boreal species, which is at the southern limit of its distribution in the Gulf of Maine (GOM) (Figure 1). Genetic evidence (Jorde et al. 2015) suggests Northern shrimp in the GOM may be genetically distinct from shrimp in the rest of the species' range. This supports the conclusion that northern shrimp in the GOM is a single stock with limited mixing with populations to the north.

Climate change is causing shifts in the distribution of many commercially important species in the Mid-Atlantic and New England regions (Nye et al. 2009, Kleisner et al. 2016). Given that northern shrimp is at the southern limit of its range one may expect this species to be similarly affected by warming waters in the GOM. However, the presence of warmer and shallower waters to the north, may limit latitudinal shifts of GOM northern shrimp. Rather, the response of northern shrimp to climate change may be to become concentrated in deeper cold water pools in the GOM.

The commercial fishery in the GOM was formally established in 1938, but it is likely that small scale artisanal fisheries occurred prior to this date. The modern fishery dates to the late 1960s and involves vessels from Maine, New Hampshire and Massachusetts. The fishery has involved a variety of gear types and vessels, but now principally involves a small mesh trawl fishery and an inshore trap fishery.

The purpose of the 2018 stock assessment was to evaluate the status of northern shrimp in U.S. waters of the GOM. Data from fisheries-dependent and -independent sources were evaluated and used to develop a suite of assessment models for characterizing shrimp stock dynamics from 1985 – Present. A statistical catch-at-length model (UME), an age-structured model (ASAP), and a Catch Survey Analysis (CSA) were developed and produced similar results with regard to fishing mortality and stock biomass.

The University of Maine assessment model was rigorously tested and is recommended for use in providing fishery management advice. The 2018 assessment indicates the biomass of shrimp is at an all-time low. Given the low biomass, the northern shrimp stock is currently depleted. High levels of past fishery removals combined with changing, less favorable environmental conditions in the GOM have led to the depleted stock status.

The following Review Report evaluates the data and methods used to assess northern shrimp; gives recommendations on suitability of model inputs and model outputs, and provides recommendations for future research and assessment methodology.

TERMS OF REFERENCE (TOR)

TOR 1. Evaluate the thoroughness of fishery-dependent (landings, discards, effort) and fishery-independent data collection, and the presentation and treatment of data in the assessment, including the precision and accuracy of the data and inclusion or elimination of data sources. Evaluate the methods used to calibrate the data from the ASMFC summer survey's new gear changes.

Term of Reference 1 was met, except for calibration of the ASMFC Summer Survey data for which currently there are too few paired tows to develop a calibration.

Fisheries for northern shrimp occur in Maine, New Hampshire and Massachusetts, with landings from Maine dominating the modern era (1960-present, Figure 2). Fishery-dependent data were derived from a combination of dealer reports, harvester reports, port sampling, sea sampling and licensing data. Landings data appeared to be adequate for use in the subsequent assessment models, particularly given the assessment model starting year of 1985. There was no evidence of large missing sources of harvest (such as the 'peddler market'), or discards or bycatch in other fisheries. In particular, the discarding and bycatch rate is reported to be very low (0.03% of commercial catch). Accordingly, assuming that discard mortality was zero in the assessment was reasonable.

Length composition data for the commercial fishery were obtained from a combination of at sea and port sampling. Port sampling was initiated in 1985. A standard 1 kg sample is collected and the biological characteristics of the sample are determined in the laboratory. Initially, the program sampled 1% of the commercial catch. This level has increased to about 8% currently, and appears adequate overall. It was not clear whether the sampling was haphazard with respect to gear and location or if there was a statistical design underlying the sampling. Given that differences seem to be are present on an east-west gradient in the fishery, a full statistical design should underlie the port sampling. Length composition data were appropriately expanded by season, stage and gear.

Four surveys potentially provided fishery-independent data for northern shrimp. The ASMFC Summer Survey is a collaborative state-federal trawl survey designed specifically to provide data on northern shrimp. The stratified random survey samples 12 strata, with station allocation proportional to stratum area. In addition, two fixed stations are occupied in each strata. The survey has been conducted since 1984 and involves a 15 minute tow of a small mesh trawl at each station. Two deeper, eastern strata (11 and 12) were dropped in the early 2000s because of consistent zero catches. Data from strata 1, 3, 5, 6, 7 and 8 were used in the assessment. Northern shrimp are also recorded in the NEFSC spring and fall bottom trawl surveys. These are stratified random surveys that sample waters from the US-Canadian border south to Cape Hatteras, NC. The spring and fall surveys were not specifically designed to sample northern shrimp. A vessel change from the RV Albatross IV to the NOAA Ship Henry Bigelow occurred following the 2008 surveys. Samples from the two vessels were not standardized for the assessment. The surveys from the two vessels were considered separate time series. Data were also available from the Maine-New Hampshire Inshore Trawl Survey which samples shallow coastal waters. This more recent survey (2000-present) was designed as a multispecies survey for fish and invertebrates.

All survey data were fully evaluated for the assessment. Survey indices used in the assessment were developed using both design-based and model-based standardization approaches. Few details of the model-based approaches were provided in the assessment report. From presentations, it is apparent that the assessment team used the mixed modeling approach described by Thorson and Minto 2015, and applied to northern shrimp first in Cao et al. (2017c), to standardize survey data to account for the effects of random, uncontrolled variation in environmental parameters and station locations in the survey time series. The model-based index standardization approach is preferred over the designed based approach. If continued moving forward, providing information on parameters used and the subsequent model fits, variances, and diagnostics would be more informative. Such details are important as they provide an objective way to estimate the CVs subsequently used in the model. Without such detail, application of survey CVs risks appearing arbitrary.

The base assessment models employed the ASMFC Shrimp Summer Survey and the NEFSC Fall Survey as these were the most informative.

Survey data were also evaluated to examine potential shifts in distribution. No significant changes were reported. Such analyses should be continued as they may provide the first indication of changes in the distribution or phenology of shrimp movements that may have important consequences for the sustainability of the fishery.

Biological samples were taken during all surveys and provided length distributions for subsequent modeling. Data for the ASMFC Shrimp Summer Survey were expanded by life stage and combined with estimates of maturity and fecundity at length to yield empirical time series of spawning stock biomass and egg production. These are important empirical data for communicating trends to fisheries managers. The empirical maturity and fecundity relationships are more than 40 years old and should be re-evaluated.

In 2017, the trawl doors and winches were changed on the RV Gloria Michelle, the principal survey vessel for the ASMFC Shrimp Summer Survey. To date, less than 10 paired calibration tows have been completed. There was no strong indication of substantial differences in catch rates. Additional paired tows will be required in the future for a full evaluation of calibration coefficients for the survey.

TOR 2. Evaluate the methods and models used to estimate population parameters (fishing mortality, biomass, and abundance). Evaluate the NSTCs consideration of environmental effects in assessment models. Evaluate the diagnostic analysis performed (sensitivity and retrospective analysis). Evaluate the NSTCs discussion of the effects of data strengths and weaknesses on model results and performance.

Term of Reference 2 was fully met. The UME length based model is appropriate and preferred for providing fishery management advice.

Three analytic assessment models were presented to estimate population parameters (UME, ASAP, and CSA). In addition, empirical approaches to illustrate trends and thresholds in key data series (traffic lights), and data poor methods were also provided. All three analytic models were presented with a reasonable amount of details. The UME model was presented as the primary candidate to be used as the basis for management advice.

The shrimp assessment model developed by the University of Maine (UME) is a statistical catch-at-length based model. The model structure and data inputs are well documented in two peer-reviewed journal papers (Cao et al. 2017a, b). A previous version of the model was presented at the 2014 review of the northern shrimp assessment. It was not accepted for management use by the Review Panel at that time. The 2014 Review Panel primarily had concerns with the minimal amount of model testing and validation conducted, lack-of-fit to the length composition data, the length dependent natural mortality function, and the subjective weighting of the different sources of information. Since the 2014 review, the UME model has been updated and improved. The model has been validated in a comprehensive and peer reviewed simulation study. The change from a one-season to a two-season dynamic model has substantially improved the fit to the length composition data (Figure 3). The relative weighting of the different information sources is still subjective, but the assessment team demonstrated that all major trends are robust by thorough sensitivity analysis and by validating the results in other structurally different models. The UME model is accepted as the basis for management.

The Age Structured Assessment Program (ASAP) is a general and well tested age-structured assessment model. ASAP is part of the NOAA Fisheries Toolbox and is the accepted model for several stocks. The length-based data for northern shrimp had sufficiently distinct peaks representing cohorts to allow for a reasonable conversion into age-based data (via Normsep). This allowed for a validation via ASAP.

The Collie-Sissenwine or Catch-Survey Analysis (CSA) is also a standard model, which is part of the NOAA Fisheries Toolbox. CSA is a two stage model of ‘recruits’ (lengths of 16-22mm) and ‘post-recruits’ (lengths of >22mm). Fewer details were presented in the assessment report regarding the CSA model compared to the two other analytic assessment models. However, the workshop presentation by the assessment group showed the necessary details.

The input data are reliable and it appears possible to identify cohorts in the populations by consistent peaks in the length distributions. The data are adequate to support the modelling approaches presented.

The suggested base run of the UME model included five defined selectivity blocks. For fishery-dependent data pre-2000, a common selection pattern for the mixed trap and trawl fleet was applied. From 2000-2013, separate selection patterns were defined for trap and trawl. After 2013, new separate selection patterns were defined for trap and trawl fleets. The selection blocks appeared reasonable and justified by changes in the fishery fleets a priori and not merely to improve the model fit.

The UME model base-run was set up using 1mm length bins (from 10 to 22mm). The data are available at 0.5mm resolution, though the choice of modelling 1mm length bins is reasonable to accurately characterize the growth expected during each 6 month season.

The subjective weighting of the different data sources remains a concern. The model-based approach to analyzing the survey data provides uncertainty estimates that are used in the model. However, for the remaining sources of information the level of confidence is arbitrarily assigned via CVs, effective sample sizes, and deviance variances. For the current assessment the assessment team has demonstrated that the important model outputs are robust, and none of the different data sources show a problematic lack of fit. This means currently the data sources are all in agreement with respect to the main trends. If at some point in the future the data sources disagree, then it will be important to reassess these fixed inputs.

The subjective weighting of the fishery-dependent data and recruitment deviances places extra emphasis on ensuring informative model validation. The model validation presented by the assessment team was very focused on retrospective diagnostics (observed versus fitted and residuals were also presented). The retrospective analysis presented was not very informative. The retrospective peels presented showed almost no visible change in the estimates, which in some sense is the desired outcome. It could also indicate the assigned uncertainties are specified too tightly. Furthermore, it should be noted that retrospective analysis should always be a secondary model validation. It should first be validated that the model is actually describing the observations. This is best achieved by presentation and evaluation of the residual pattern. If the model is not describing the data, then it is simple to make the retrospective perfect (the model just needs to be sufficiently conservative).

The assessment team confirmed that the suggested base-run converged to the same solution when initialized at different values. Such analysis should be included with the standard model diagnostic graphs. Similarly, the bubble plots of the residuals for the length compositions, which were presented at the review meeting, should be added to the assessment document as they help ensure the first level of model validation - that the model fits the observed data.

The residuals provided for the length composition data were helpful and clearly showed positively correlated residuals. The UME model assumes a multinomial model for the length compositions, which assumes negative correlations. This mismatch is not uncommon in assessment models. A typical response is to decrease the effective sample size assumed as an ad-hoc measure to more correctly weigh the contribution from the length compositions. This was briefly explored during the review meeting, and results were almost identical.

The UME model involves both length varying and time varying natural mortality. The biological justification of the U-shaped length varying natural mortality was not fully convincing. This was noted by the 2014 Review Panel as well. The U-shaped curve was included in both Cao et al. (2017a, b) peer-reviewed journal papers. The U-shaped curve used assumes that mortality increases strongly and discontinuously between 28 and 29 mm, implying that larger shrimp undergo rapid senescence (Figure 4). The peer-review process did not raise a critical concern that using the U-shaped mortality curve would strongly affect model predictions; however, the discontinuities in the U-shaped length-based mortality function continue to be a cause for concern. The assessment team may want to consider using the Lorenzen M curve (e.g., Lorenzen 1996) as a more parsimonious explanation of length varying M. Alternatively, the assessment team should provide a much stronger justification for the U-shape length varying mortality function.

The time varying M is an important part of the model. The role of predation is likely an important contributor to changing M over time, but the inclusion of the predator-prey index (PPI) as the sole driver of time varying M raised concerns. The scaling of the baseline M to the time-specific M_t was described by the relationship:

$$M_t = M \cdot \frac{PPI_t}{\overline{PPI}}$$

Two concerns arise from the equation. The implied scaling between natural mortality and predation is arbitrary and causes M_t to become >4 in one case. Additionally, the equation is ill posed in extreme cases, as PPI approaches 0, M also approaches 0 (although this was not a concern for the range of observed PPI values). Predation is likely an important driver of M_t, but may not be the only one and the proposed relationship could be investigated further. This could be achieved either by estimating the scaling constant internally in the model (may not be possible), or by sensitivity runs with different scalings. Several approaches are possible including

$$M_t = M + \alpha \frac{PPI_t}{\overline{PPI}},\text{ where } \alpha \text{ is a scaling factor, or}$$

$$Mt = M * \left(\frac{PPI}{\underline{PPI}} * s - (s - 1\right),\text{ where } 0 < s < 1/(min(PPI)/\underline{PPI}\text{-}1)\text{, or}$$

$$Mt = M * \left(\frac{PPI}{\underline{PPI}}\right)^{\beta}\text{, where ß is an empirical scaling factor}$$

It is noted that the first two equations solve the challenge of M approaching 0 when PPI approaches 0, whereas the third equation does not.

The proportion of females at length seems stable from year to year, and is estimated externally to the model. It is suggested that the proportion could have been estimated within the model and thereby the uncertainty around the transition could have been propagated to the model results.

A specific term of reference for the assessment was to explore the impacts of environmental effects on the shrimp population using the assessment model. Environmental effects could be expressed through factors that have direct impacts on physiology and energetics, such as temperature. Environmental effects could also be expressed through indirect factors such as predation. Environmental effects were included via the PPI in the time varying part of the natural mortality as described above. The assessment team further showed sensitivity runs of the UME model in which environmental effects (temperature and temperature/PPI PCA coefficients) were included as raw scaling on the recruitment deviations. These additions did not change the overall trend in the quantities of interest and the retrospective pattern was slightly worse. The scaling constant between the standardized environmental coefficient and the recruitment deviance was arbitrarily fixed to one and with a penalty variance that was not updated from the version with mean zero deviances. The Review Panel suggests exploring different scaling constants, or a different penalty variance, to improve the effect of including environmental coefficients.

The assessment team provided a thorough array of sensitivity runs: different assumed CVs on data sources, time/size invariant M, different M levels, different drivers of recruitment deviances, using designed-based indices, and including or excluding data sources. In addition to these standard sensitivity runs around the proposed base-model, the assessment team produced sensitivity runs where the size-specific part of the natural mortality followed a more conventional Lorenzen curve (preferred by the reviewers), and where the effective sample size was reduced. The model results and especially the main trends were robust to these changes. However, the recruitment in the proposed base-run exhibited wider fluctuations (including reaching higher levels) than any of the sensitivity runs. This in combination with the Review Panel's skepticism towards the somewhat unconventional U-shaped size-specific natural mortality led the Panel to recommend the assessment team use either the Lorenzen curve, or more clearly describe the rationale for the U-shape of the length varying mortality function in the assessment.

After the Review Workshop, the assessment team completed additional UME model runs using the Lorenzen M approach. The Panel finds the Lorezen M-based model runs more robust and recommends that model results with the new configuration be used to provide advice to fishery managers.

In addition to all of the within-model sensitivities described above, the assessment team was able to compare important output quantities across the three analytic models. These consisted of comparisons of relative trends of the most closely comparable model outputs, since the three models did not directly provide the same outputs. The comparison showed that major conclusions to be drawn are consistent across three very structurally different models (Figure 5). The comparison of model outputs greatly strengthened the confidence in the assessment results and model choice.

TOR 3 Evaluate the NSTCs choice of reference points and the methods used to estimate them. Recommend best estimates of population parameters (fishing mortality, biomass, and abundance) from the assessment for use in management, if possible, and a stock status determination based on BRPs developed.

Term of Reference 3 is no longer relevant because no MSY-based reference points were developed.

The decision by the assessment team not to develop MSY-based reference points or stock status indicators is appropriate. All evidence indicates the shrimp stock is not well-described with a fixed measure of productivity; conversely, there is consistent evidence that both recruitment and natural mortality have fluctuated substantially over time. Therefore, the risk-based approach used by the assessment team (Figure 6) that forecasts the probability the stock will stay the same or increase, given a specified fishing mortality and pattern of recruitment, is appropriate for use in management decisions.

Both predation mortality (as measured by the PPI index) and climatic conditions (as measured by surface and bottom temperatures) are consistent with higher natural mortality currently than at the beginning of the time series (Figure 5), and neither predation nor climatic conditions are likely to improve in the short term. Therefore, statistical forecasts of stock change under different F regimes should be based on the short-term distributions of either M, R, or short-term distributions for both series (rather than the distributions from the whole time series). It is appropriate that managers select the likelihood that the spawning stock biomass (SSB) will increase over the previous year, but likelihoods of SSB increases of less than 50% should not be considered, given the current low level of the stock compared to the long-term level (Figure 6).

TOR 4 Evaluate the methods used to characterize uncertainty in model estimates of fishing mortality, biomass and recruitment, and biological reference points.

Term of Reference 4 was partially met. Estimates of uncertainty in time series of fishing mortality, biomass, and recruitment were provided. However, because of concerns of the subjective nature of the CVs used in the models (see TOR 2), it is highly likely the provided uncertainties are underestimates of the true uncertainties.

All methods used to characterize uncertainty were internal to the model. The assessment team did not attempt to forecast out of sample data to determine if the uncertainty bounds produced by the model gave an accurate description of the true uncertainty deriving from the data and model fitting process. Further, the level of uncertainty around data used to fit the model - CVs of catch, natural mortality, and the assumed variance in year-to-year recruitment deviations - were arbitrarily assigned, and several key parameters such as natural mortality were assumed to be estimated without error. Only the uncertainty around survey biomass estimates and sample sizes for length-frequency observations were data-driven. As a result, the resulting confidence statements are a direct consequence of the fixed CVs and deviances. The review committee felt the uncertainty in the model outputs (Figure 7) is accordingly almost certainly underestimated, and further exploration of model uncertainty would be beneficial. In addition, the assessment document did not include uncertainty estimates for all components (including growth projection matrices and selectivity curves), which made it difficult to determine if these components were also estimated with too high a degree of certainty.

However, the close agreement in the pattern of change between the three models presented (UME, ASAP, and CSA) does give confidence in the robustness of the average trends from the model, given that the three models were based off somewhat different sources of information and made different assumptions about the dynamics of the stock. Further, the relative insensitivity of model outputs to changing model assumptions implies that model estimates and forecasts are likely robust to changes in modeling assumptions.

Going forward, better estimates of model uncertainty may be achieved by estimating more parameters (such as the relationship between PPI and mortality, or the standard deviation of recruitment) as part of the model fitting process, and by bootstrapping data inputs to account for measurement uncertainty (Patterson et al. 2001).

TOR 5. Evaluate the methods used to calculate the annual target catch and used to characterize uncertainty of target catch estimates.

Term of Reference 5 was met. The approach to calculate annual catch targets is appropriate.

As mentioned in TOR 3, the current approach taken by the assessment of not recommending a specific target catch but instead providing forecasts of probabilities of population growth under alternate fishing mortality scenarios (Figure 6), is appropriate for the shrimp fishery. The risk of decline that is considered acceptable (which will depend on the catch target) should be a management choice, not a scientific issue.

The current forecasts may be underestimating the true level of uncertainty of decline or increase for a given fishing rate, for the same reasons that model uncertainty was likely underestimated as mentioned in TOR 4. However, the approach for forecasting is reasonable, and improving uncertainty estimates in the UME model will also improve how uncertainty is characterized for catch forecasts.

TOR 6. Review the research, data collection, and assessment methodology recommendations provided by the TC and make any additional recommendations warranted. Clearly prioritize the activities needed to inform and maintain the current assessment, and provide recommendations to improve the reliability of future assessments.

The following research recommendations, provided by the TC, are all considered appropriate and effectively prioritized:

Fisheries-dependent research priorities:

- Evaluate selectivity of shrimp by traps and trawls (high priority, short term)

- Continue sampling of the northern shrimp commercial fishery, including port, sea, and RSA sampling to confirm, and if necessary update, the length-frequency of the species and identify any bycatch in the fishery (high priority, long term)
- Conduct a study comparing the effectiveness of the compound grate versus the double Nordmore grate (moderate priority, short term)

Fisheries-independent research:

- Continuing sampling through Shrimp Summer Survey despite the current low abundance of shrimp and the closure of the shrimp fishery in 2013 (high priority, long term)
- Explore ways to sample age 1 and younger shrimp (moderate priority, short term)

Life history, biological, and habitat research

- Investigate application of newly developed direct ageing methods to ground truth assumed ages based on size and stage compositions (high priority, long term)
- Evaluate larval and adult survival and growth, including frequency of molting and variation in growth rates, as a function of environmental factors and population density (high priority, long term)
- Study the effects of oceanographic and climatic variation (i.e., North Atlantic Oscillation) on the cold water refuges for shrimp in the GOM (high priority, long term)
- Explore the mechanisms behind the stock-recruitment and temperature relationship for GOM northern shrimp (high priority, long term)

The Review Panel also considered the following research topics, focused on improving model performance and understanding the spatial dynamics of the stock, to be potentially useful research directions:

General

- The assessment document relies on external journal documents for details. For future reference, such required documents should be included in the assessment document for ease of future analysts and reviewers.
- It is likely that model-based index standardization will become more widely used in assessments. In such cases, details of model parameterization, estimation, and output of relevant parameters should be provided, either in the body of the assessment or in an appendix.

Life history

- Re-evaluate size-based relationships for maturity and fecundity which are used to expand fishery-independent data and to inform the model. Relationships for maturity and fecundity at size, specific to the GOM, appear to have been last determined more than 40 years ago. Given the impact of climate change, the empirical relationships may no longer be valid (low priority - but easy, short term).

Fishery-independent

- Adapt the current model-based approach for estimating trawl biomass indices to estimates of length structure (moderate priority, short term).
- Evaluate potential benefits of re-stratification of the ASMFC Shrimp Survey. Two strata have already been dropped, and the remaining strata may be less optimal. Given the possibility that shrimp may move to deeper waters as surface waters warm, higher depth resolution of strata may be useful (moderate priority, short term).
- As the GOM northern Shrimp stock is the southernmost stock, it is highly likely to be sensitive to changing temperature regimes. If temperatures continue to increase, a substantial change in the spatial distribution of the stock may result. The current spatial distribution and potential changes in distribution should be explored, with a particular view to how the future data may inform subsequent model runs. (Moderate term, high priority)

Modeling

- Explore alternate forms of time-varying natural mortality, relaxing the current assumption of direct linear dependence of M_t on PPI. The current equation is ill-posed and includes the potential that $M_t = 0$ if PPI=0. (High priority, short term).
- Extend the current modelling approach to allow for directly estimating the functional relationship between M_t and PPI or other environmental factors (high priority, moderate term).
- Explore incorporating time-varying M as a random effect estimated as part of the model, to determine if the assumed patterns of M_t are consistent with estimated M_t values, and to determine if a simple increasing M_t trend is appropriate (high priority, moderate term).
- Improve representation of temperature and other environmental predictors on recruitment. Currently the variance scaler used for sensitivity tests assumes temperature and recruitment deviations have equivalent uncertainties, whereas the relationship between temperature and recruitment deviations could be directly estimated in the model (long term, moderate priority).
- Increased evaluation and estimation of uncertainty and covariances are encouraged. Explore either predicting data out of sample, or resampling approaches to quantify the uncertainty in model predictions. Evaluation of the impacts of effective sample size on model outputs is also encouraged (short to moderate term, high priority).
- The population is spatially structured with seasonal differences in distribution. Growth is currently the only seasonal feature of the model, yet it is likely that M could also vary seasonally, as shrimp migrate from inshore to offshore and back. The reviewers recommend developing a spatially implicit model, with length-specific mortality rates varying seasonally to determine what effects this might have on the fishery (longer term, moderate to low priority).

TOR 7. Recommend timing of the next benchmark assessment and updates, if necessary, relative to the life history and current management of the species.

The current sampling regime and the UME model are appropriate for giving management advice, and do not need to be re-reviewed through a benchmark assessment before being used to assess the stock. Further, the combination of the current detailed monitoring program, traffic light approach, and UME model forecasts should be sufficient to detect substantial changes in the state of the stock. As such, annual updates to the UME model and traffic light are appropriate to monitor the state of the stock. Given the 3-6 year lifespan of shrimp and the effectiveness of UME at fitting observed population dynamics, a five year period until the next benchmark assessment is appropriate. However, an earlier benchmark assessment may be necessary if 1) the UME model detects substantial increases or decreases in the stock relative to the current year, 2) if model predictions deviate substantially from data observations, or 3) if large changes in the spatial distribution of shrimp are observed in the summer or fall surveys.

ADVISORY REPORT

A. Status of the stock: Current and projected

Based on the material reviewed and presented during the meeting, the Review Panel concluded there is a high likelihood the GOM northern shrimp stock is at a low level of abundance. This conclusion is supported by the agreement in the results of three analytical models with differing structures and regardless of the assumptions made about inputs to the model.

An important feature of the models is the inference that natural mortality rates have increased over time and are likely higher now than in previous years. Additionally, annual recruitments have trended down and are likely lower than in previous years. These trends suggest that abundance of GOM northern shrimp is likely to continue to remain at low levels over the short term.

B. Stock Identification and Distribution

Northern shrimp (*Pandalus borealis*) is a broadly distributed boreal species at the southern limit of its distribution in the GOM (Figure 1). Genetic evidence suggests northern shrimp in the GOM may be genetically distinct from shrimp in the rest of the range. This supports the conclusion that northern shrimp in the GOM is a single stock with limited mixing with northern shrimp populations to the north.

Climate change is causing shifts in the distribution of many commercially important species in the Mid-Atlantic and New England regions. Given that northern shrimp are at the southern limit of their range one may expect the species to be similarly affected by warming waters in the GOM. Due to the presence of warmer and shallower waters to the north, the response of northern shrimp to climate change may be to concentrate in deeper cold water pools in the GOM, rather than to induce a northern shift in their distribution.

C. Management Unit

From the Northern Shrimp Benchmark Stock Assessment, p. 28:

"The management unit is defined as the northern shrimp resource throughout the range of the species within U.S. waters of the northwest Atlantic Ocean from the shoreline to the seaward boundary of the Exclusive Economic Zone (EEZ)."

D. Landings

The commercial fishery in the GOM was formally established in 1938. It is likely that small scale artisanal fisheries occurred earlier. The modern fishery dates to the late 1960s and involves vessels from Maine, New Hampshire, and Massachusetts. The fishery has involved a variety of gear types and vessels, but now principally involves a small mesh trawl fishery and an inshore trap fishery.

The fishery is highly seasonal, taking advantage of the seasonal movements of northern shrimp by which the species migrates between shallower coastal regions in winter months, and deeper waters in the GOM during the summer.

The Northern Shrimp Stock Assessment Report provides a summary of landings from 1960-present (Figure 2). Evident in Figure 2 is a period of high landings in the late-1960s – early 1970s after which the stock collapses and a moratorium was imposed (1977-1978). The fishery reopened, and a period of variable but more sustainable landings followed (1979-2013). The average landings during this period was 3297mt. In 2014, the fishery was again closed following a sharp decline in survey indices. Since 2014, the only fishery occurring is under provisions of a research set aside (RSA) provision.

E. Data and Assessment

The previous GOM northern shrimp benchmark assessment (ASMFC 2014) was not accepted for use in management because of concerns over substantial differences between the size distributions predicted by the model and those observed in the surveys and in the landings.

The 2018 GOM northern shrimp benchmark assessment sought to resolve these issues. Both fishery independent (surveys) and fishery dependent (landings) data were available for use in the assessment. Three assessment models were brought forward by the Northern Shrimp Technical Committee. The three models used similar data inputs but had very different structures and hence assumptions. The use of multiple models with such different structures is a particular strength of the assessment. All three models use data from two surveys: the ASMFC Shrimp Summer Trawl Survey, and the NEFSC Fall survey (with the data from the RV Bigelow and RV Albatross considered separately). The models used were:

UME: A length based model developed by scientists at the University of Maine assumes that the length of the shrimp is its most important characteristic. The model is similar in structure to the model used in the lobster and sea urchin stock assessments. The model predicts the most likely growth of shrimp during separate summer and winter seasons. The UME model uses the length of the shrimp to estimate the likelihood it is caught, dies by natural causes, and/or produces offspring. This was model was the preferred model for management.

CSA: A catch survey model was used as supportive of the UME model. The model represents northern shrimp as occurring in one of two size classes (Recruits and Post Recruits). The CSA model was used previously for northern shrimp and is also used in the blue crab fisheries in Delaware and in the Chesapeake Bay. CSA assumes the stage the shrimp is in is the most important feature determining its fate.

ASAP: An age structured model was also used as supportive of the UME model. The specific age-structured model used for northern shrimp is used widely to assess a number of fish species in the Mid-Atlantic and New England region. Because shrimp cannot be reliably aged through an analysis of the hard parts of the body, as fish can be using bones (otoliths) in their inner ears, the size of shrimp has to be converted to age by a technique called modal analysis, which identifies size classes that are equivalent to age classes.

The UME model is preferred for providing management advice. The current model provides much improved fits to data, including length frequencies (Figure 3). The predictions of the UME model are supported by the concordance of all three models in their predictions of fishing mortality rates (Figure 5A), recruitment (Figure 5B), and spawning stock biomass (Figure 5C).

F. Biological Reference Points

Attempts to estimate MSY based biological reference points are not recommended because of the low current abundance of shrimp, the highly episodic nature of recruitment, and the relatively short lifespan.

Instead, a projection approach is recommended in which a certain probability is selected that any desired catch will lead to a spawning stock biomass of at least the same magnitude as present in the terminal year of the assessment (2017). In this way management advice will take the form of “a catch of X mt will have a Y probability of leading to a spawning stock biomass of equal size to that estimated for the last year”. Although the level of risk assumed is clearly a management decision, it is recommended that the probability selected be no less than 50% - i.e, a coin toss.

The intent of management advice of this type is to keep the northern shrimp stock increasing over the short term. Accordingly, short term estimates of mortality and recruitment should be used in projections. An example of the type of management advice recommended is provided in Figure 6.

G. Fishing Mortality

The current northern shrimp fishery is under a moratorium and the only fishing that occurs is under a research set aside program. As a direct result, recent fishing mortality rates, F, are low (Figure 7A).

No statement of whether or not the stock is experiencing overfishing is possible because no reference points were accepted.

H. Recruitment

All three models indicate recent recruitment is low (Figure 7B). However, levels of recruitment of a similar magnitude have sustained large fisheries in the past. This suggests there has been a change in the production dynamics in northern shrimp such that young shrimp are either not growing and/or surviving in numbers like they did in the past. An exploration of whether climate change, increased predation, or other ecosystem factors are responsible for this difference is warranted.

I. Spawning Stock Biomass

Stated with high confidence, the spawning stock biomass of northern shrimp is currently low (Figure 7C). Estimates of SSB for the last four years are the lowest in the time series predicted by the UME model (preferred) and the CSA and ASAP models. The low level of spawning stock biomass is unlikely to be able to support the fisheries and other ecosystem services (food for predators) that northern shrimp have provided in the past.

A continuing pattern of low spawning stock biomass would be of utmost concern, particularly given the concerns of shifts in environmental conditions noted above. It is noted that because of northern shrimp's reproductive potential and short life spans, rapid expansion of spawning stock biomass is possible, as evidenced for the years 2003-2006 in Figure 7C.

J. Bycatch

Discarding, the death of undesirable shrimp in the northern shrimp fishery, and bycatch, the capture of northern shrimp in other fisheries, are of minimal concern in part because of the use of bycatch reduction devices, e.g., the Nordmore grate. Bycatch is thought to be very minimal in trawl fisheries not targeting shrimp due to large mesh sizes that allow shrimp to escape.

K. Other Comments

Concerns regarding the impacts of a changing environment on the long term sustainability of northern shrimp in the GOM have been stated several times in this advisory report, but are worth restating here.

Oceans around the world are changing and there is evidence that nowhere is this change more evident than in the GOM. There is clear evidence from New England waters of latitudinal shifts in the distribution of red hake and other species - that is they occur in more northerly waters than they used to 30 years ago. It is less clear as to whether poleward shifts will occur in the GOM because of the presence of a deep pool of cooler water in the southwestern GOM. This may provide a refuge of suitable habitat going forward. But conditions in shallow coastal waters are likely to warm during summer months at a time when shrimp are present in nearshore waters. The impacts of warming on growth, reproduction, and the abundance of the prey and predators or northern shrimp have not been quantified.

It is clear from all three assessment models that each model is better able to describe the data if natural mortality rates are allowed to increase over time. All three model attribute the increase to predation. Other factors may be at play as well, including temperature-induced physiological stresses on all stages of the northern shrimp life cycle.

These ongoing changes and natural processes are cause for concern for the future of a long term sustainable northern shrimp fishery at levels seen in the period 1979-2013.

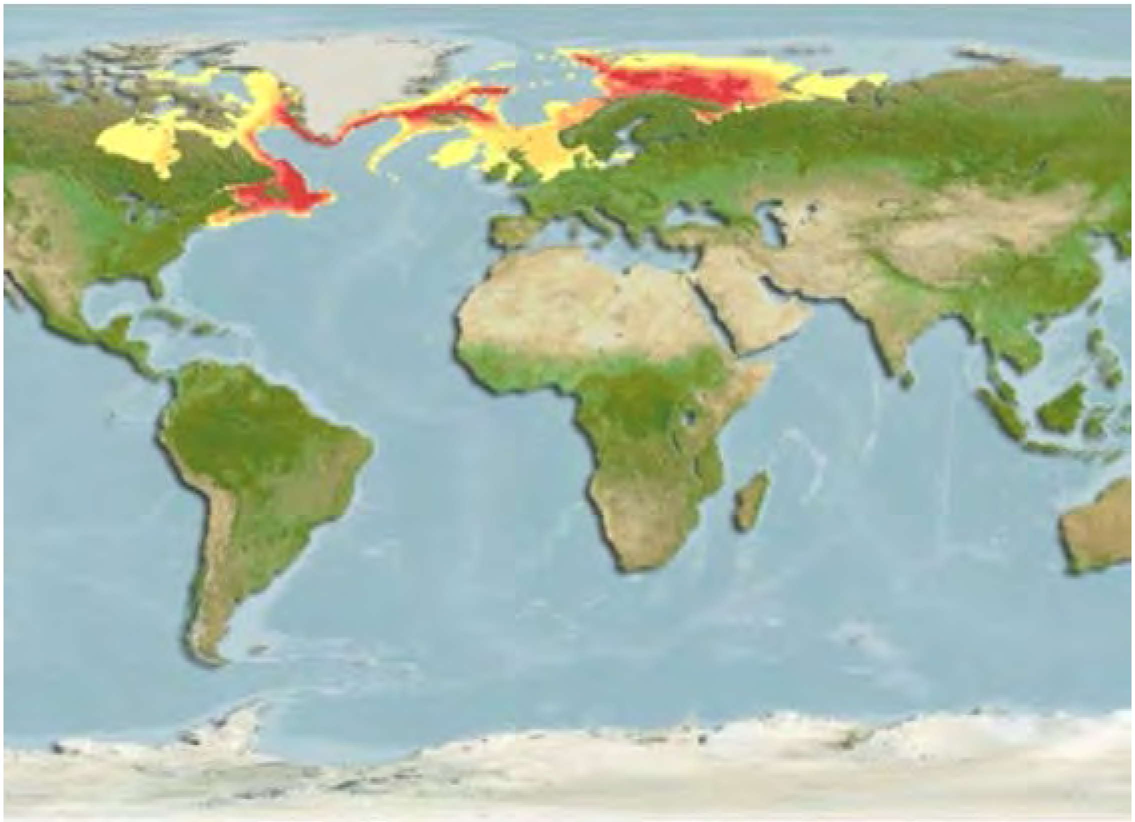

Figure 1. Distribution of Northern Shrimp (Credit: Sealifebase.org, 2018). Red colors indicate higher abundances, yellow lower abundances.

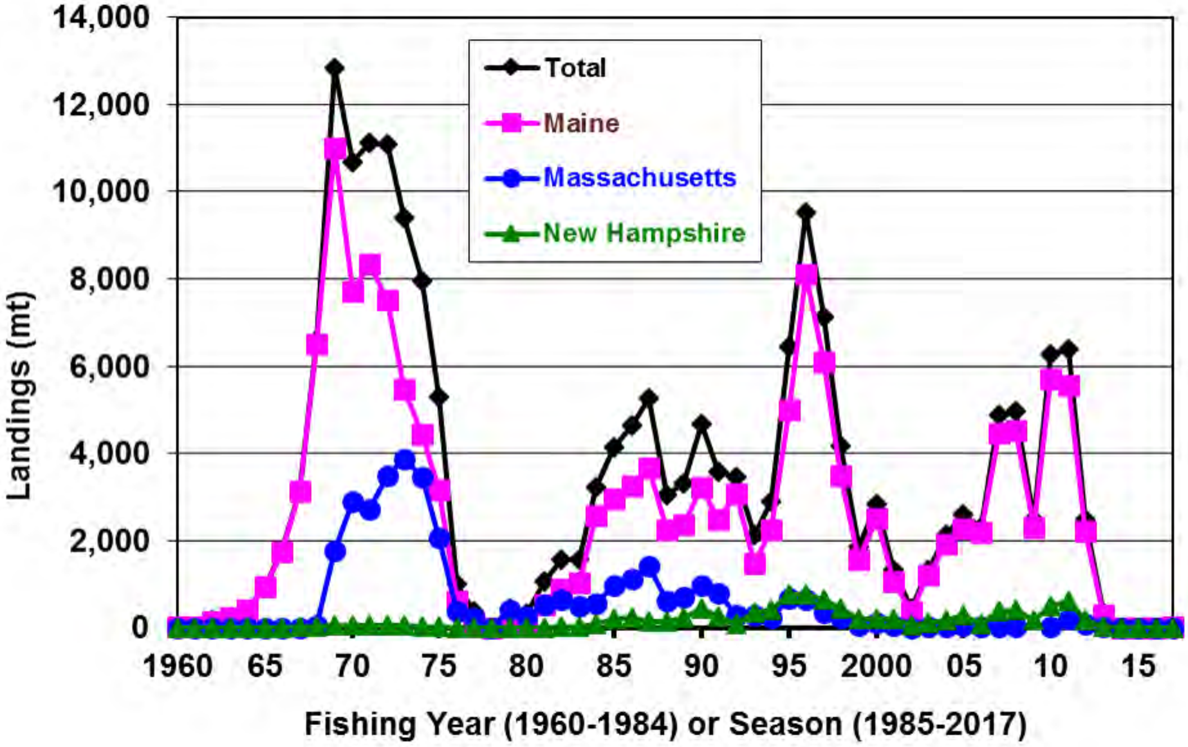

Figure 2. U.S. commercial landings (mt) of northern shrimp in the Gulf of Maine, by season and state. Massachusetts landings are combined with New Hampshire landings in 2009 to preserve confidentiality. Landings in 2014 are from Maine cooperative sampling trip catches. Landings in 2015 - 2017 are from the RSA program catches. (Figure 2.1 from Northern Shrimp Benchmark Assessment report).

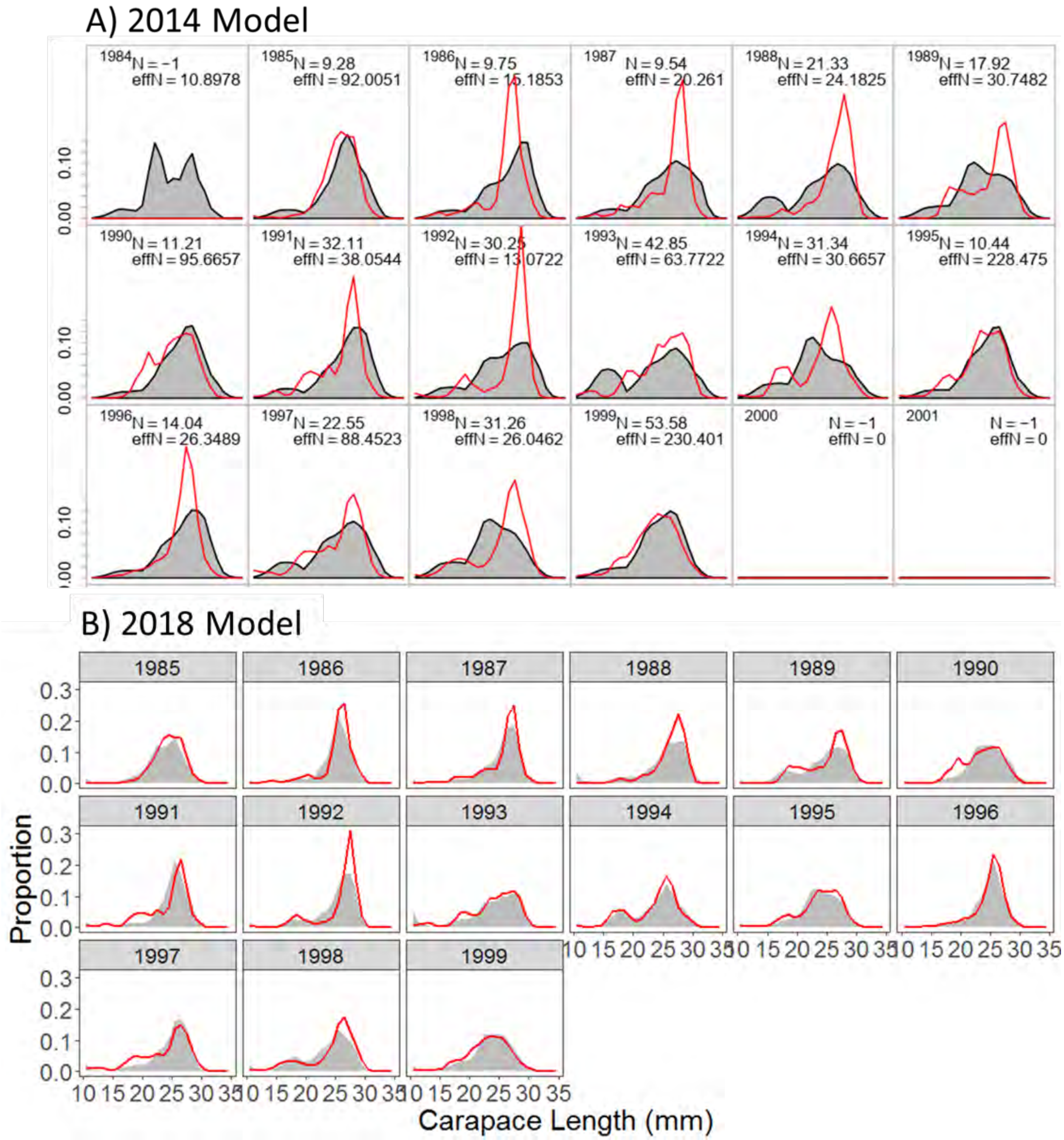

Figure 3. Comparison of the UME model performance in predicting length compositions for the mixed fleet. A) 2014 benchmark assessment model, and B) 2018 benchmark assessment model. Observed (solid grey histogram) and predicted (solid red line) length composition (From 2018 Northern Shrimp Benchmark Assessment)

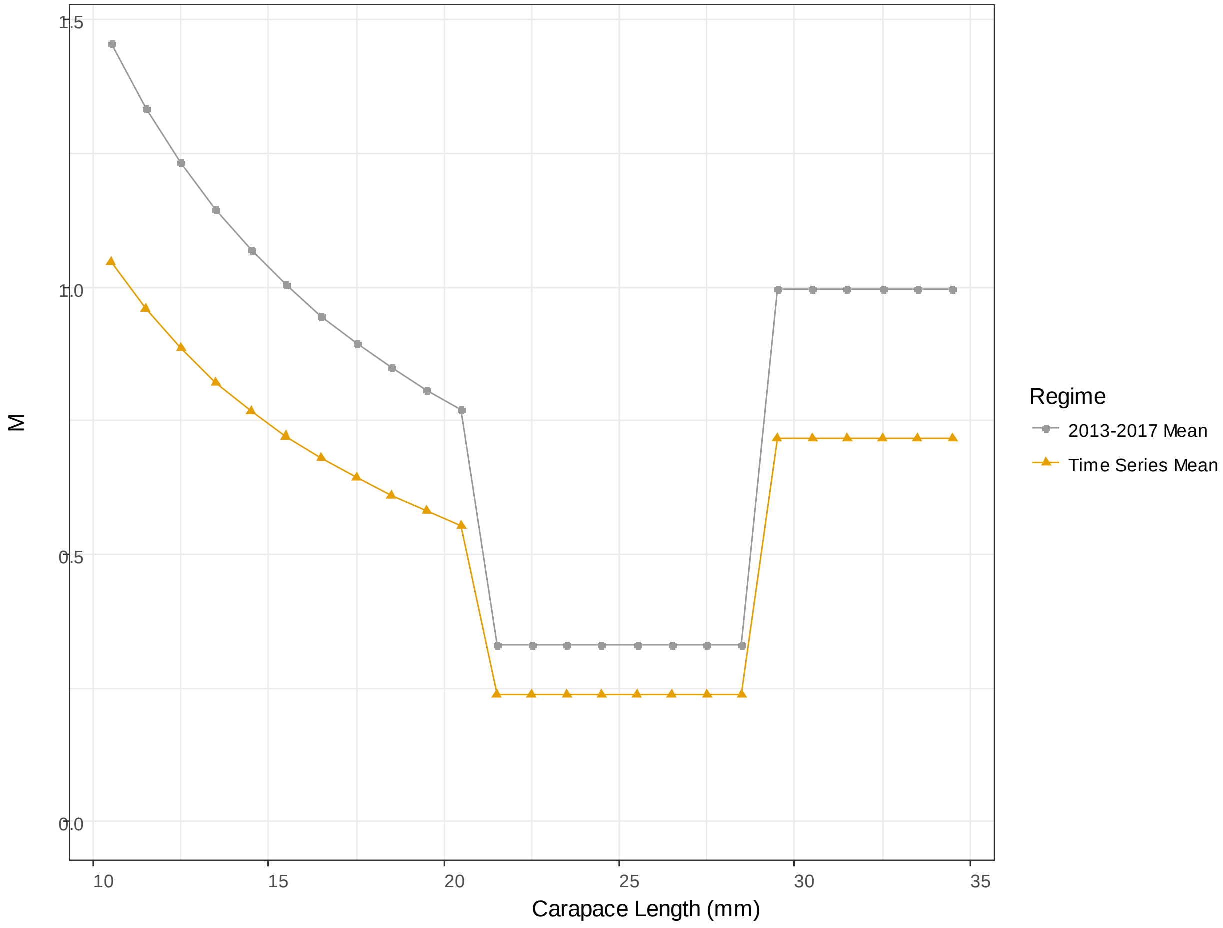

Figure 4. Natural mortality (M) used in the UME model projections (Figure 6.2 from 2018 Northern Shrimp Benchmark Assessment).

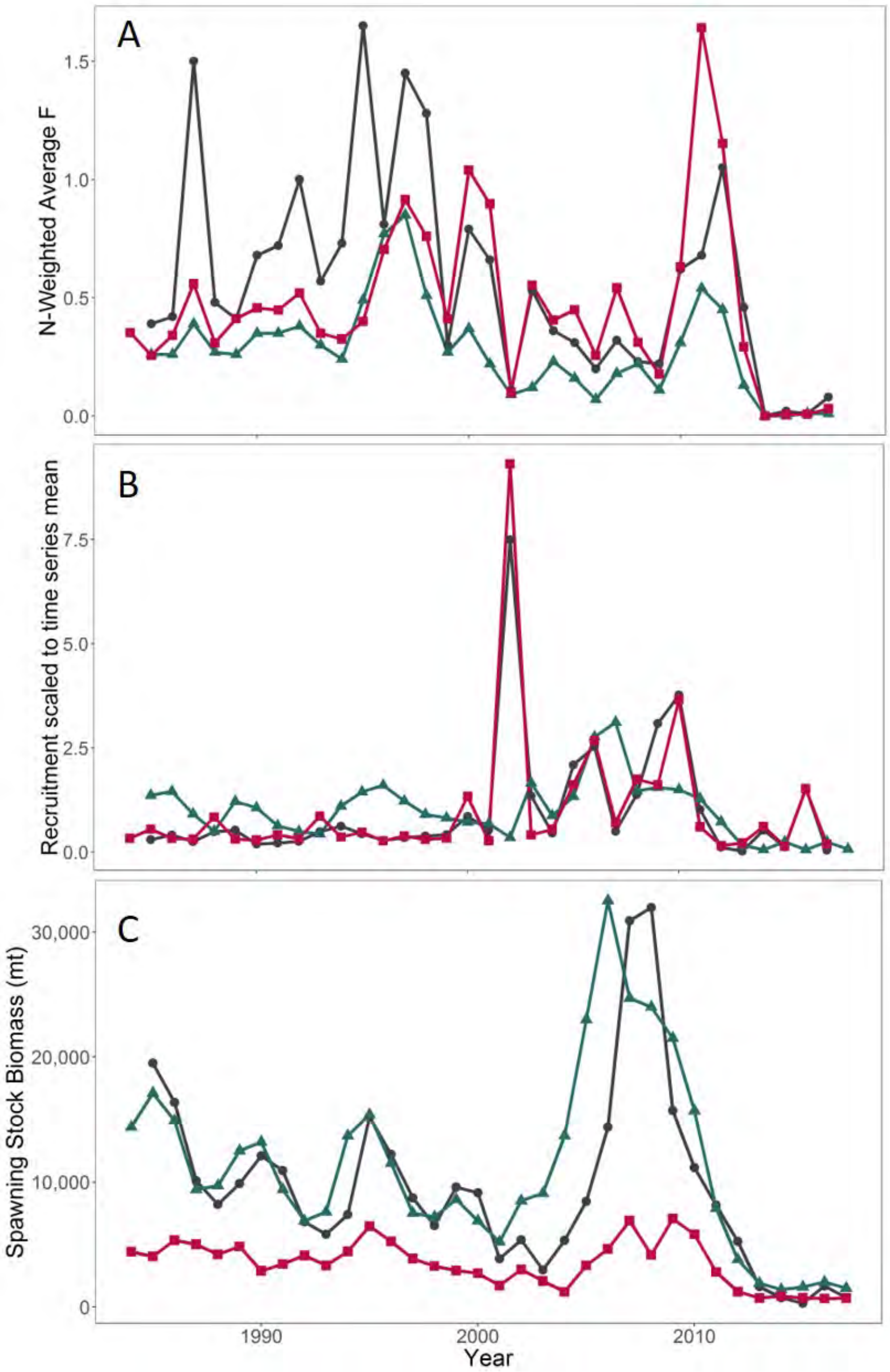

Figure 5. Comparisons of the three models developed by the NSTC for the Northern Shrimp benchmark assessment for A) Spawning stock biomass, B) Recruitment and C) Fishing mortality rates. The UME model, which is the preferred model for management is shown in red, the CSA model is shown in green and the ASAP model is shown in black.

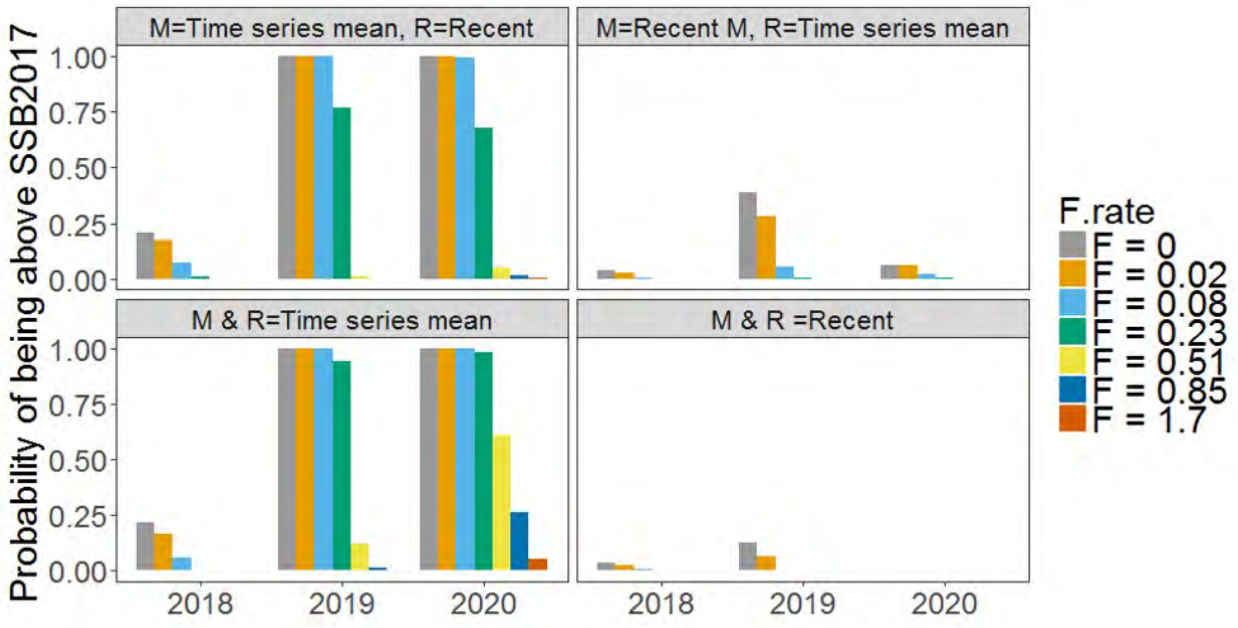

Figure 6. Example of management advice that could be provided from the UME model. The four panels represent the likelihood that the spawning stock biomass will be above the 2017 level in 2018, 2019 and 2020 for a range of different fishing mortality rates. Each panel represents different assumptions about natural mortality (M) and recruitment (R). The results indicate that the combination of M and R from the recent period is the most likely to occur in the short term future. (Figure from the final presentation of the assessment, August 15, 2018, Portland, Maine).

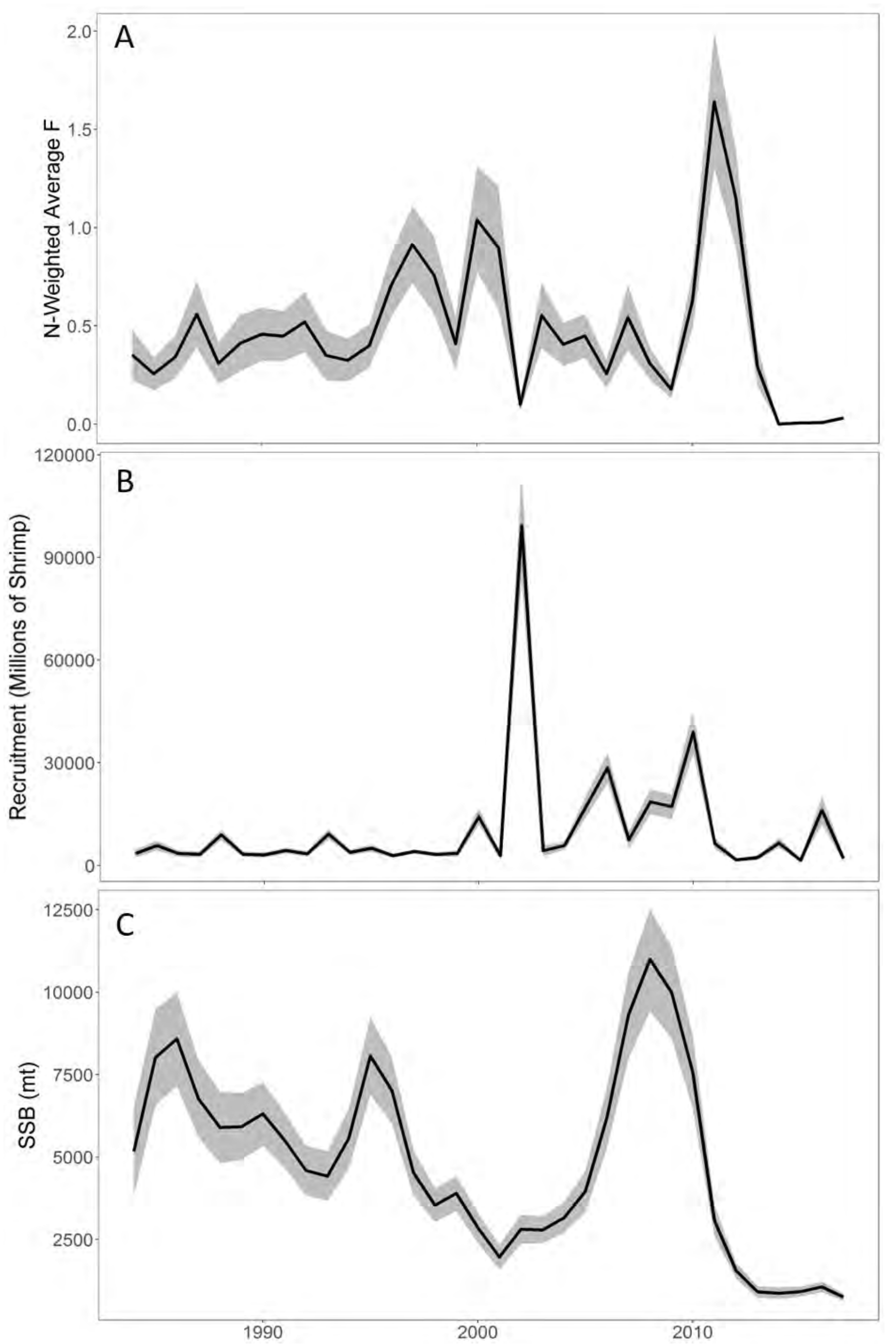

Figure 7. Estimates of A) fishing mortality rates, B) recruitment and C) spawning stock biomass of Northern Shrimp from the base run of the UME model. Grey shading indicates 95% confidence intervals of the estimates. (From 2018 Northern Shrimp Benchmark Assessment)

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Atlantic States Marine Fisheries Commission

2018 Northern Shrimp Benchmark Stock Assessment Report

Prepared by the
ASMFC Northern Shrimp Technical Committee & Stock Assessment Subcommittee

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EXECUTIVE SUMMARY

1. Present the Gulf of Maine northern shrimp landings, discards, effort, and fishery-independent data used in the assessment. Characterize the precision and accuracy of the data and justify inclusion or elimination of data sources. Develop and apply a calibration method to account for gear changes in the most recent year of the ASMFC summer trawl survey.

The northern shrimp fishery in the Gulf of Maine formally began in 1938; landings have fluctuated greatly over the course of the fishery. The time series used in the current Gulf of Maine northern shrimp stock assessment begins with 1984, when the dedicated summer shrimp survey began. Landings ranged from 2,100 to 4,700 mt during 1984-1994, and then rose dramatically to 9,500 mt in 1996, the highest since 1973. Landings declined to an average of 2,000 mt for 1999–2001, and dropped further in the 25-day 2002 season to 450 mt. Landings then increased steadily, averaging 2,100 mt during the 2003 to 2006 seasons, then jumping to 4,900 mt in 2007 and 5,000 mt in 2008. In 2009, 2,500 mt were landed during a season that was likely market-limited; landings in 2010 and 2011 were over 6,000 mt each year. From 2010-2012, the fishery exceeded the recommended catch level by about 36%. In 2013, the total allowable catch was set at 625 mt, but the fishery could not catch the full TAC during the winter season; the fishery was closed at the end of winter to prevent fishers from harvesting males in offshore waters. The Northern Shrimp Section implemented a complete moratorium for the 2014 season, based on severe declines in the fishery independent indices, very poor recruitment from the 2010-2012 year classes, and unfavorable environmental conditions. The fishery has remained closed since then, but a small winter sampling program via selected commercial shrimp vessels occurred each year to continue the time series of biological data on size composition and egg-hatch timing from earlier commercial sampling.

Size and sex-stage composition data have been collected from port samples of fishery landings from each of the three states throughout the assessment time period, including the moratorium. Northern shrimp size composition data from landings and surveys indicate that trends in landings have been influenced by the abundance of recruited year classes.

Discard rates of northern shrimp in the fishery are thought to be near zero because no size limits are in effect and most of the fishing effort occurs in areas where only the larger females are present. Data from limited trap and trawl observer studies supported this idea, indicating about 0-0.2% of shrimp catch is discarded. Data from the Northeast Fisheries Observer Program in the Gulf of Maine suggested discarding of northern shrimp was also minimal in other fisheries.

The number of boats participating in the northern shrimp fishery during 1980 to 1999 varied from 30-40 in 1980 to about 390 in 1988. Since 2000, the number has varied from a low of 144 in 2006 to a high of 342 in 2011. In the 2013, the last year of the open fishery, a total of 208 vessels (including both trawlers and trappers) from Maine, New Hampshire, and Massachusetts participated in the fishery.

Prior to 1994, effort (numbers of trips by state and month) was estimated from landings data collected from dealers, and landings per trip information (LPUE) from dockside interviews of vessel captains. Beginning in the spring of 1994, a vessel trip reporting system (VTR) supplemented the collection of effort information from interviews. The average number of trips per season was approximately 8,800 from 1985 – 1998, with highs of over 10,000 trips per season in 1987 and 1995-1997. Total trip numbers declined after that, with an average of approximately 3,800 trips per season from 2001 – 2013; 2008, 2010, and 2011 were well above that average with more than 5,500 trips in each year, but still below the average number of trips in the earliest part of the time series.

Catch per unit effort for the shrimp fishery is typically measured in landings per trawl hour (from Maine interview data) or catch per trawl trip. Catch rates can be affected by many factors in addition to stock abundance, such as possible increasing trawler efficiency, the timing of the season (catch rates are generally highest in January and February), attrition of less successful harvesters, and, most importantly, annual differences in the inshore/offshore migrating and aggregating behavior of northern shrimp in the Gulf of Maine. Maine trawler catch rates were very stable during the 2008-2012 seasons at around 169 kg/hr (before plummeting in 2013) compared with the rates during the 1985-1994 "stable period", which averaged 62 kg/hr. In contrast, the summer survey indices during those two periods were very similar (averaging 13.3 and 14.1, respectively). Therefore, catch rates have not historically been reliable indices of shrimp abundance or biomass, and are not used as such in this assessment.

The Northern Shrimp Technical Committee (NSTC) considered three fishery-independent indices of abundance for use in this assessment: the NEFSC Fall Bottom Trawl Survey, the Maine-New Hampshire Inshore Trawl Survey, and the ASMFC Summer Shrimp Survey. The indices of abundance from these surveys have traditionally been calculated with design-based estimators (stratified arithmetic or geometric means), but for this assessment, a spatio-temporal standardization approach was used to account for habitat information and spatial auto-correlation in the survey data.

The NEFSC Fall Survey samples waters from Maine to Cape Hatteras, NC, but only strata within the Gulf of Maine were used to develop the NEFSC Fall Survey index. The index showed a substantial increase through the mid- to late 1980's, reflecting recruitment and growth of the strong presumed 1982 and 1987 year classes and continued to vary with the influences of strong and weak year classes through the 1990s and 2000s. 2005-2008 were well above average, and 2006 was a time-series high. This was consistent with the trend seen in the ASMFC Summer Survey as well. The NEFSC time series was broken in 2008, as the survey changed vessels, gear and protocols; the index values since 2009 are not directly comparable to earlier years and are treated separately in the models. Since 2009, the index has shown a steady decline to low levels, also consistent with trends in the summer survey.

The Maine-New Hampshire inshore trawl survey takes place during spring and fall, in five regions and four depth strata in Maine and New Hampshire waters. The fall indices for northern shrimp are more erratic and have higher CV's than the spring indices; however, trends in the spring ME/NH survey may be affected by inter-annual variation in the timing of the offshore migration of post-hatch females. Because of this, NSTC did not use this survey in model base runs.

The ASMFC NSTC shrimp survey, or “summer survey”, has been conducted offshore (depths > 50 m) each summer (July-August) since 1984 aboard the *RV Gloria Michelle*. It employs a stratified random sampling design and gear specifically designed for Gulf of Maine conditions. The ASMFC summer survey is considered to provide the most reliable information available on abundance, distribution, stage, and size structure because all adult life history stages are present offshore during the summer. The summer survey index was relatively stable from 1984 through 1990, before gradually declining through 2001. Between 2003 and 2006, the index increased markedly, reaching a new time series high in 2006. After 2008, the index declined steadily to a time series low in 2017. Indices of total abundance and biomass for 2012-2017 were the six lowest values on record for the survey. 2012, 2013, 2015, and 2017 were also time series lows for recruits, indicating recruitment failure of the assumed 2011, 2012, 2014, and 2016 year classes respectively.

Prior to 2017 sampling, the winches and trawl doors of the survey vessel were replaced. Eight pairs of calibration tows were conducted in July 2017 at the beginning of the survey to compare the performance of the old and new gear. The number of calibration tows that could be conducted was limited by funding and the survey timeline. The differences in catch in both weight and numbers were minimal and not statistically significant, and therefore 2017 survey values were not calibrated. Additional calibration tows are planned for the summer of 2018 to increase sample size and develop a more reliable calibration coefficient if necessary.

2. **Provide best estimate of population parameters (fishing mortality, biomass, and abundance) through assessment models. Evaluate model performance and stability through sensitivity analyses and retrospective analysis, including variation in life history parameters. Include consideration of environmental effects where possible. Discuss the effects of data strengths and weaknesses on model results and performance.**

A statistical catch-at-length model developed in collaboration with the University of Maine (UME model; Cao et al. 2017b&c) was used to estimate F, SSB, and abundance of northern shrimp. The NSTC ran a Collie-Sissenwine Analysis (CSA) and an age-structured model (ASAP) as complementary, supporting models. The NSTC also developed a traffic light approach as a qualitative, more intuitive way to summarize a range of fishery independent, dependent, and environmental indicators of stock health.

Natural mortality was modeled as time-varying in all three population models; in the UME model and the ASAP model it was also size/age varying. Length/age- and time-constant scenarios for M, as well as different levels of M, were considered as sensitivity runs. Recruitment was estimated as deviations from mean recruitment in the UME and ASAP models and as independent annual parameters in the CSA model. The UME model also explored deviations from a stock-recruitment curve and the use of environmental variables to fit recruitment deviations as sensitivity runs.

All three models indicated that biomass was at extremely low levels and had been since 2013. The UME model estimated that SSB in 2017 was 709 mt, well below the time series mean of 3,473 mt. SSB show three large peaks over the time series in 1995, 2007, and 2009, ranging from 6,000 – 6,500 mt, with a decline in SSB after each peak.

F has also been at time series lows in recent years. In the UME model, full F for the mixed fleet peaked in 1997 after being relatively stable for 1984-1994; the trawl and trap fleets were more variable from 2000 onward; although the trap F was much lower than the trawl F for the entire time period, both fleets showed a strong peak in 2011-2012.

Recruitment has also been low in recent years, with the UME model estimating recruitment in 2017 at 2.05 billion shrimp, well below median recruitment (4.38 billion shrimp). The 2015 year class was above average, but the 2014, 2011, 2016, and 2012 year classes were the lowest on record. Variability in recruitment has increased since 2000, with higher highs and lower lows in recruitment deviations than 1984-1999.

The retrospective pattern in the UME model was minimal, with F being slightly underestimated and SSB and recruitment being slightly overestimated through the time series, although the terminal year estimates were not consistently above or below the 2017 time-series estimates.

Although it's difficult to compare model output directly across the UME, CSA, and ASAP models, due to differences in how they model the population, all three models showed similar trends in biomass, abundance, recruitment, and fishing mortality, and all three models produced estimates of similar magnitude.

Overall, trends in recruitment, SSB, and average F were similar across the different M parameterizations, but there were differences in scale. Size constant estimates of M resulted in lower estimates of recruitment. Time-constant estimates of M resulted in higher estimates of M in the beginning of the time-series, when M was low in the time-varying M scenario. Time-constant M scenarios were slightly more optimistic about the level of SSB in the most recent years, showing a recovery to levels around where the stock was in the mid-2000s, while the time-varying M scenarios remained low relative to the rest of the time series and relatively flat. The time-constant M scenarios had stronger retrospective patterns, overestimating SSB and underestimating exploitation rate in the terminal year to a greater degree than the time-varying M scenario.

Overall, the models fit with environmental data identified the same strong and weak year classes as models fit without environmental data; however, the models that incorporated environmental data estimated higher recruitment for strong year classes and lower recruitment for weak year classes than the models without environmental data. There are some small differences between estimates of SSB between models that do and do not incorporate environmental effects, with a slightly more pronounced effect from 2014-2017, where the base model SSB estimate was approximately 10% higher than the other models. Differences in average F were minimal across the different scenarios. Fitting to the environmental deviations made the retrospective patterns slightly worse, particularly for recruitment and SSB. Richards et al. (2012) showed that the relationship between indices of SSB, indices of recruitment, and environmental factors has changed over time, so using a single relationship for the 1984-2017 time series may cause problems with the model fit.

3. **Update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY}, SSB_{MSY}, F_{MSY}, MSY). Evaluate stock status based on BRPs. Include consideration of environmental effects where possible.**

Previous biological reference points for northern shrimp were based on estimates of F during a period in the fishery (1985-1994) when biomass and landings were considered stable and sustainable. However, this approach may no longer be appropriate for northern shrimp in the Gulf of Maine. There is strong evidence that recruitment strength is driven by both spawning stock size and environmental conditions, particularly temperature. Unfortunately, environmental conditions in the Gulf of Maine are currently in flux, with surface and bottom temperatures showing a long-term increasing trend and climate models predicting continued warming in the region. Model-based reference points that assume equilibrium conditions and historical reference points calculated from a different temperature regime may not be appropriate for the future dynamics of this stock. As temperatures in the Gulf of Maine continue to rise, levels of F and biomass that were sustainable in the past may become unsustainable as the productivity of the stock declines.

The NSTC chose a projection-based approach to establishing reference points for this assessment. A length-based projection model in R was developed to project the population forward under various scenarios about recruitment, M, and F. The projection was repeated 1,000 times with stochastic draws of recruitment, initial abundance-at-size for non-recruits, and fishery selectivity parameters.

Overall, the northern shrimp stock in the Gulf of Maine is depleted relative to the stable period mean. Low recruitment and high natural mortality hinder stock recovery. Projections suggest the stock could recover to moderate levels under current recruitment levels, but not if natural mortality remains high. If M continues to increase, the likelihood of recovery is extremely low, even in the absence of fishing, although fishing would hasten the decline.

4. **Characterize uncertainty of model estimates of fishing mortality, biomass and recruitment, and biological reference points.**

Overall, across multiple models and parameterizations, population trends in F, biomass, and recruitment were consistent. The northern shrimp population has declined precipitously since 2010 and recruitment in recent years has been low. Recruitment variability has increased since 2000. Fishing mortality is also at low levels since the moratorium. The true uncertainty is in the future of the population. In time constant M scenarios, there has been a small increase in the population in the most recent years under reduced F; however, under time-varying M scenarios, M has been well above the time series average in the most recent years and the population trajectory has remained flat since the moratorium.

Similarly, the assumptions about M and recruitment had the largest effects on the projection trajectories in the short term and in the long term projections. Projections conducted with M equal to the time series mean and recruitment drawn from the 2011-2017 mean indicated the population would grow under no fishing pressure and SSB would stabilize around 2,039 mt, less than the "stable period" mean (1985-1994) of 4,162 mt, but more than double the 2017 estimate of 709 mt. However, under higher natural mortality scenarios, with M equal to the average of the last five years, the population declined even under no fishing.

5. Review the methods used to calculate the annual target catch and characterize uncertainty of target catch estimates.

To develop catch recommendations, the population was projected forward 3 years under different F scenarios and the probability that SSB was above 2017 SSB was calculated. The allocation of F between the trap and trawl fisheries was set using the ratio catch for each fleet over the last 3 years of the open fishery (2011-2013); trap catch was 12% of trawl catch over that time period. The projection was repeated 1,000 times with stochastic draws of recruitment, initial abundance-at-size for non-recruits, and fishery selectivity parameters. A weight-length relationship was used to convert the predicted catch in numbers into catch in weight.

Recruitment was drawn from a log-normal distribution with a mean equal to recruitment from 2013-2017; the time-series mean was used as a sensitivity run. M was length-varying and set equal to the time-series mean M-at-length; average M-at-length over the last five years (higher than the time-series average) was used as a sensitivity run.

The assumptions about M and recruitment had the largest effects on the amount of catch that was sustainable in the short term. For the high, recent M scenarios, even low levels of harvest (F=0 or F=status quo) caused a decline in SSB, regardless of the recruitment scenario. For the time-series average M scenarios, higher levels of harvest caused the population to decline from 2018 to 2019, but most harvest scenarios had a greater than 50% chance of being above SSB_{2017} in 2020.

6. Develop detailed short and long-term prioritized lists of recommendations for future research, data collection, and assessment methodology. Highlight improvements to be made before the next benchmark assessment.

The NSTC identified a number of research recommendations to improve the assessment and our understanding of northern shrimp population dynamics in the Gulf of Maine. The highest priority included evaluating survival and growth as a function of environmental factors and population density, exploring the mechanisms behind the stock-recruitment and temperature relationship, investigating the length-based model's growth parameters and potential incorporation of spatial or temporal variation, continuing to refine annual estimates of consumption by predators and M, and maintaining existing fishery-independent and -dependent sampling.

7. Based on the biology of species, and potential scientific advances, comment on the appropriate timing of the next benchmark assessment and intermediate updates.

The NSTC recommends that the assessment be updated annually to incorporate the most up-to-date data on abundance and recruitment into management recommendations. A benchmark assessment should be considered in five years if improvements in the length-based model or significant changes in the population warrant it.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

TERMS OF REFERENCE

For the 2018 ASMFC Northern Shrimp Benchmark Stock Assessment

Board Approved March 2017

Terms of Reference for the Northern Shrimp Assessment

1. Present the Gulf of Maine northern shrimp landings, discards, effort, and fishery-independent data used in the assessment. Characterize the precision and accuracy of the data and justify inclusion or elimination of data sources. Develop and apply a calibration method to account for gear changes in the most recent year of the ASMFC summer trawl survey.

2. Provide best estimate of population parameters (fishing mortality, biomass, and abundance) through assessment models. Evaluate model performance and stability through sensitivity analyses and retrospective analysis, including variation in life history parameters. Include consideration of environmental effects where possible. Discuss the effects of data strengths and weaknesses on model results and performance.

3. Update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY}, SSB_{MSY}, F_{MSY}, MSY). Evaluate stock status based on BRPs. Include consideration of environmental effects where possible.

4. Characterize uncertainty of model estimates of fishing mortality, biomass and recruitment, and biological reference points.

5. Review the methods used to calculate the annual target catch and characterize uncertainty of target catch estimates.

6. Develop detailed short and long-term prioritized lists of recommendations for future research, data collection, and assessment methodology. Highlight improvements to be made before the next benchmark assessment.

7. Based on the biology of species, and potential scientific advances, comment on the appropriate timing of the next benchmark assessment and intermediate updates.

Terms of Reference for the Northern Shrimp Peer Review

1. Evaluate the thoroughness of fisheries-dependent (landings, discards, effort) and fisheries-independent data collection and the presentation and treatment of data in the assessment, including the precision and accuracy of the data and inclusion or elimination of data sources. Evaluate the methods used to calibrate the data from the new ASMFC summer survey gear changes

2. Evaluate the methods and models used to estimate population parameters (fishing mortality, biomass, and abundance). Evaluate the NSTCs consideration of environmental effects in assessment models. Evaluate the diagnostic analysis performed (sensitivity and retrospective analysis). Evaluate the NSTCs discussion on the effects of data strengths and weaknesses on model results and performance.

3. Evaluate the NSTCs choice of reference points and the methods used to estimate them. Recommend best estimates of population parameters (fishing mortality, biomass, and abundance) from the assessment for use in management, if possible, and a stock status determination based on BRPs developed.

4. Evaluate the methods used to characterize uncertainty in model estimates of fishing mortality, biomass and recruitment, and biological reference points.

5. Evaluate the methods used to calculate the annual target catch and used to characterize uncertainty of target catch estimates.

6. Review the research, data collection, and assessment methodology recommendations provided by the TC and make any additional recommendations warranted. Clearly prioritize the activities needed to inform and maintain the current assessment, and provide recommendations to improve the reliability of future assessments.

7. Recommend timing of the next benchmark assessment and updates, if necessary, relative to the life history and current management of the species.

8. Prepare a report summarizing the panel’s evaluation of the stock assessment and addressing each peer review term of reference. Develop a list of tasks to be completed following the workshop. Complete and submit the report within 4 weeks of workshop conclusion.

1 INTRODUCTION

1.1 Life History

1.1.1 Species Range

Northern shrimp (*Pandalus borealis*) inhabit boreal waters of the North Atlantic (Figure 1.1), ranging from about 42^{o} to 77^{o} N latitude (Shumway et al. 1985). *P. borealis* was previously thought to occur in the north Pacific as well, but the north Pacific species has been found to be a separate species (*Pandalus eous*, Squires 1992; Bergstrom 2000). The population of *P. borealis* in the Gulf of Maine is thought to be a single stock that does not mix with other populations further north (Jorde et al. 2015). Northern shrimp undergo seasonal, sex-specific migrations inshore and offshore (Shumway et al. 1985).

1.1.2 Age, Growth, Reproduction

Northern shrimp are protandric hermaphrodites, usually functioning first as males at 1.5-2.5 years of age and then transforming to females at approximately 3 years of age in the Gulf of Maine (Figure 1.2). Spawning takes place in offshore waters beginning in late July. By early fall, most adult females have extruded eggs onto their abdomen. Egg-bearing females move inshore in late autumn and winter, where the eggs hatch. The planktonic larvae pass through six larval stages and settle to the bottom of inshore waters after metamorphosing to a juvenile state (Berkeley 1930; Haynes and Wigley, 1969; Apollonio and Dunton 1969; Stickney and Perkins 1977; Stickney 1980). Juveniles remain in coastal waters for a year, or more, before migrating to deeper offshore waters to join the adult stock. The males pass through a series of transitional stages before maturing as females. After spawning, some females survive their first egg hatch to repeat the spawning process. Females that have never extruded eggs are referred to here as “female I”. Non-ovigerous females that have carried eggs in the past are “female II”. Female I’s and II’s can be distinguished by the presence or absence of sternal spines (McCrary 1971).

The extent, location, and timing of the sexual transitions and migrations are variable. Several factors may influence the size and age at sex transition (Bergström 2000). Although the majority of post-larval northern shrimp develop first into males, a small percentage may develop directly into females or initiate the sex transition early (early-maturing females, EMF). When this occurs, both sexes may appear in the same year class, possibly as a reaction to stress in the population as predicted by sex allocation theory (Charnov et al. 1978). Temperature (Apollonio et al. 1986; Hansen and Aschan 2000), density dependent growth (Koeller et al. 2000), and/or selective removal of larger females by the fishery may be factors affecting the timing of sex transition (Marliave et al. 1993; Bergström 2000). EMF has been observed in several year classes in the Gulf of Maine over the last decade (see Figure 3.7). In addition, the 2001 year class showed evidence of both very early- and late-maturing females, with some EMF appearing at assumed age 1.5 and other shrimp remaining as males at assumed age 3.5.

Growth, as in other crustaceans, is a discontinuous process associated with molting of the exoskeleton (Hartnoll 1982). Information on growth of Gulf of Maine northern shrimp has been reported by Haynes and Wigley 1969; Apollonio et al. 1986; Terceiro and Idoine 1990; and Fournier at al. 1991. Differences in size-at-age by area and season can be ascribed, in part, to temperature effects, with more rapid growth rates at higher temperatures (Apollonio et al. 1986; Shumway et al. 1985). It is believed that most *P. borealis* in the Gulf of Maine do not live past age 5 (Haynes and Wigley 1969; Apollonio and Dunton 1969).

1.1.3 Natural Mortality

Northern shrimp are an important component of marine food chains, being consumed by many commercially important fish species, such as cod, redfish, and silver and white hake. Species that include *P. borealis* in their diet are documented by many authors (see Synopsis: Shumway et al. 1985, Link and Idoine 2009, and Richards and Jacobsen 2012.) Diseases in Pandalid shrimp are described by Bergstrom, 2000. Black gill syndrome and shell disease have been observed in GOM commercial samples but the extent and impact of these diseases is not known.

The natural mortality rate (M) used in previous assessments for US Gulf of Maine northern shrimp assessments (M=0.25; NEFSC 2007) was one of the lowest approximations for northern shrimp in the North Atlantic. The assumption of M=0.25 was based on direct estimates from the Gulf of Maine northern shrimp population and fishery data, as approximated from the intercept of a regression of total mortality by year class in 1968-1972 on effort (Rinaldo 1973, Rinaldo 1976, Shumway et al. 1985) and from catch curve analysis of survey data for age 2+ shrimp during a fishery closure in 1978 (Clark 1981, 1982). The review panel for that assessment concluded that M must be higher than 0.25 because the model estimates of abundance were lower than estimated consumption (from preliminary data later published by Link and Idoine, 2009). The panel suggested that a higher M, around M=0.6, was likely more realistic for this population.

The models for the 2018 benchmark assessment explored both constant and time- and size-varying M (Figure 1.4). Constant M was set equal to either 0.95, based on a recent review of natural mortality estimators (Then et al. 2015), or M=0.5, which was used in the 2014 benchmark assessment based on the 3/M ‘rule of thumb’ (maximum age of shrimp=6 years) (Quinn and Deriso 1999).

Time-varying (annual) M was related to inter-annual variation in predation pressure on shrimp. A weighted index of predator biomass was developed from Northeast Fisheries Science Center (NEFSC) survey data, where the weights were the long-term average percent frequency of shrimp in each predator’s diet estimated from food habits sampling (NEFSC 2014; Richards and Jacobson 2016). The time series of predation pressure indices (PPI) were used to adjust an assumed baseline (average) M. The adjustment to M was proportional to the long term average of the PPI, so that M was scaled up in years with above average PPI and down in years with below average PPI:

$$M_i = M_b * \frac{PPI_i}{\overline{PPI}}$$

where i=year and M_b=baseline M. NEFSC fall surveys were used to estimate predator biomass for all species except spiny dogfish, which is more reliably estimated from spring survey data.

Size-varying natural mortality was calculated using an approach similar to what has been used for the Torres Strait prawn fishery in Australia (Watson et al. 1993), which assumes a U-shaped M. In this model, the youngest, smallest shrimp experience higher rates of natural mortality than the exploitable size/age classes, as do the largest, oldest shrimp, which are not present in the catch or surveys to the extent that would be expected with a lower M. To determine values for the U-shape over the life span of the shrimp, M was calculated by weight for the smallest size/weight bins (Lorenzen 1996), then reduced to 0.5 for the mid-weight classes, and for the largest size classes, a M was increased so that only 1.5% of the population would remain at age six (Hoenig 1983). Time- and age/size-varying M was calculated by multiplying the M for each size or age class by the PPI scalar.

1.1.4 Habitat Requirements

In the Gulf of Maine, the northern shrimp population is considered to be a single stock (Clark and Anthony 1980), which is concentrated in the southwestern region of the Gulf (Haynes and Wigley 1969; Clark et al. 2000). Water temperature, salinity, depth, and substrate type have all been cited as important factors governing shrimp distribution (Haynes and Wigley 1969; Apollonio et al. 1986; Shumway et al. 1985). In the Gulf of Maine, northern shrimp are most frequently found in depths ranging from 10 m to over 300 m (30-1000 ft) (Haynes and Wigley 1969), with juveniles and immature males occupying shallower, inshore waters and mature males and females frequently occupying cooler, deeper offshore waters (Apollonio and Dunton 1969, Haynes and Wigley 1969, Apollonio et al. 1986). During the summer months, adult shrimp inhabit water from 93-183 m (300-600 ft) (Clark et al. 2000); ovigerous and post-hatch female shrimp are found in shallower, near-shore waters during the hatch period in winter and spring (Apollonio and Dunton 1969, Clark et al. 2000; Richards 2012).

Northern shrimp most commonly inhabit organic-rich mud bottoms or near-bottom waters (Hjort and Ruud 1938; Bigelow and Schroeder 1939; Wigley 1960; Haynes and Wigley 1969), where they prey on benthic invertebrates; however, shrimp are not limited to this habitat and have been observed on rocky substrates (Schick 1991). Shrimp distribution in relation to substrate type, as determined by trawl surveys, clearly shows northern shrimp primarily occupy areas with fine sediments (sand, silt, and clay) (ASMFC 2004). Shrimp are often associated with biotic or abiotic structures such as cerianthid anemone (Langton and Uzmann 1989) and occasional boulders in these fine sediment habitats (Daniel Schick, Maine Department of Marine Resources, pers. comm.).

Male and non-ovigerous female shrimp exhibit diurnal vertical migration, from bottom and near-bottom during the day, up into the water column to feed at night. Egg-bearing females are less likely to exhibit vertical diurnal migration, and are more likely to stay on the bottom (Apollonio and Dunton 1969; Apollonio et al. 1986).

The most common temperature range for this species is 0-5 °C (Shumway et al. 1985). The Gulf of Maine marks the southern-most extent of the species' range, and it occurs primarily in the western portion of the Gulf where deep basins provide cold water refuges for adult shrimp populations (Apollonio et al. 1986). It is hypothesized that shrimp are less abundant in the northeastern region of the Gulf because bottom waters are not protected from seasonal warming, due to continual mixing from intense tidal currents nearer to the Bay of Fundy (Apollonio et al. 1986).

Ocean temperature has an important influence on population processes of northern shrimp in the Gulf of Maine (Dow 1964; Apollonio et al. 1986; Richards et al. 2012; Richards et al. 2016). Survival during the first year of life has been negatively correlated with ocean temperature during the time of the hatch, early larval period, and the late summer when ocean temperatures and water column stratification are reaching their maximum (Richards et al. 2016). Relatively cool winter/spring ocean temperatures during these two periods of early life are associated with higher recruitment indices in the summer shrimp survey. Spawner abundance also influences recruitment, with more recruits produced with higher spawner abundance; however, environmental influences appear to have increased in importance since 1999 (Richards et al. 2012).

Ocean temperatures also affect timing of the shrimp larval hatch (Richards 2012). The hatch period started earlier in the 1990s as temperatures increased, and by the mid-2000s was beginning roughly a month earlier than it did prior to 2000 (10% line in Figure 1.5). In contrast, the midpoint of the hatch period has changed less dramatically than the start of the hatch (50% line in Figure 1.5). During the past four years (2014-2017), hatch timing has been similar to hatch periods observed prior to 2000 (Figure 1.5).

Sea surface temperature (SST) has been measured daily since March of 1905 at Boothbay Harbor, Maine, near the center of the inshore nursery areas for northern shrimp. Average winter SST (Feb-Mar) at Boothbay has increased steadily from an average of 0.8^{o} C during 1906-1948 to 3.3^{o} C during 2008-2017 (Figure 1.6E). Average winter SST during 2018 was 4.5^{o} C, the fourth highest in the time series. Late summer SST (July 15-Sept. 1) did not show a similar long term increasing trend during the 20th century, but increased sharply during the mid-1990s, reaching a record high in 2006 (20.2^{o} C) (Figure 1.6F). Late summer SST in 2017 was equal to the long term mean of 16.3^{o} C.

Spring surface and bottom temperature anomalies (temperature changes measured relative to a standard time period) in offshore shrimp habitat areas were cooler in 2017 than in 2016, but remained high relative to the baseline period (1978-1987) (Figures 1.6A and 1.6C). Fall temperature anomalies have consistently been above the baseline average (anomaly=0) for a decade, although the fall bottom temperature was cooler in 2015 than in the most recent years (Figures 1.6B and 1.6D).

1.1.5 Regime Shifts

To evaluate whether there may have been a recent ‘regime shift’ in temperatures affecting shrimp, or shrimp population dynamics, a regime shift detection algorithm (STARS, Rodionov 2004; Rodionov and Overland 2005) was applied to the temperature times series discussed above, and to biological data relevant to shrimp. The biological data included the time series of shrimp recruitment indices, mean size of recruits (presumed age 1.5), size at sex transition, early life survival indices, and predation pressure indices (NEFSC 2014; Richards and Jacobson 2016) based on fall and spring NEFSC surveys (see Appendix 1 for details).

Overall, the results of the regime shift detection algorithm suggested that a shift in temperature regime occurred around 2010, but with no clear effect on shrimp. Temperature time series that suggested a potential shift were the spring SST anomaly, summer shrimp survey bottom temperature, fall bottom temperature anomaly, a composite temperature index derived from principal components analysis (Appendix 1), timing of the spring thermal transition, and length of summer. Winter surface temperature at Boothbay Harbor and spring bottom temperature anomaly did not show a change point near 2010.

For the biological variables, potential change points were identified for mean size at age 1.5 (in 2014) and possibly for early life survival (in 2015). Both of these change points were very recent and thus bear watching to determine whether a regime shift has occurred. It should be noted that the survival indices may not be very meaningful at the current low abundance. A possible regime shift was detected in the time series of recruitment indices using a model-based method of estimating shrimp abundance (Cao et al. 2017a, see Section 3), but not in the standard recruitment indices used in past northern shrimp assessments. The regime shift was only detected in one of the three statistical configurations tested. The results for the spring and fall predation pressure indices suggested change points near the end of the time series (2015, 2016), which will need to be evaluated as more years of data are added.

1.2 Fisheries Management

The Gulf of Maine Northern Shrimp fishery is managed by the ASMFC Northern Shrimp Section (Section). Participation on the Section includes Commissioners from Maine, New Hampshire, and Massachusetts.

1.2.1 Management Unit

The management unit is defined as the northern shrimp resource throughout the range of the species within U.S. waters of the northwest Atlantic Ocean from the shoreline to the seaward boundary of the Exclusive Economic Zone (EEZ).

1.2.2 Regulatory History

The initial northern shrimp management framework evolved during 1972–1979 under the auspices of the State/Federal Fisheries Management Program. In 1980, this program was restructured as the Interstate Fisheries Management Program (ISFMP) of the Atlantic States Marine Fisheries Commission (ASMFC). The first Fishery Management Plan (FMP) for Northern

Shrimp was approved under the ISFMP in October 1986 (McInnes 1986, ASMFC 1986). The FMP sought to generate the greatest possible economic and social benefits from the harvest of northern shrimp and implemented measures to optimize yield. Specific regulations included a minimum mesh size, season limitations, and reporting requirements.

In 2004, the Section implemented Amendment 1 which established biological reference points for the first time in the northern shrimp fishery (ASMFC 2004). In addition, the document expanded the tools available to manage the fishery, including gear modifications. Management of northern shrimp under Amendment 1 resulted in a rebuilt stock and increased fishing opportunities. However, due to untimely reporting and higher than anticipated landings, the 2010 and 2011 fishing seasons exceeded the recommended total allowable catch (TAC) and were closed for the remainder of the season.

In 2011, the Section implemented Amendment 2. The amendment provided management options to slow catch rates throughout the season, including trip limits, trap limits, and days out of the fishery (ASMFC 2011). The amendment also modified the fishing mortality reference points to include a threshold level, a more timely and comprehensive reporting system, and allowed for the initiation of a limited entry program to be pursued through the adaptive management process.

In November 2012, the Section implemented Addendum I to Amendment 2. The addendum clarified the annual specification process and allocated the annual hard TAC between gear types, with 87% allocated to the trawl fishery and 13% allocated to trap fishery (ASMFC 2012). Addendum I also implemented a season closure provision designed to close the northern shrimp fishery when a pre-determined percentage (between 80–95%) of the annual TAC had been projected to be caught. Lastly, the addendum instituted a research set aside (RSA) program which allowed the Section to “set aside” a percentage of the annual TAC to help support research on the Northern Shrimp stock and fishery.

In 2013, the Northern Shrimp Section imposed a moratorium on the fishery for the 2014 season. The Section considered several factors prior to closing the fishery: (1) Northern shrimp abundance in the western Gulf of Maine had declined steadily since 2006; (2) the 2012 and 2013 survey indices of total biomass and spawning stock biomass (SSB) were the lowest on record; (3) the stock experienced failed recruitment for three consecutive years prior to 2014 (2010– 2012 year classes); and (4) long term trends in environmental indices were not favorable for northern shrimp in the Gulf of Maine. The 2014 through 2017 stock status reports indicated continued poor trends in biomass, recruitment, and environmental indices which prompted the Section to extend the moratorium each year through 2018. Winter sampling via selected commercial shrimp vessels occurred in each year of the moratorium to continue the time series of biological samples that had been obtained from the Gulf of Maine commercial northern shrimp fishery.

1.2.3 Current Management

Given the low abundance and unfavorable environmental conditions which resulted in a highly uncertain future for the resource, the Section implemented Amendment 3 in August 2017. Amendment 3 is designed to improve management of the northern shrimp resource, in the event the fishery reopens (ASMFC 2017). Specifically, the Amendment refines the FMP objectives and implements a state-specific allocation program to better manage effort in the fishery; 80% of the annual TAC is allocated to Maine, 10% to New Hampshire, and 10% to Massachusetts. The Amendment also implements mandatory use of size sorting grate systems to minimize the harvest of small shrimp, specifies a maximum fishing season length, and formalizes fishery-dependent monitoring requirements.

Amendment 3 also outlines the specification process for the northern shrimp fishery. Annually, the Section meets in-person to adjust commercial fishery management measures. Based upon the best available science as well as recommendations from the Technical Committee and Advisory Panel, the Section sets a hard TAC for the fishing year. In addition, the Section can specify the fishing season, the projected percentage of harvest at which the fishery will close (between 80-95%), trip limits, traps limits, days out of the fishery, and a research set aside. These management tools can be specific to a gear type and the Section can establish harvest triggers to automatically initiate or modify any option.

1.3 Assessment History

Stock assessments for the Gulf of Maine northern shrimp resources have been conducted since the late 1970s. Many of these stock assessments have identified strong year classes (e.g. those that hatched in 1982, 1987, 1992, 2001, 2004) which generally supported the fishery three years after hatching. In addition to benchmark stock assessments (beginning in 1997), yearly Stock Status Reports for Gulf of Maine northern shrimp have been conducted since 2000. These Stock Status Reports use the assessment method from the previous peer-reviewed benchmark stock assessment and incorporate new data to provide the Section with the most up-to-date information on stock health.

1.3.1 2014 Benchmark Assessment and Review

A set of three stock assessment models for northern shrimp were presented to the Northeast Fisheries Science Center's Stock Assessment Workshop (SAW) for review as part of the most recent benchmark assessment (NEFSC 2014). Several important conclusions came from the peer review panel. These are summarized below (the reviewers' reports can be accessed at http://www.nefsc.noaa.gov/saw/saw58/index.html):

- Despite the high quality data available for northern shrimp, the models have difficulty fitting the data because of extreme fluctuations in recent years, including the exceptionally high 2006 shrimp survey index, and the sudden decline of all indices in 2012 followed by sustained extreme lows.
- A new statistical framework was developed for the catch-survey analysis (CSA, Collie and Sissenwine 1983; Cadrin et al. 1999). CSA has been used to guide management decisions

in the shrimp fishery since 1997. The review panel considered the new statistical framework an important advance, but felt the results were overly sensitive to weightings chosen for different components of the model (e.g. catch data, survey data). On this basis, they rejected the new CSA for management use. They were not able to comment on the applicability of the previously-accepted version of CSA because there was insufficient time to review the previous version.

- The review panel concluded that a new length-based model developed for northern shrimp has promise but needs further development and testing before application to management.
- The review panel agreed that the use of a surplus production model (ASPIC) as a confirmatory analysis should be discontinued. ASPIC is unable to adequately handle the large fluctuations in recruitment which are typical of northern shrimp population dynamics.

In light of the review panel's comments on the new version of CSA, the Northern Shrimp Technical Committee (NSTC) conducted exploratory work to evaluate whether the previous CSA version had similar issues (these issues could not have been detected under the previous statistical framework). The results of the exploratory analysis suggest that the previous CSA also had difficulty with the major swings in data in recent years, although the conclusions with respect to overfishing status were robust and did not differ with different weighting scenarios.

Given the results of the benchmark assessment review and exploratory CSA analysis, the NSTC has evaluated the stock status of northern shrimp using an index-based approach since 2014. The NSTC has deemed this the best available science to support management since the 2014 peer review. The index based approach has been updated annually through the Stock Status Reports to include new data.

2 COMMERCIAL FISHERY DATA AND TRENDS

2.1 Fishery Description

Northern shrimp support important commercial fisheries in boreal and sub-arctic waters throughout the North Atlantic. In the western North Atlantic, commercial concentrations occur off Greenland, Labrador, Newfoundland, in the Gulf of St. Lawrence, and on the Scotian Shelf. The Gulf of Maine marks the southernmost extent of its Atlantic range (Parsons and Fréchette, 1989). In the Gulf of Maine, primary concentrations occur in the western Gulf where bottom temperatures are coldest.

The fishery formally began in 1938; during the 1940s there were a few landings in Massachusetts, but most of the landings were by Maine vessels from Portland and smaller Maine ports further east. This was a winter trawl fishery, directed towards egg-bearing females as they migrate inshore (Scattergood 1952). Landings declined from the late 1940's until the fishery stopped altogether from 1954 through 1957. Reports from fishers at the time indicate that this decline was associated with low shrimp abundance. The fishery resumed in 1958 (ASMFC 1986).

New Hampshire vessels entered the fishery in 1966, but throughout the 1960s and 1970s, New Hampshire landings were minor. New Hampshire accounted for about 9% of the total Gulf of Maine catch during 2010-2013 (Table 2.1).

Landings by Massachusetts vessels were insignificant until 1969, but in the early 1970s the fishery developed rapidly, with Massachusetts landings increasing from 14% of the Gulf of Maine total in 1969 to over 40% in 1974–1975. Massachusetts landings have declined to about 3% of total during 2010-2013, while Maine vessels have accounted for about 88% (Table 2.1 and Figure 2.1).

The Gulf of Maine fishery has been seasonal in nature, peaking in late winter when egg-bearing females move inshore and terminating in spring under regulatory closure (Table 2.3). Northern shrimp have been an accessible and valuable resource to fishermen working inshore areas in smaller vessels who otherwise have few winter options due to seasonal changes in availability of groundfish, lobsters, and other species (Clark et al. 2000). Charts of the areas fished in 2010 and 2013 are shown in Figure 2.2.

Summer fisheries which existed in the 1970s caught shrimp of all ages, including age 1 and 2. These immature and male shrimp made up 40-50% of the catch by numbers in April-June, increasing to 70-80% for July-September, during 1973-1974 (Clark et al. 2000). Since 1976, fishing has been restricted to months within a December to May timeframe. (Throughout this document, references to a particular fishing year will include the previous December unless otherwise indicated – e.g. the 2006 season includes December 2005 but not December 2006, which will belong to the 2007 season.) Since 2000, the months of January and February have accounted for about 80% of landings, and there has not been a significant spring fishery (April-May) since 1999 (Table 2.3) due to management or market constraints. The most recent fishing season that extended from December into May was in 2010 (Table 2.3).

A wide variety of vessels have been used in the fishery (Bruce 1971; Wigley 1973). The predominant type during the 1960s and 1970s appears to have been side rigged trawlers in the 14-23 m (45-75 ft) range. During the 1980s and 1990s, side trawlers either re-rigged to stern trawling, or retired from the fleet. Currently, the shrimp fleet is comprised of lobster vessels in the 9-14 m (30-45 ft) range that re-rig for shrimping, small to mid-sized stern trawlers in the 12-17 m (40-55 ft) range, and larger trawlers primarily in the 17-24 m (55-80 ft) range (ASMFC 2011). The number of vessels participating in the fishery since 2000 varied from a high of about 342 in 2011 to a low of about 144 in 2006 (Table 2.9).

The otter trawl remains the primary gear employed and is typically roller rigged. There has been a trend in recent years towards the use of heavier, larger roller and/or rock hopper gear. These innovations, in concert with substantial improvements in electronic equipment, have allowed for much more accurate positioning and towing in formerly unfishable grounds, thus greatly increasing the fishing power of the Gulf of Maine fleet. Legal restrictions on trawl gear require a minimum 44.5 mm (1.75 inch) stretch mesh net and the use of a finfish separator device known as the “Nordmore grate” with a maximum grate spacing of 25.4 mm (1 inch) (ASMFC 2017). Some trawlers voluntarily used a combination grate, which includes a section that performs as a finfish separator and a second section that selects for larger shrimp. The use of a combination grate or a double grate system to reduce catches of small shrimp became a requirement in 2017 (ASMFC 2017). Additional restrictions on trawlers include the closure of Maine territorial waters from April 1 through December 31, a limit on the length of the bottom legs of the trawl bridle (Maine DMR Regulations, Chapter 45), and limitations on chafing gear and liners (ASMFC 2017).

Inshore trawl trips during the winter months are usually single day trips. A typical fishing day consists of about four tows of about two hours each (from port interviews). In April and May, two- and three-day offshore trips are more common for Maine boats.

A small trap fishery has also existed in mid-coastal Maine since the 1970s where, in many areas, bottom topography provides favorable shrimp habitat that is too rough or restricted for trawling. The trapped product is of good quality, as the traps target only female shrimp as they migrate inshore (see Figure 2.5). Trappers use baited rectangular wire mesh traps with a V-shaped trough opening on top, set in single, double, or triple trap strings (Moffett et al 2012). In 2010, trappers hauled an average of 114 traps on an average of three-day sets (from port interviews). Most shrimp trappers also trap lobsters at other times of the year. Trappers accounted for about 13% of Maine’s landings in 2000-2013 (Table 2.4).

Since the trap fishery is dependent on the inshore availability of shrimp in a specific area, the fishing season is naturally shorter for trappers than for draggers (e.g. see 2010 in Table 2.4). There is some indication that trap fishing for shrimp has grown in a few areas such as South Bristol and Boothbay Harbor (mid-coast Maine), and might continue to grow if stock conditions were favorable. The trap fishery accounted for 21% of Maine landings in 2010 (Table 2.4). Early season closures and other restrictions in 2011–2013 may have disadvantaged trappers. The commercial fishery has been closed since 2013 due to low stock abundance. In 2014, Maine hired one trawler to collect winter samples, and in 2015–2017 the states conducted RSA programs to collect winter fishery samples.

2.2 Landings

2.2.1 Commercial Landings Data Sources

Commercial landings by state, month, and gear (trawl vs. trap) were compiled by the National Marine Fisheries Service (NMFS) — later NOAA Fisheries — port agents from dealer reports until the mid-late 1990’s, and are available electronically back to 1964. A dealer reporting system became mandatory in 1982 but was repealed in 1991, and NMFS began collecting the data again. In 2004, shrimp reporting for federally permitted dealers buying from federally permitted harvesters became mandatory, but “state-only” dealers, mostly in Maine, continued to report voluntarily. Trip level reporting became mandatory for all licensed Maine shrimp dealers in 2008, although “peddlers” selling directly to the public were not required to have a license, so catches sold in the peddler market were mostly unreported. This was remedied in 2013, and during the next shrimp season, anyone buying shrimp for resale will need to be licensed in Maine and report landings.

In 1994, a Vessel Trip Report (VTR) system was implemented for many federally permitted harvesters and in 1999 (but not implemented until the 2000 season), reporting became mandatory for all shrimp harvesters landing in Maine. Harvesters report “hail” weights, which are estimates of the catch weight.

The time series used in the current Gulf of Maine northern shrimp stock assessment begins with 1984, when fishery-independent summer shrimp survey data became available. For the period 1984 through 1999, the assessment uses landings data from the NMFS commercial fisheries database, based on dealer reports. For the period 2000-2013, the assessment uses the more complete mandatory harvester report data.

Late harvester reporting was a chronic problem with the terminal year of the annual assessment, and sometimes dealer reports were used for the terminal year. Each year the landings from the previous two seasons were recalculated using updated harvester report data. However, an effort in Maine to improve dealer reporting compliance in 2012 resulted in only a 2% increase in landings when they were recalculated in 2013 based on 2012 harvester reports.

It is likely that landings are most completely reported in the 2001-2013 period and are less complete in the 1984-1999 period, but there are minimal means to determine the extent or magnitude of early misreporting. Model sensitivity runs described in Section 4 address this issue. It is also difficult to separate trawl and trap landings before 2000. For this reason, the length-based model discussed in Section 4 uses a mixed fleet before 2000, and separate trawl and trap fleets for 2000-2017.

2.2.2 Commercial Landings, 1958–2013

Annual landings of Gulf of Maine northern shrimp are listed in Tables 2.1 to 2.4 and displayed in Figure 2.1. Landings declined from an average of 11,400 metric tons (mt) during 1969-1972 to about 400 mt in 1977, culminating in a closure of the fishery in 1978. The fishery reopened in 1979 and landings increased steadily to over 5,000 mt by 1987. Landings ranged from 2,100 to 4,700 mt during 1988-1994, and then rose dramatically to 6,500 mt in 1995 and 9,500 mt in 1996, the highest since 1973. Landings declined to an average of 2,000 mt for 1999–2001, and dropped further in the 25-day 2002 season to 450 mt. Landings then increased steadily, averaging 2,100 mt during the 2003 to 2006 seasons, then jumping to 4,900 mt in 2007 and 5,000 mt in 2008. In 2009, 2,500 mt were landed during a season that was likely market-limited.

In 2010, the proposed 180-day season was cut short at 156 days due to landing rates being higher than expected, and concerns about catching small shrimp. Landings were estimated at 6,263 mt, while the TAC was set at 4,900 mt. In 2011, the season was similarly closed early due to landings exceeding the TAC. A total of 6,398 mt of shrimp were landed, above the recommended TAC of 4,000 mt. The average price per pound was $0.83 and the estimated value of the catch was $11.7 million (inflation-adjusted values, Table 2.2). In 2012, the season was further restricted by having trawlers begin on January 2 with three landings days per week and trappers begin on February 1 with a 1,000-pound limit per trap vessel per day. The TAC was set at 2,000 mt (later increased to 2,211 mt on January 20th) and would close when the projected landings reached 95% of the TAC. The season was closed on February 17; trawlers had a 21-day season and trappers had a 17-day season. Landings for 2012 were 2,485 mt and the average price per pound was $1.02 with an estimated landing value of $5.6 million. In 2013, the TAC was set at 625 mt (with 5.44 mt set aside for research tows) and would close when the projected landings reached 85% of the TAC in each fishery (trap and trawl). The trawl fishery was allocated a 539.02 mt TAC and the trap fishery was allocated an 80.54 mt TAC with 800 lb daily limits for trappers. Trawlers fished for 54 days and trappers fished 62 days culminating in 345.5 mt landed, which is 280 mt under the TAC. The average price per pound was $1.90 and is the highest observed since 1989 (Table 2.2) with an estimated value of $1.4 million.

2.2.3 Winter Sampling, 2014–2017

In the absence of a commercial fishery in 2014, the State of Maine contracted with a commercial shrimp trawler to collect northern shrimp samples during January-March near Pemaquid Point, in midcoast Maine. This location was chosen as best representing the spatial "center" of a typical winter Maine shrimp fishery (Hunter 2014). No shrimp were landed during the 2014 cooperative winter sampling program, except the collected samples. About 0.3 mt was caught and discarded, but is included in "landings" tables and figures, and as removals in model inputs described in Section 4.

In 2015, the sampling program was expanded; four trawlers and five trappers collected northern shrimp during January-March under the RSA program implemented through Addendum II to Amendment 2 (Whitmore et al. 2015). The traditional spatial range of the trawl fishery was divided into four regions: Massachusetts-New Hampshire, western Maine (Kittery to Phippsburg), midcoast Maine (Phippsburg to Rockland), and eastern Maine (Vinalhaven to Lubec). One trawler was picked at random from qualified applicants for each of the four sampling regions. Each trawler fished about once every two weeks, conducting at least three tows per trip, and made no more than five trips. Five trappers were also selected from Midcoast and Eastern Maine and each fished ten traps, tended as often as needed. 2015 RSA catches were estimated at 6.7 mt from data sheets maintained by the captains or state observers.

In 2016, four trawlers and two trappers collected northern shrimp during January-April under the RSA program (Hunter 2016). Fishing regions were defined as in 2016, except for eastern Maine which consisted of the region east of Monhegan Island. Similarly, one trawler was picked for each of the four sampling regions. Each trawler fished about once every two weeks, conducting at least three tows per trip, and made no more than five trips. Two trappers were also selected from midcoast Maine and each fished forty traps, tended as often as needed. 2016 RSA catches were estimated at 13.3 mt.

In 2017, the RSA program continued and was expanded to ten trawlers and five trappers collecting northern shrimp during January-March (Hunter et al. 2017): one vessel from Massachusetts, one from New Hampshire, three from western Maine, three from midcoast Maine, and two from eastern Maine were picked at random from among qualified applicants from that state and region. Four trappers were also selected from midcoast Maine and one from eastern Maine, and each fished up to forty traps, tended as often as needed. 2017 RSA catches were estimated at 32.6 mt.

All 2014–2017 winter sampling catches, including discards, are included in landings tables and figures, and are included as removals in model inputs described in Section 4.

2.3 Size, Sex, and Maturity Stage of Landings

Size and sex-stage composition data have been collected from port samples of fishery landings from each of the three states. One-kilogram samples were collected from randomly selected landings. The samples were separated and weighed in the lab by species, sex (male, transitional, or female) and development stage, where females were described as: ovigerous, female I (have not carried eggs yet), or female II (have carried eggs). Female stage I or II were determined by the presence (stage I) or absence (stage II) of pronounced sternal spines (McCrary 1971). Measurements were made of all shrimp dorsal carapace lengths (CL), to the nearest 0.5 mm prior to 1994, and to the nearest 0.01 mm since 1994. The numbers of interviews conducted, northern shrimp measured, and the total weight of samples collected each season since 1985 are summarized in Table 2.8. Data were expanded from the sample to the vessel's landings, and then from all sampled landings to total landings for each gear type, state, and month (Figures 2.3, 2.5, and 2.6). Northern shrimp size composition data from landings and surveys indicate that trends in landings have been influenced by the abundance of recruited year classes. Year class abundance is discussed further in Section 3.

Landings more than tripled with recruitment to the fishery of a strong assumed 1982 year class in 1985–1987, and then declined sharply in 1988. A strong 1987 year class was a major contributor to the 1990–1992 fisheries. A strong 1992 year class, supplemented by a moderate 1993 year class, partially supported large annual landings in 1995–1998. Low landings in 1999–2003 were due in part to poor 1994, 1995, 1997, 1998, and 2000 year classes with only moderate 1996 and 1999 year classes. A very strong 2001 year class supported higher landings in 2004–2006. In the 2007 fishery, landings mostly comprised assumed 4-year-old females from the moderate to strong 2003 year class, and possibly 6-year olds from the 2001 year class. Landings in 2008 mostly comprised the assumed 4-year-old females from the strong 2004 year class, and the 2003 year class (assumed 5-year-old females, which first appeared as a moderate year class in the 2004 survey).

In the 2009 fishery, landings comprised mainly assumed 5-year-old females from the strong 2004 year class. Catches in the 2010 fishery consisted of assumed 5-year-old females from the

2005 year class and possibly some 4-year-old females from the weak 2006 year class. The 2011 fishery consisted mainly of 4-year-old females from the assumed 2007 year class. Numbers of 5-year-old shrimp were limited likely due to the weak 2006 year class. Transitional stage shrimp and female stage Is (ones) from the 2008 year class, and some males and juveniles from the assumed 2009 year class were observed in 2011, especially in the Massachusetts and New Hampshire landings as well as Maine's December and January trawl landings. Trawl landings in the 2012 fishery were likely 4-year olds from the moderate 2008 year class, but they were small for their age. Low percentages of males and juveniles were caught in 2012 likely due to the later start date of January 2. In the 2013 fishery, landings were limited but likely comprised 4- and 5-year olds from the moderate 2009 and 2008 year classes that were small for their assumed age. Limited numbers of males and transitionals were observed in landings.

Samples from the cooperative winter sampling program in 2014 comprised assumed 5-year-old shrimp from the 2009 year class and some small males assumed to be from the fast-growing 2013 year class. Samples from the 2015 RSA program exhibited an unusually high percentage of small ovigerous females, likely early-maturing and fast-growing females from the 2013 year class. The small females were more prevalent in the Maine trawl samples than in the trap samples or the Massachusetts trawl samples. Some larger females from the assumed 2010 year class were also evident in all samples. Samples from the 2016 RSA program confirmed that members of the 2013 year class were ovigerous (at only three years old), available inshore, and represented a greater proportion of the catch than older year classes (2010-2012). Some 2016 samples, particularly those from the New Hampshire boat, contained a portion of very large females, possibly from the assumed 2010 year class. Samples from the 2017 RSA program were composed mostly of ovigerous females from the 2013 year class and males probably from the 2015 year class. See Figure 2.4 for the relative abundance and growth of the 2012–2015 year classes from season to season as detected in recent surveys and cooperative winter sampling projects.

Size and sex-stage composition data also exhibit spatial and temporal differences in the abundance of small male vs. larger female shrimp, in the timing of egg hatch, and differences between gear types. Figure 2.5 and Figure 2.6 display data from 2010, the most recent year when there was a six-month fishing season. The relative abundance of male (small) shrimp was lowest in February, and highest in April and May when boats typically fish in deeper water after eggs have hatched and the larger female shrimp begin to move offshore. The timing of the egg-hatch can be estimated by noting the proportion of mature females that have hatched their brood (Female 2), both during the season and across geographic locations. In general, most female northern shrimp caught in the Gulf of Maine fishery are carrying eggs in December to early February, and most have hatched off their eggs by the end of March. Egg hatch usually occurs earlier in the western Gulf of Maine and progresses eastward — e.g. Hunter et al. 2017, and Figure 2.5 and Figure 2.6 which compare Maine vs New Hampshire and Massachusetts in 2010. Figure 1.5 displays the estimated date (from probit analysis of egg hatch data for Maine samples (Richards 2012)) from 1982–2017. Differences in size and sex-stage composition for Maine trawl catches compared with trap catches for 2010 are shown in Figure 2.5. Traps typically catch fewer small shrimp than trawls, and traps are more likely to catch female shrimp after they have hatched their eggs than trawls.

2.4 Discards

Discard rates of northern shrimp in the fishery are thought to be near zero because no size limits are in effect and most of the fishing effort occurs in areas where only the larger females are present. Data from a study which sampled the northern shrimp trap fishery indicated overall discard/kept ratios (by weight) for northern shrimp of 0.2% in 2010 and 0.1% in 2011 (Moffett et al. 2012). Sea sampling data from Gulf of Maine shrimp trawlers in the 1990s indicated no discarding of northern shrimp (Richards and Hendrickson 2006). The Northeast Pelagic Observer Program sampled 89 trips targeting Pandalid shrimp from 2001-2012; over that period, 0.03% of the observed catch was discarded. On an anecdotal level, port samplers in Maine reported seeing manual shakers (used to remove small shrimp) on a few trawl vessels during April 2010, but made no similar observations in 2011 through 2013. It is possible that discarding occurred in 2012 when a 1,000 lb (454 kg) trip limit was implemented for trappers. About 10% of trap trips caught more than 950 lbs that season (from harvester reports), but no comments from trappers about dumping shrimp were heard by port samplers. Discarding of northern shrimp in other Gulf of Maine fisheries is low (Table 2.5), averaging about 0.03 kg/trip for observed trips. For these reasons shrimp discards from the shrimp and other fisheries are assumed zero in this assessment.

2.5 Effort and Distribution of Effort

2.5.1 Vessel Data

The approximate number of vessels participating in the fishery is listed in Table 2.9. Data for fishing seasons before 2000 were gleaned from NSTC annual assessment documents, and were probably derived from the NMFS dealer weightout database. As a result, they must be considered approximations. The number of boats participating during 1980 to 1999 varied from 30-40 in 1980 to about 390 in 1988. Data from 2000–2013 are from harvester VTRs. Since 2000, the number has varied from a low of 144 in 2006 to a high of 342 in 2011. In the 2013 fishery, there were 13 vessels from Massachusetts, 182 from Maine (110 trawling, 72 trapping), and 14 from New Hampshire for a total of 208.

2.5.2 Trip Data

Prior to 1994, effort (numbers of trips by state and month) was estimated from landings data collected from dealers, and landings per trip information (LPUE) from dockside interviews of vessel captains:

$$Effort = \frac{Total\ Landings}{LPUE}$$

Beginning in the spring of 1994, a vessel trip reporting system (VTR) supplemented the collection of effort information from interviews. From 1995 to 1999, landings per trip (LPUE) from these logbooks were expanded to total landings from the dealer weighouts to estimate the total trips:

$$Total\ Trips = VTR\ Trips \cdot \frac{Total\ Landings}{VTR\ Landings}$$

Since 2000, VTR landings have exceeded dealer weighout landings, and the above expansion is no longer necessary. The 1996 NSTC assessment report (Schick et al. 1996) provides a comparison of 1995 shrimp catch and effort data from both the interview and logbook systems and addresses the differences between the systems at that time. It showed a slightly larger estimate from the logbook system than from the interview system. Thus, trip estimates reported through 1994 are not directly comparable to those collected after 1994. However, patterns in effort can be examined if the difference between the systems is taken into account. An additional complication of the logbook system is that one portion of the shrimp fishery may not be adequately represented by the logbook system during 1994-1999. Smaller vessels fishing exclusively in Maine coastal waters are not required to have federal groundfish permits and were not required to submit shrimp vessel trip reports until 2000. In the 1994–1999 time series, effort from unpermitted vessels is characterized by effort of permitted vessels.

From 2000 through 2013, landings, vessels, and trips are calculated from harvester trip reports (VTRs) only. Winter sampling trips made in 2014-2017 are from captain or observer data sheets. Trip data for 1985-2017 are in Table 2.6 (by state and month) and Table 2.7 (Maine by month and gear).

Locations of 2010 and 2013 fishing trips from federal and state VTRs (preliminary) are plotted by 10-minute square in Figure 2.2. Note that landings and effort in 2010 were relatively high, with some offshore trips in the spring, while 2013 was characterized by lower landings and lower effort with very few offshore trips.

2.5.3 Hours Towing from Port Interviews, Port Sampling Program

A port sampling program was established in the early 1980s to characterize catch at length and developmental stage (described in Section 2.4 above), as well as to collect effort data. Samplers strived to achieve representative sampling (but see Moffett et al 2011) by maintaining lists of active buyers and visiting ports in proportion to their estimated landings activity. Sampling consisted of interviewing boat captains for hours towing or numbers of traps hauled, numbers of set-over-days, fishing depth, and location. In addition, a 1 kg sample of shrimp was collected from each catch.

2.6 Commercial Catch Per Unit Effort

Catch per unit effort for the shrimp fishery is typically measured in landings per trawl hour (from Maine interview data) or catch per trawl trip. A trip is a less precise measure of effort, because: 1) trips (as presented in Figure 2.7) from interviews and logbooks include both trawl and trap trips (difficult to separate before 2000 as discussed in Section 2.1.1 above); 2) there are single day trawl trips and multiple day trawl trips (in the spring), and the proportion of such trips can vary from season to season; 3) in some years, buyers imposed trip limits on their boats; and 4) in 2012 and 2013, Maine DMR imposed day-length limits.

Average landings per trip (pooled mean kg) was calculated by dividing each season's landings (Table 2.1) by the total number of trips (Table 2.6) and is presented in Table 2.10 and Figure 2.7. It averaged 640 kg (1,410 lb) during 1995-2000, dropped to 322 kg (710 lb) in 2001, the lowest in the time series until 2013, and remained low in 2002. During 2003-2005 it averaged 638 kg (1,407 lb). The increasing trend continued in 2006 and in 2007 the highest kg per trip of the time series was observed with 1,172 kg (2,584 lb). During 2008-2011, kg per trip averaged 917 (2,021 lb), with a value of 1,044 kg (2,301 lb) in 2010, which is the second highest in the time series. There was a decrease in 2012 to 678 kg (1,495 lb) per trip. In 2013, the average landings per trip was 223 kg (492 lb), with 279 kg (616 lb) per trawl trip, both the lowest of their time series.

More precise CPUE estimates from port interviews (landings per hour trawling) were calculated by dividing the pooled landings from interviewed Maine catches by the pooled hours towing for those catches, and agree well with the (less precise) landings per trip data (see Table 2.10 and Figure 2.7). Maine's season average for 2013 was 50 kg (110 lbs) per hour, less than half the time series average of 113 kg (250 lb) per hour (Table 2.10 and Figure 2.7).

Because catch rates can be affected by many factors in addition to stock abundance, such as possible increasing trawler efficiency (discussed in Section 2.0 above), the timing of the season (catch rates are generally highest in January and February), attrition of less successful harvesters, and, most importantly, vagaries in the inshore/offshore migrating and aggregating behavior of northern shrimp in the Gulf of Maine, catch rates have not historically been reliable indices of shrimp abundance or biomass, and are not used as such in this assessment. See Figure 2.7, in which annual Maine trawler catch rates are plotted against the summer survey biomass index from the previous summer (see Section 3 for more about the survey). Note that Maine trawler catch rates were very stable during the 2008-2012 seasons at around 169 kg/hr (before plummeting in 2013) compared with the rates during the 1985-1994 "stable period", which averaged 62 kg/hr. In contrast, the summer survey indices during those two periods were very similar (averaging 13.3 and 14.1, respectively).

3 FISHERY INDEPDENDENT SURVEYS

Trends in abundance of Gulf of Maine northern shrimp were monitored between 1968 and 1983 from data collected in the NEFSC autumn bottom trawl surveys and summer surveys conducted by the State of Maine DMR (discontinued in 1983). The NEFSC fall survey has continued; however, the survey vessel and gear were replaced in 2009, and this is considered the beginning of a new survey time series for shrimp. A state-federal (ASMFC) survey was initiated by the NSTC in 1984 to specifically assess the shrimp resource in the western Gulf of Maine. This survey is conducted each summer aboard the RV *Gloria Michelle* employing a stratified random sampling design and shrimp trawl gear designed for Gulf of Maine conditions. An inshore trawl survey has been conducted by Maine and New Hampshire aboard the FV *Robert Michael* each spring and fall, beginning in the fall of 2000.

The NSTC has placed primary importance on the ASMFC summer shrimp survey (described in more detail below) for fishery-independent data used in stock assessments, although the other survey data are also considered. See Figure 3.1 for a chart of the areas covered by the different surveys.

The indices of abundance from these surveys have traditionally been calculated with design-based estimators (stratified arithmetic or geometric means). Thorson *et al.* (2015) found that a spatio-temporal standardization approach to index development produced similar trends to design-based estimators but improved precision. The spatio-temporal standardization approach uses a spatial delta-generalized linear mixed model (delta-GLMM) to incorporate habitat information and spatial auto-correlation in survey data to develop indices of abundance. Cao *et al.* (2017a) applied this approach to the ASMFC northern shrimp summer survey and found it improved the performance of the length-based assessment model, so the spatio-temporal standardization method was applied to all indices in the assessment. Index standardization was done using the VAST package in R (Thorson and Barnett, 2017).

3.1 NEFSC Trawl Survey

The NEFSC fall survey has been conducted in the northern shrimp resource area (NEFSC strata 24, 26-28, and 37-40, Figure 3.1) since 1963; however, Pandalid shrimp were not identified to species until 1973, and detailed data on northern shrimp (length, sex, life history stage) were not consistently collected until 1991. The survey is based on a stratified random design (Despres-Patanjo et al. 1998). A similar survey in the spring has been conducted since 1968. Correspondence among research surveys and fishery indices of abundance suggested that the autumn survey tracked resource conditions more closely than the spring survey (Clark and Anthony 1980, Schick *et al.* 1996), and the NSTC has not used the spring survey data in assessments since 1994.

During 1963-2008, the fall survey was conducted aboard the RV *Albatross IV*. In 2009 the *Albatross IV* was replaced by the RV *Henry B. Bigelow* and the sampling gear was re-designed. No conversion coefficients between the two platforms were developed for northern shrimp because none of the experimental calibration tows were conducted in the shrimp resource area. Thus, the NEFSC fall survey is treated as two time series in this assessment (1984-2008, 2009-2016). Fall survey data for 2017 became available as this report was going to press and, as a result, indices for the fall 2017 are included in the report but model runs do not include 2017 fall survey data.

For the *Albatross* years (1968 to 2008), the survey biomass index (stratified arithmetic mean kg per tow) was near time series highs (above 3.0 kg/tow) in the late 1960's and early 1970s (Table 3.1). In the late 1970s, the index declined precipitously, reaching a time-series low (0.2 kg/tow) in 1977 as the stock apparently collapsed; this was followed by a substantial increase in the mid- to late 1980's, reflecting recruitment and growth of the strong presumed 1982 and 1987 year classes; the index did not return to the high values of the late 1960's. The index continued to vary with the influences of strong and weak year classes through the 1990s and 2000s, and the survey ended in 2008 with values well above the time series mean (>1.8 kg/tow) during its last four years, including the time series high of 6.6 kg/tow in 2006. This high value corresponded with the time series high seen in the ASMFC summer survey the same year (Figure 3.2 and Table 3.3). In 2009, the NEFSC fall survey changed vessels, gear and protocols; thus, indices since 2009 are not directly comparable to earlier years. The biomass index from the *Bigelow* NEFSC fall survey declined rapidly, from a high of 7.8 kg/tow in 2009 to its time-series low of 0.5 kg/tow in 2016, parallel to trends in the summer shrimp survey (Figure 3.2). The 2017 fall survey arithmetic biomass index was 0.7 kg per tow.

3.2 ME/NH Trawl Survey

The Maine-New Hampshire inshore trawl survey (Sherman *et al.* 2005) takes place during spring and fall, in five regions and three depth strata (1 = 5-20 fa, 2 = 21-35 fa, 3 = 36-55 fa) (1 fa = 1 fathom = 6 feet = 1.9 meters). A deeper stratum (4 = > 55 fa out to about 12 miles) was added in 2003. The survey consistently catches shrimp in regions 1-4 (NH to Schoodic Pt, ME) and depths 3-4 (> 35 fa), and more shrimp are caught with less variability in the spring than the fall. The $\log_e$-transformed (see discussion in Section 3.3 below) stratified mean weights per tow for northern shrimp in the spring and fall surveys uses regions 1-4 and depths 3-4, and are presented in Table 3.2 and Figure 3.2 (spring only). Because the fall indices for northern shrimp are more erratic and have higher CV's than the spring indices, only the spring survey was considered for inclusion in the assessment.

The Maine-New Hampshire spring index rose steadily from 4.2 kg/tow in 2003 to a time series high of 17.9 kg/tow in spring 2011. The index then dropped abruptly and reached a time series low of 1.7 kg/tow in 2013 and 2015. The 2017 value was 2.1 kg/tow. In 2010 and 2011, the spring ME-NH inshore trawl survey data did not match the declining trend in the summer survey data. However, the low 2013–2017 biomass indices are consistent with the 2013–2017 ASMFC summer survey results (described below in Section 3.3).

This survey also has provided evidence that northern shrimp populations have not shifted to the northeastern Gulf of Maine.

Because trends in the spring ME/NH survey may be affected by inter-annual variation in the timing of the offshore migration of post-hatch females, the NSTC did not use this survey in model base runs.

3.3 ASMFC Northern Shrimp Summer Survey

The ASMFC NSTC shrimp survey, or "summer survey", has been conducted offshore (depths > 50 m) each summer (July-August) since 1984 aboard the RV *Gloria Michelle*. It employs a stratified random sampling design and gear specifically designed for Gulf of Maine conditions (Figure 3.1) (Blott et al. 1983, Clark 1989). The ASMFC summer survey replaced a survey conducted by the Maine DMR during 1967-1983 at 5-12 fixed stations (Figure 3.1). The ASMFC summer survey is considered to provide the most reliable information available on abundance, distribution, stage, and size structure because all adult life history stages are present offshore during the summer. Indices of abundance and biomass are based on catches in the strata that have been sampled most intensively and consistently over time (strata 1, 3, 5, 6, 7, and 8; Figure 3.1 and Figure 3.3). Survey catches have been highest in strata 1, 3, 6, and 8 – the region from Jeffreys Ledge and Scantum Basin eastward to Penobscot Bay, Maine. Survey sites for 2017 and stratum boundaries are shown in Figure 3.3.

The statistical distribution of the summer survey catch per tow (in numbers) was investigated to determine the best estimator of relative abundance (Cadrin et al. 1999). Catches within strata were distributed with significant positive skew, and arithmetic stratum means were correlated to stratum variances. Log-transformed catches (Ln[x+1]) were more normally distributed; therefore, stratified geometric mean numbers and weights per tow have been used since 1999 to estimate relative abundance and biomass respectively (Cadrin et al. 1999).

See Figure 3.4 for spatio-temporal model-based standardized indices compared with geometric mean design-based indices.

In 2017, the R/V Gloria Michelle's winches were replaced and new Bison trawl doors replaced the old Portuguese trawl doors which had been in use since the first year of the survey. In July 2017, eight pairs of calibration tows were made to compare the performance of the gear with the old and new doors, and winches. Results for these tows are shown in Appendix 2. Averaged over the eight pairs of tows, the new gear caught 98% of what the old gear caught, in northern shrimp weight, and 100.05% of the old gear, in numbers. The differences were not statistically significant (Wilcoxon paired-sample test, p=0.46 for shrimp weight, p=0.95 for shrimp numbers). The data and discussion below assume that there was no significant difference in the performance of the 2017 survey gear compared with prior years. More calibration tows will be conducted in 2018.

Abundance and biomass indices (stratified geometric mean catch per tow in numbers and weight) for northern shrimp from the ASMFC summer survey from 1984–2017 are given in Table 3.3 and Figures 3.5 and 3.6. Length-frequencies by year and sex-stage are provided in Figures 3.7 and 3.8. Indices were calculated using data from successful random tows in strata (areas) 1, 3, 5, 6, 7, and 8 only (Figures 3.1 and 3.3). Total biomass averaged 15.9 kg/tow from 1984 through 1990, then gradually declined to 4.3 kg/tow in 2001. Between 2003 and 2006, the index increased markedly, reaching a new time series high in 2006 (66.0 kg/tow). Although 2006 was a high abundance year, as corroborated by the fall survey index (see above), the 2006 summer survey index should be viewed with caution because it was based on 29 survey tows compared with about 41 tows in most years (Table 3.3). The summer survey index was 16.8 kg/tow in 2008, and dropped steadily to a time series low of 0.9 kg/tow in 2017. The 2016 value of 3.8 kg/tow was higher than each of the previous four years but is the sixth lowest in the time series, well below the time series average of 11.6 kg/tow (Table 3.3). The six values for 2012-2017 (2.5, 1.0, 1.7, 1.3, 3.8, and 0.9, respectively) are the six lowest values in the time series. The total mean number of shrimp per tow demonstrated the same general trend as biomass over the time series (Table 3.3 and Figure 3.5).

The stratified mean catch per tow in numbers of assumed 1.5-year-old shrimp (Table 3.3) and graphically represented as the first (left-most) size mode in Figure 3.7 and Figure 3.8 represents a recruitment index. Although these shrimp are not fully recruited to the survey gear, this index appears sufficient as a preliminary estimate of year class strength. The recruitment index indicated strong (more than 700 per tow) 1987, 1992, 2001, and 2004 year classes. The assumed 1983, 2000, 2002, and 2006 year classes were weak (fewer than 100 per tow), well below the time series mean of 334 individuals per tow. From 2008 to 2010, the recruitment index varied around 500 individuals per tow, indicating moderate but above average 2007, 2008, and 2009 year classes. The index dropped markedly to 44 individuals per tow in 2011. Time series lows (fewer than 10 per tow) were observed in 2012, 2013, 2015, and 2017, indicating recruitment failure of the assumed 2011, 2012, 2014, and 2016 year classes respectively. In 2014, the index was 116 per tow, reflecting below-average recruitment of the 2013 year class. The recruitment index for the 2016 survey (the assumed 2015 year class) was 226 individuals per tow, the highest since 2010, but still below the time series average of 334 per tow. Surveys since 2011 have shown an unprecedented seven consecutive years (2010–2016 year classes) of below-average recruitment, including the four lowest values in the time series.

Mean numbers per tow at size for 2012-2017 are too low to be clearly visible in Figure 3.7, which uses a constant y-axis scale for the time series. Expanded vertical axes for the 2012-2017 data show that the mean CLs of the assumed age-1.5 shrimp in the 2014 and 2016 surveys were unusually large (17.6 mm CL vs 16.0 CL for the time series), suggesting a high growth rate for the 2013 and 2015 year classes (Figure 3.8).

Further information about growth can be gleaned by comparing size-sex-stage frequency data from spring inshore, summer (offshore), and fall inshore surveys, as well as the winter commercial catch. Although the surveys and commercial fisheries have different size selectivities, it is still possible to verify the relative strengths of year classes, and track their growth throughout the year. See Figure 3.9, which tracks the progress of the 2013 and 2015 year classes (as well as the very poor 2012 and 2014 year classes).

Individuals larger than 22 mm CL in the summer are likely to be egg-bearing females (Figure 3.7), available to the fishery the following winter (as primarily age 4 and older). Thus, survey catches of shrimp in this size category provide indices of harvestable numbers and biomass for the coming winter (Table 3.3). The harvestable biomass index exhibited peaks in 1985, 1990, and 1995, reflecting the strong assumed 1982, 1987, and 1992 year classes, respectively. The index then trended down through 2001 to a time series low (at that time) of 1.5 kg/tow, and is indicative of small assumed 1997 and 1998 year classes. From 2003 to 2006, the index increased dramatically, reaching a time series high in 2006 (29.9 kg/tow). The index has declined steadily since 2006 despite above average recruitment of the 2007, 2008, and 2009 year classes discussed above, and reached a new time series low in both 2014 and 2017 (both 0.2 kg/tow). This is consistent with the low recruitment of the 2010, 2011, 2013 and 2014 year classes.

An index of SSB was estimated by applying a length-weight relationship for non-ovigerous shrimp (Haynes and Wigley 1969) to the abundance of females at each length, and summing over lengths. The spawning biomass index averaged about 4.9 kg/tow during 1984–1993, then declined to an average of 2.7 kg/tow during 1994–2003. It then rose to a time series high of 28.4 kg/tow in 2006. Since 2006, the index declined to less than 1.0 kg/tow in 2012–2015, and reached a new time series low (0.1) in 2017 (Table 3.3).

A population egg production index (EPI) was estimated from summer shrimp survey data as the sum of the number of females at length times their fecundity at length:

$$EPI_t = \sum N_{tL} Fec_L$$

where t = year, L = carapace length (mm), N = abundance of females, Fec_L = fecundity at length. The length-fecundity relationship was derived from data in Haynes and Wigley (1969) (Richards et al. 2012):

$$Fec_L = -0.198L^2 + 128.81L - 17821 \qquad (r^2 = 0.76)$$

The EPI index for Gulf of Maine northern shrimp varied from about 0.3 million to 1.5 million until 2006 when it rose to a high of 5.6 million followed by a steep decline to time series lows in 2012–2015 (<0.2 million; Table 3.3 and Figure 3.10). The value was 0.03 million in 2017, the lowest value in the time series.

An index of survival to age 1.5 was estimated for each year class as the log ratio of the number of age 1.5 recruits to the number of eggs that produced each year class, using summer shrimp survey data:

$$S_t = \exp(\ln(R_t) - \ln(EPI_{t-2}))$$

where S = survival index, R = abundance index of recruits (age 1.5), t = year, and EPI is expressed in millions. The survival index was high (greater than 1,000) for the assumed 1999, 2001, and 2004 year classes, and low (less than 20) for the 2006, 2011, 2012, and 2016 year classes (Table 3.3). The index for the 2013 year class was slightly above the average, and the 2015 year class index was 5,291, the highest in the time series. This is encouraging, but it should be noted that estimating the survival index (a ratio) is difficult when abundance is at extreme lows, as is currently the case.

4 STOCK ASSESSMENT MODELS

4.1 Catch-Survey Analysis

Collie-Sissenwine Analysis (CSA) is a two-stage stock assessment model that estimates abundance, fishing mortality (F), and recruitment to the fishery using total catch numbers and survey data (Collie and Sissenwine 1983; Conser 1995). The “recruit” stage group consists of animals that will recruit to the fishery during the current time step. The “post-recruit” animals are those that were fully recruited before the start of the time step. The two stages may correspond to age groups, length groups, or any other natural division (e.g. genders in hermaphroditic species). The initial application of CSA to Gulf of Maine northern shrimp is described in Cadrin et al. (1999), and a more recent application based on the 2014 benchmark assessment is described in Richards and Jacobson (2016).

The software for CSA was updated in 2013; the 2014 and 2018 shrimp benchmark assessments used CSA version 4.2 from the NOAA Fisheries Toolbox (http://nft.nefsc.noaa.gov/). Technical documentation for the new software was provided in Appendix C3 of the 2014 benchmark report (NEFSC 2014). The most significant improvements were the use of maximum likelihood methods rather than weighted sums of squares to estimate parameters, and the capability to incorporate more than one survey index in fitting the model.

The surveys in CSA version 4.2 can be of two types. "Recruit/post-recruit" surveys consist of two indices (one for recruits and the other for post-recruits) usually derived from the same survey. In contrast, aggregate surveys are not divided into recruits and post-recruits. For recruit/post-recruit surveys, the user must specify annual selectivity parameters (sometimes called q-ratios) which cannot be estimated and which measure catchability of recruits relative to post-recruits in each year. It is inadvisable to include multiple recruit/post-recruit surveys because fixed selectivity parameters for the two surveys are likely to conflict.

The model may include any number of "aggregate" surveys. The aggregate surveys involve a single selectivity parameter for recruits that may be fixed or estimated. The selectivity of post-recruits is assumed to be one; the parameter for recruits measures selectivity relative to the selectivity of post-recruits.

The user must specify the time of year (as a fraction) that each survey observation was collected. The model uses this information in comparing the observed survey observation to predicted abundance at the time the observation was collected. This facilitates use of multiple surveys collected at different times of the year and surveys with variable start dates, particularly when mortality rates are high.

The effects of the new software and model configuration were tested for the 2014 benchmark assessment (NEFSC 2014). The effect of the estimation procedure (least squares vs. maximum likelihood) on the population estimates was undetectable and the effect of adding the NEFSC fall surveys was minor. Sensitivity runs were done which explored a range of values of natural mortality (M). The final model used time-varying M based on PPI and baseline M=0.5, and included the NEFSC autumn surveys but did not include the ME-NH spring inshore survey.

The CSA model was not accepted for use in management by the 2014 benchmark review committee. The committee's primary concerns included the temporal patterns in the residuals and sensitivity of the estimates (and thus status determination) to the likelihood weights. The total likelihood did not vary greatly with extreme changes in the likelihood weighting (catch lambda ranging from 0.50 to 0.01), thus making it difficult to choose the appropriate weights. In addition, there was concern among the reviewers about the close fit to the catch (catch

CV=0.05). Some of this concern may have stemmed from a misconception that CSA uses catch to represent abundance when in fact catch only estimates removals. The misconception was not fully understood by the assessment team until after the review.

For the 2018 benchmark assessment, the CSA model was fit over a series of assumptions about M (see Table 5.1) using both design-based and model-based survey indices. Recruits and post-recruits were defined by length and selectivity-at-length based on an empirical study using shrimp trawls (Schick and Brown 1999). The summer shrimp survey was considered the start of the year and the fall survey occurred 0.25 years later. Selectivity of the aggregate surveys was estimated within the model. Annual survey CVs were adjusted prior to performing the benchmark model runs to bring the assumed CV values close to those implied by the model residuals. Catch CV was assumed equal to 0.05. Confidence limits for final model estimates were generated from Markov chain Monte Carlo (MCMC) calculations using 1000 iterations with a thinning rate of 10. The model time period was survey years 1984-2017; however, fall survey data were only available through 2016.

4.2 Length Structured Model

Starting with the 2014 benchmark, the NSTC has worked with researchers at the University of Maine to develop a statistical catch-at-length model for northern shrimp (NEFSC 2014, Cao *et al.* 2017b, Cao *et al.* 2017c).

For the base case implementation of the UME length structured model, 25 length bins were modeled, from 10 mm to 35 mm carapace length. A seasonal time-step was used to capture the temporal dynamics of the fishery. Season one included Dec – May, when the fishery operates, and season two included June-November, when fishing does not occur. This also allowed for seasonal growth patterns; ovigerous shrimp do not molt and therefore do not grow for a large part of season one.

The growth transition matrices were developed internal to the model by estimating the mean and standard deviation of the von Bertalanffy growth parameters L_∞ and K, as well as the correlation between L_∞ and K. A separate set of parameters is estimated for each season and time-block. The base case of the model used a single time-block (growth varies within the year, but not across years). Growth regimes were examined as sensitivity runs, with time-blocks based on time (pre-2000 and post-2000) or on temperature (positive or negative spring bottom temperature anomalies).

Natural mortality was modeled as length- and time-varying in the base case (Figure 4.1; see Section 1.1.3 for more information). Length- and time-constant scenarios for M were considered as sensitivity runs.

Recruits enter the population on Dec. 1st (the beginning of season 1) as 10-12mm shrimp. Recruitment in the base case was modeled as deviations from mean recruitment. Sensitivity runs used other assumptions about recruitment. Sensitivity runs were conducted linking recruitment deviations to environmental variables, specifically spring surface and bottom temperature anomalies from the NEFSC spring survey lagged by one year.

Three fleets were modeled: a mixed fleet from 1984-1999 (when trap and trawl landings could not be separated), a trawl fleet from 2000-2017, and a trap fleet from 2000-2017. Five selectivity blocks were used: one block for the mixed fleet from 1984-1999, and two blocks each for the trap and trawl fleets, 2000-2013 and 2014-2017. The split for the trap and trawl fleets was based on the closure of the directed fishery and the switch to a research fishery.

The UME length-structured model has the ability to assess the probability of sex change as a logistic function of length; this was not implemented in the base case. The observed proportion female at length from the ASMFC summer survey was used to calculate female SSB.

4.3 ASAP Model

ASAP (Age Structured Assessment Program v. 3.0.16, part of the NOAA Fisheries Toolbox, http://nft.nefsc.noaa.gov/ASAP.html) was used as alternative model to the CSA and to the UME length-structured model. ASAP is a forward-projecting, statistical catch-at-age model that uses a maximum likelihood framework. ASAP provides estimates of the asymptotic standard error for estimated and calculated parameters from the Hessian. The objective function is the sum of the negative log-likelihood of the fit to various model components. Monte Carlo Markov chain (MCMC) calculations provide more robust characterization of uncertainty for F, SSB, total biomass, and reference points. Technical documentation and the user manual for ASAP are provided in Appendix 3.

ASAP was applied to the northern shrimp stock, as it represents an intermediate level of complexity of modeled life history parameters between the CSA and UME models. ASAP has not been used to assess the Gulf of Maine northern shrimp stock in prior assessments given shrimp are crustaceans which lack permanent calcified structures, or other morphological age markers, for direct ageing of animals. For application to ASAP, Gulf of Maine northern shrimp length-frequency data were analyzed through modal analysis to infer sizes and proportions-at-age.

The following input data were required in the ASAP model for the Gulf of Maine northern shrimp: natural mortality and maturity by age, annual survey indices and associated CV, survey proportions-at-age and effective sample size (ESS), weights-at-age, and annual commercial catch (and associated CV and ESS) by fleet.

For the 2018 benchmark assessment, the NSTC fit the ASAP model over a series of assumptions about M to examine the effects of input data and model configuration on model performance and results (Table 4.1). The NSTC concluded that the base case model for ASAP would use a time-varying natural mortality (scaled by a PPI from a base of M=0.5 (Table 4.2), also see Section 1.1.3). Base case M was also age-varying for the ASAP model to reflect the assumption that natural mortality for Gulf of Maine northern shrimp varies with age (i.e. size), where juvenile and oldest-aged shrimp are subject to higher natural mortality than those in mid-life stages (see Section 1.1.3). The time-period of analysis for the base case ASAP age-structured model is 1985-2017.

Survey indices included in the model were the ASMFC Gulf of Maine Northern Shrimp summer survey and the NEFSC fall survey, with summer survey data from 1985-2017. NEFSC fall survey data composed two indices due to a change of survey vessel: Albatross survey data from 1985-2008 and Bigelow survey data from 2009-2016. The summer shrimp survey was considered to start on month 8 of the calendar year and the fall survey occurred at month 10. The indices of abundance were calculated using a spatio-temporal standardization process to create model-based indices (as used in the CSA and length-based models). Model-based survey indices and associated CVs were applied for the base model (Tables 3.1 - 3.3). CVs for the summer survey averaged 0.16 with a range of 0.12-0.25. CVs for the Albatross survey averaged 0.29 with a range of 0.23-0.36. CVs for the Bigelow survey averaged 0.52 with a range of 0.26-1.0 (Table 3.1, 3.3). Sample size for the summer survey was based on the number of stations sampled annually, and averaged 42 with a range of 29-50. Sample sizes for the Albatross and Bigelow were set to 10.

Four age groups (“ages”) were defined (ages 1, 2, 3 and 4 plus group) for the northern shrimp stock (Table 4.3 and Table 4.4). Proportions-at-age by number were estimated for commercial and RSA landings (1985-2017), ASMFC Summer shrimp survey catches (1984-2017), and NEFSC fall survey catches (1991-2016), by modal analysis of length-frequency data using the NORMSEP program (Gayanilo *et al*. 2005). NORMSEP was run on mean number at dorsal carapace lengths (CL) in 0.5 mm intervals for each year applying methods described by Freschette and Parsons (eds., 1982), using all data, data separated by sex, and sometimes by female stage. Attempts were made to identify four age groups (year classes), where Age 1 shrimp from the summer survey were approximately 16 mm CL and about 17 months old, Age 1 shrimp from the fall survey were about 17 mm CL and 20 months, and Age 1 shrimp from the winter fishery were about 18 mm CL and 23 months. The estimates derived through NORMSEP were compared to modes identified visually through an “eye-splice” technique and were confirmed to be similar. In some instances, NORMSEP failed to separate out a year class if it was very weak relative to other adjacent year classes, thus estimating a zero for that age-class/year. The NORMSEP method presented a more rigorous approach to mode separation, thus was applied to all survey indices and catch.

Selectivity by age was applied for the three survey indices, with initial guesses for Age 1= 0.25, Age 2=0.5, and Age 3= 1, and 4+= 1. Maturity was knife edge at Age 3 and age and time invariant. Recruitment CV was constant at 0.5. Weights-at-age were determined by applying the NORMSEP-derived annual average lengths-at-age to established Gulf of Maine northern shrimp length-weight tables developed from ASMFC Summer shrimp survey data (NEFSC unpub. data; Table 4.5).

Removals were modeled as a single commercial fishing fleet, with three selectivity blocks for the fishery over the time period. Selectivity time blocks were based on changes in landings reporting, where from: 1) 1985-1999 catch from trawl and trap fisheries were not separate (i.e.

mixed), 2) 2000-2013 catch for trap and trawl fisheries was reported separately - but were combined as one index, and 3) 2014-2017 catch represents landings from a research set-aside (RSA) program during a commercial harvest moratorium. Selectivity by age was applied. Catch ESS was a proportion of the number of trips taken annually by the fleet (trap and trawl) and averaged 38 with a range of 10-83 (Table 4.3). Fleet CVs were 0.3 for 1985-1999, 0.25 for 2000-2013, and 0.1 for 2014-2017, corresponding to fleet selectivity time blocks. There were no assumed discards or releases for this stock (an exception to this occurred in 2014 when catch from the winter sampling program was discarded; however, it was included in the commercial catch time series (see Section 2.2.3)).

In addition to the base case, the NSTC ran several alternative scenarios to evaluate the sensitivity of the assessment results with respect to various settings hypothesized in the base case (Table 4.1). The scenarios evaluated sensitivity of settings for natural mortality (Scenarios B-G), design-based versus model-based survey indices (Scenario H), importance of survey indices (Scenarios I-K), and underreporting of commercial landings in early years (Scenario L), and alternative catch CV. ASAP was used to derive estimates of stock size, recruitment, and F. Confidence limits for base model estimates were generated from MCMC calculations using 1000 iterations with a thinning rate of 10.

Retrospective analyses were performed on the base run and sensitivity permutations for terminal year estimates of stock abundance, SSB, Age 1 recruitment, and F. The most recent selectivity block began in 2014, thus, a 3-year peel with a terminal year of 2017 was applied for the retrospective analyses (i.e. 2014-2017).

4.4 Traffic Light/Data Poor Approach

4.4.1 Traffic Light Approach

The NSTC utilized an index-based approach to assess stock status of Gulf of Maine northern shrimp. The Traffic Light Approach, developed by Caddy (1999*a*, 1999*b*, 2004) and extended by McDonough and Rickabaugh (2014) was applied to the northern shrimp stock to characterize indices of abundance, fishery performance, and environmental trends from 1984 to the present. The approach categorizes annual values of each index as one of three colors (red, yellow, or green) to illustrate the state of the population, environmental conditions, and fishery. Red designates unfavorable conditions or status, yellow designates intermediate values, and green designates favorable conditions or status.

The NSTC applied the Strict Traffic Light Approach (STLA, Caddy 1999*a*, 1999*b* and 2004) to a suite of indices. Fishery independent indices included survey total abundance and biomass, as well as model-based indices, estimated from the ASMFC summer shrimp and NEFSC fall surveys; harvestable biomass, SSB, recruitment, and early life survival were estimated from the ASMFC summer shrimp survey. The survival index represents the number of eggs that survived to become recruits at age 1.5 ($\log_e$ ratio $R/E_{lag\ 2}$, scaled by 1,000,000). Environmental indices included an index of predation pressure on Gulf of Maine northern shrimp that was developed for the benchmark assessment (NEFSC 2014; Richards and Jacobson 2016), and several sources of temperature data for the northern shrimp resource area. Fishery performance indices included commercial CPUE, price per pound, and annual landings value. Price per pound and annual landings values were standardized to 2018 US dollars (www.bls.gov).

Two qualitative stock status reference levels were developed for the traffic light approach, one based on the ‘stable period’ mean (SPM, 1985–1994), which was the time period used to define the reference points in Amendment 2. The second qualitative status indicator was based on the entire time series of observations. The 20th percentile of the time series (1984-2017) was considered to delineate an extremely adverse state. For fishery dependent and fishery independent indices, red denotes values at or below the 20th percentile, while green denotes values at or above the SPM. For environmental indices, red denotes values at or above the 80th percentile and green denotes values at or below the SPM.

The NSTC also examined a subset of key indicators using the Fuzzy Traffic Light Approach (FTLA; McDonough and Rickabaugh 2014). The FTLA gives a finer view of the classification of each indicator in each year. For each indicator, a table shows trends in the time series and the relation to the stable period mean (SPM) and the 20th percentile levels. A stacked bar graph reflects the proximity of each annual value to the SPM. The greater the proportion of green or red in each stacked bar, the further that year’s index is in a favorable or unfavorable direction, respectively, relative to the SPM. A bar that is 100% yellow indicates a value close to the SPM. These reference levels are not management triggers, as they are not defined in the ASMFC Northern Shrimp FMP or its Amendments. The levels are used to illustrate the current condition of the stock relative to earlier time periods.

The NSTC evaluated 11 indicators using the FTLA, including: 1) model-based summer survey indices, 2) total biomass, 3) recruit abundance, 4) spawning biomass, 5) harvestable biomass, 6) commercial fishery CPUE (metric tons landed per trip; fishery closed 2014 – 2017), 7) early life survival, 8) PPI, 9) spring sea surface temperature at Boothbay Harbor, ME, 10) spring bottom temperature anomaly from NEFSC surveys in shrimp resource areas, and 11) summer bottom temperature from the ASMFC summer shrimp survey (1 – 5 and 7 are also from the ASMFC summer shrimp survey).

4.4.2 Data Poor Quota Calculation

The TLA is a straight-forward, intuitive way to summarize different metrics of abundance and the environmental factors that affect northern shrimp population dynamics. However, the TLA cannot provide quantitative quota recommendations.

As a comparison to the quota recommendations from the UME model, the NSTC also explored data poor quota setting methods. Extensive work has been done in recent years to develop methods to establish quotas in data-limited situations (e.g., Carruthers *et al.* 2016). The NSTC used an approach based on the methods the Mid-Atlantic Fishery Management Council (MAFMC) used to establish catch advice prior to the completion of a benchmark assessment for black sea bass (Miller 2015).

The MAFMC used an average of 4 different data-limited methods (3 index based, 1 constant catch scenario), but the NSTC only considered the index based approaches.

These methods require an estimate of catch or catch advice in the most recent year and an index of relative abundance. The NSTC used research set-aside removals (32.6 mt) in 2017 as the catch estimate, and the ASMFC Summer Shrimp Survey index of exploitable numbers (>22mm) and SSB as the indices.

The index-based methods use changes in the index of abundance over time to determine how to adjust the current removals to set a new quota. If the index has been increasing in recent years, the quota can be increased, but if the index has been decreasing, the quota should be decreased. The original methods used the slope of the logged index values over the last 5 or 8 years; however, given northern shrimp's short lifespan, the NSTC used the slope of the index over the last 3 years (the number of presumed age classes in the catch).

Method 1: GB Slope (Geromont and Butterworth, 2014)

$$TAC_{y+1} = C_y \cdot \left(1 + \lambda \cdot slope\left(I_{y:y-3}\right)\right)$$

Where:
TAC_{y+1} = the total allowable catch in year $y+1$
C_y = the catch in year y
λ = a scalar (1, in this case)
$slope(I_{y:y-3})$ = the slope of the log-linear regression of the index over the last three years

Method 2: I Slope 1 (Geromont and Butterworth, 2014)

$$TAC_{y+1} = C_y \cdot \left(1 + \lambda \cdot slope\left(I_{y:y-3}\right)\right)$$

Where:
TAC_{y+1} = the total allowable catch in year $y+1$
C_y = the catch in year y
λ = a scalar (0.4, in this case)
$slope(I_{y:y-3})$ = the slope of the log-linear regression of the index over the last three years

Method 3: SBT1 (CCSBT, 2013)

$$TAC_{y+1} = TAC_y \cdot \left(1 - k_1 \left|slope(I_{y:y-8})\right|^{\gamma}\right) \qquad \text{if } slope(I_{y:y\text{-}8}) < 0$$

$$TAC_{y+1} = TAC_y \cdot \left(1 + k_2 \cdot slope(I_{y:y-8})\right) \qquad \text{if } slope(I_{y:y\text{-}8}) \geq 0$$

Where:
TAC_{y+1} = the total allowable catch in year $y+1$

TAC_y = the total allowable catch in year y
k_1 = a scalar (1.5, in this case)
k_2 = a scalar (3, in this case)
γ = a scalar (1, in this case)
slope($I_{y:y-3}$) = the slope of the linear regression of the index over the last three years

For both method 1 and method 2, constraints are in place to ensure that the TAC in year *y+1* will not increase or decrease more than 20% from the total catch in year *y*. Values for the scalars (λ, k_1, k_2, and γ) were those used in the original publications.

5 MODEL RESULTS

5.1 Catch-Survey Analysis

5.1.1 Diagnostic Results

CSA runs that used model-based survey indices generally performed better (as judged by the negative log likelihoods (NLL)) than those that used various types of design-based indices. Thus all subsequent runs were done using the model-based indices. The models that assumed a baseline M=0.95 (as either constant or basis for time-varying M) had the highest NLL (poorest fit) of the seven M configurations tested (Table 5.1). The best fit was obtained for the assumption of time-varying M=0.5*PPI, and this was chosen as the final run for the CSA.

Figure 5.1 shows the final model fits to survey and catch inputs. Standardized residuals (Figure 5.2) show some strong temporal patterns, particularly overestimation of recruits during the 1990s and underestimation in more recent years. Post-recruits were underestimated in the first decade of the series, but the patterning in the residuals is less strong than for the pre-recruits. Temporal patterns in the residuals are also evident in the aggregate surveys.

The retrospective analysis showed that the CSA estimates were very stable as years were removed from the model (average Mohn's rho=0.12, Table 5.2, Figure 5.3). However, the run with a terminal year of 2013 deviated from the others more substantially. This was likely related to the sudden drop in abundance of shrimp in 2012, which would have had a strong influence on the estimates of post-recruits in 2013. Mohn's rho was near zero for runs terminating after 2013.

5.1.2 Population Estimates

Based on the final CSA model, abundance of exploitable shrimp (millions of shrimp, recruits + post-recruits) fluctuated between about 560 and 1,700 during 1985-2005, then jumped to over 3,370 in 2007. Abundance subsequently declined, dropping to 800 in 2012, and less than 300 in 2013. Stock size has remained below 300 since 2013. Corresponding estimates of exploitable biomass were 4.3-13.6 (000s) mt during 1985-2005, 24.6 (000s) mt in 2007, 5.9 (000s) mt in 2012, and less than 2.7 (000s) mt since 2013 (Figure 5.4).

Estimates of F from the CSA peaked at 0.95 in 1997, with the second and third highest values in the time-series occurring in 2011 and 2012 (0.68 and 0.62, respectively). F dropped to 0.16 in 2013 and has remained below 0.02 since then (Figure 5.4).

5.1.3 Sensitivity Runs

Sensitivity runs were done to examine the influence of the assumed catch CV. When catch CVs were initially set to 0.25 and adjusted along with the survey indices to align the CV values with those implied by the model residuals, the adjustments led to catch CVs=0.07, very close to the original assumed CV (0.05). When catch CVs were held constant at 0.25 and only the survey CVs adjusted, the NLL was higher (-118.2) than the final run with catch CV=0.05 (NLL=-154.2). These analyses support use of the low CV (0.05) on catch.

Sensitivity runs were also done using varying catch and survey likelihood weights, in light of the concerns raised at the 2014 benchmark assessment review. In the current configuration using model-based indices, the revised PPI, and an additional 5 years of data, the estimates are no longer highly sensitive to the weights and the NLL does vary with the weights (Figure 5.5, Table 5.3a). Mohn's rho was stable across different weighting schemes (Table 5.3b).

An exploratory run was done to examine the joint influence of time-varying predation and temperature on population estimates. A composite predation-temperature series was developed by conducting a principal components (PC) analysis that included the PPI and surface and bottom temperature anomalies from the NEFSC spring and fall surveys. This series did not include 2017 because the fall survey temperature data were not yet available. The first PC explained 68% of the variance and the PC1 scores were used to scale M (using average M=0.5) against the PPI (Section 1.1.3) (Figure 5.6). The resulting model fit was improved over the final run that used PPI-scaled M only (NLL=-165.0 vs. -152.5 for final 0.5*PPI run without 2017, Table 5.1). Temporal patterns in the residuals remained, but the magnitude of the residuals was reduced, and retrospective patterns were further improved (Mohn's rho = 0.05, 0.02, -0.02, 0.04 for recruits, post-recruits, F and exploitable biomass respectively). Using a 3-year average of the composite environmental index did not improve model fit compared to the PPI-scaled M (NLL=-154.5). Abundance and biomass estimates from this run tended to be higher than estimated from the final run using the 0.5*PPI-scaled M, and F slightly lower (Figure 5.7).

5.2 Length Structured Model Results

5.2.1 Diagnostic Results

The model was able to fit the length-composition data relatively well for both the indices (Figure 5.8-5.10) and the catch (Figure 5.11-5.14), fitting both the broader size range of the survey length composition and the narrower distribution of the catch composition. In some years, the predicted peak of the length frequency was in the right place, but was smaller than the observed peak (e.g, 1984, 1988, 1989, 1993; Figure 5.8). In other years, the model predicted a larger proportion of small shrimp than were observed (e.g., 2006, 2013, 2015, 2017; Figure 5.8), suggesting either an overestimate of recruitment, or slower growth in subsequent years than calculated by the model.

The model fit the total annual indices well, with more patterning in the residuals in the NEFSC Fall Trawl survey than in the ASMFC summer survey (Figure 5.15-5.16). The model still struggled to fit the extremely high value in 2006. Overall, the model fit the total catch well, although it underestimated the peak catches in the late 1990s, prior to a steep decline into the early 2000s (Figure 5.17-5.18). There was some slight patterning in the residuals by fleet, with two or three years of positive residuals followed by two or three years of negative residuals before reversing again (Figure 5.19).

The retrospective pattern was minimal. The time series of exploitation rates were slightly lower than the base 2017 run (Figure 5.20; Mohn's rho=0.019) and the time series of SSB and recruitment were slightly higher (Figure 5.21 and Figure 5.22; Mohn's rho=0.063 for SSB and -0.13 for recruitment). The terminal year estimates of each time series were not consistently above or below the equivalent 2017 estimate.

5.2.2 Population Estimates

The estimated growth transition matrix produced distributions of size-at-age that were consistent with published growth curves (Figure 5.23). The fleet selectivity curves were shifted further to the right than has been traditionally assumed for the mixed fleet and the open fishery trawl fleet; while the trap fleet reached full selectivity sooner than the other two fleets (Figure 5.24). There was not a large difference in the selectivity between the two time blocks for the trap fleet, but the trawl fleet had a higher selectivity on smaller shrimp in the research time block (2014 - 2017) than in the open fishery (2000-2013) (Figure 5.24). The estimated selectivity of the ASMFC summer survey and the NEFSC Fall Trawl were similar for the Bigelow years (2009 – 2017), but the NEFSC Fall Trawl had a lower selectivity on smaller shrimp than the ASMFC summer survey during the Albatross years (Figure 5.25).

SSB is at extremely low levels and has been since 2013 (Table 5.5, Figure 5.26). SSB in 2017 was estimated at 709 mt, well below the time series mean of 3,473 mt. SSB shows three large peaks over the time series in 1995, 2007, and 2009, ranging from 6,000 – 6,500 mt. There was a decline in SSB after each peak, and after the peaks in 1995 and 2009, the decline continued for 6 or more years afterwards, leading to time series lows.

F has also been at time series lows in recent years (Table 5.5, Figure 5.27). Full F for the mixed fleet peaked in 1997 after being relatively stable for 1984-1994; the trawl and trap fleets were more variable from 2000 onward; although the trap F was much lower than the trawl F for the entire time period, both fleets showed a strong peak in 2011-2012. An average F for the time series was calculated to account for differences in selectivity patterns; the numbers-weighted average F on shrimp ≥22 mm carapace length peaked in 2011 and 2012 before dropping to 0.031 in 2017, below the time series mean of 0.48 (Table 5.5, Figure 5.28). This is a function of the fishery closure implemented in 2014.

Recruitment has also been low in recent years, with recruitment in 2017 estimated at 2.05 billion shrimp (Table 5.5, Figure 5.29). The median of the time series is 4.38 billion shrimp. The

2015 year class was above average, but the 2014, 2011, 2016, and 2012 year classes were the lowest on record. Variability in recruitment has increased since 2000, with higher highs and lower lows in recruitment deviations than 1984-1999 (Figure 5.29). The highest year class on record is the 2001 year class at 99.4 billion recruits, an order of magnitude larger than the median value.

5.2.3 Sensitivity Analyses

Natural Mortality

The base model used a size- and time-varying estimate of M. As a sensitivity analysis, the NSTC looked at the effects of using a length-constant and time-varying estimate of M (M=0.5 and M=0.95, scaled by the PPI), a length-varying and time-constant estimate of M, and a length and time constant estimate of M (M=0.5).

Overall, trends in recruitment, SSB, and average F were similar across the different M parameterizations, but there were differences in scale (Figures 5.30-5.32). Unsurprisingly, length-varying estimates of M resulted in higher estimates of recruitment, since M on smaller, younger shrimp was higher than M on larger shrimp (Figure 5.30). The predation index used to scale estimates of M in the time-varying scenarios has generally increased over time, and as a result, time-constant M scenarios had higher estimates of recruitment in the early part of the time-series (Figure 5.30).

Time-constant M scenarios were slightly more optimistic about the level of SSB in the most recent years, showing a recovery to levels around where the stock was in the mid-2000s, while the time-varying M scenarios remained low relative to the rest of the time series and relatively flat (Figure 5.31). This was true for both the length-constant and length-varying versions of M.

Estimates of average F were more similar across M scenarios, although the estimate of average F from the high M (M=0.95, time-varying) scenario were lower for most of the time-series (Figure 5.32).

The NSTC chose the length- and time-varying M as the base case because it was more biologically realistic, it improved the fit of the model, and it improved the retrospective pattern (Figure 5.33-5.35). In addition, the use of a length-varying M provided more realistic estimates of selectivity for the mixed fleet and the early part of the trawl fleet, with more smaller shrimp being selected in that scenario than in the length-constant scenarios, where only the largest size classes were strongly selected (Figure 5.36).

Environmental Deviations and Recruitment

The UME model has two ways to incorporate environmental effects into recruitment estimates. The first is to fit a Cushing-type stock-recruitment relationship, which has a parameter for environmental effects in the relationship between SSB and recruitment. Recruitment deviations would then be estimated from this relationship. This approach did not work with the northern shrimp data; the model failed to converge when attempting to estimate the Cushing environmental stock-recruitment relationship. Richards et al. (2012) showed that while there was a relationship between indices of recruitment and both indices of spawning and lagged spring ocean temperatures prior to 2000, that relationship deteriorated after 2000 and only environmental factors were significantly related to recruitment indices during 2000-2011. Therefore, it is not surprising that the UME model struggled to fit a single relationship over the 1984-2017 time period.

The other option, which was successfully explored, is to treat environmental data as an index of recruitment deviations. The environmental index used was the mean of spring surface and bottom temperature anomalies from the NEFSC trawl survey; the environmental index was normalized to a mean of zero and multiplied by -1 so that positive temperature anomalies corresponded to negative recruitment deviations, as warmer temperatures should result in lower recruitment (Figure 5.37). The base run modeled recruitment as deviations from mean recruitment with no environmental information incorporated. For the sensitivity analysis, runs were also done where recruitment was modeled as deviations from a Beverton and Holt curve, with and without fitting to environmental deviations, and where recruitment was modeled as deviations from mean recruitment with recruitment deviations fit to the environmental index.

Overall, the models fit with environmental data identified the same strong and weak year classes as models fit without environmental data; however, the models that incorporated environmental data estimated higher recruitment for strong year classes and lower recruitment for weak year classes than the models without environmental data (Figure 5.38). There are some small differences between estimates of SSB between models that do and do not incorporate environmental effects, with a slightly more pronounced effect from 2014-2017, where the base model SSB estimate was approximately 10% higher than the other models (Figure 5.39). Differences in average F were minimal across the different scenarios (Figure 5.40).

Fitting to the environmental deviations made the retrospective patterns slightly worse, particularly for recruitment and SSB (Figure 5.41-5.43). Cao et al. (2017c) showed that incorporating environmental data into this model improved the model estimates of SSB and recruitment in a simulation study. However, they did not look at a scenario where the environmental driver is mis-specified in the assessment model, or a scenario where the relationship between the environmental driver and recruitment changes over time. Although the environmental driver had an effect on the estimates of recruitment and SSB in this assessment, it may be in conflict with other recruitment information in the length composition data, resulting in poorer performance as more years of information are added.

Index Choices

The base run of the UME model used the ASMFC summer survey and the NEFSC Fall Trawl Survey. The indices of abundance were calculated using a spatio-temporal standardization process to create model-based indices. For the sensitivity analyses, runs were conducted with the traditional design-based indices for the summer survey and the NEFSC Survey, as well as with the ME-NH Inshore Trawl Survey included, and with the summer survey only.

The design-based indices resulted in slightly higher estimates of SSB at the beginning of the time-series and lower estimates of SSB from 2012-2017 compared to the model-based indices (Figure 5.44). The design-based indices resulted in slightly lower estimates of recruitment for some of the stronger year classes, but otherwise showed similar trends (Figure 5.45). Estimates of average F were very similar across all scenarios (Figure 5.46). Adding and removing indices did not have a strong effect on the trends or magnitude of the population estimates, indicating all three indices are providing similar information.

The design-based indices were fit less well than the model-based indices, resulting in a higher log-likelihood. The design-based indices also resulted in a slightly worse retrospective pattern compared to the base run, as did the addition of the ME-NH Inshore Survey (Figure 5.47-5.49).

Growth Blocks

The base run of the UME model estimated two growth matrices, one for each season. To look at potential differences in growth from year to year, model runs that fit four sets of growth matrices were conducted, one for each season and growth block combination. Growth blocks were identified in three different ways: warm and cold years, based on seasonal temperature anomalies from the NEFSC trawl surveys; above or below average size-at-age years from the ASMFC summer survey data (see Section 4.3); and a regime change with a pre- and post-2000 set of seasonal growth matrices.

The parameterization that had the largest effect on estimates of SSB and average F was the regime change, with lower estimates of SSB and higher estimates of F prior to 2000 compared to the other model configurations (Figure 5.50 and Figure 5.51). There were not large differences in recruitment among the different growth models (Figure 5.52). The model estimated slower growth in warmer years, years after 2000, and years where the size-at-age was above average (Figure 5.52). Two growth blocks did reduce the log-likelihood of the model, but showed worse retrospective patterns, possibly related to difficulties in estimating multiple growth models (Figure 5.53).

Although constant year to year growth is biologically unrealistic, adding in additional growth blocks did not appear to improve model performance. This may be because the variability in growth from year to year is not any better captured by two blocks than by a single block, or because there are cohort effects that cannot be captured with this model configuration, or a combination of both.

5.3 ASAP Model

5.3.1 Diagnostic Results

Model results, including diagnostics and population estimates, are summarized in Tables 5.7 and 5.8 for all ASAP model runs.

Generally, ASAP was robust to alternative model scenarios. ASAP runs that used model-based survey indices generally performed better than those that used design-based indices, thus all subsequent runs were done using model-based indices (Table 3.1, 3.3). The best fit (as judged by objective function, RMSE, and Mohn's rho values, as well as biological knowledge of the stock) was obtained for the assumption of age-varying and time-varying (scaled by PPI) natural mortality adjusted from a base of M=0.5; this was chosen as the final run for the ASAP (base run M values in Table 4.3).

The deviation of base model fits to inputs over time were similar in scale for survey indices and for catch (Figure 5.57). The model estimated lower indices for the peak observed in fishery-independent surveys in 2006. Patterning in the standardized residuals was less evident for the summer survey and Bigelow indices than for the Albatross index and catch (Figure 5.58). The magnitude of the input ESS appeared appropriate given that the predicted ESS generally bisected input ESS (Figure 5.59). Observed age composition was modeled closely in the base case for all ages and survey indices (Figure 5.60).

5.3.2 Population Estimates

The base model estimates of SSB fluctuated between about 6 and 16 (000s) mt during 1986-2000, then declined to 2.9 (000s) mt in 2003, followed by a rapid increase to unprecedented highs in 2007 and 2008 (31-32 (000s) mt). SSB subsequently declined dramatically to a resource low of 0.3 (000s) mt in 2015 and has fluctuated at a low level in recent years. In 2017, SSB was 0.7 (000s) mt, well below the time series mean of 9.6 (000s) mt (Table 5.7, Figure 5.61.1). Trends in exploitable biomass fluctuated similarly at a slightly lower level over the time series (e.g. 4.5-12 (000s) mt from 1986-2000; high in 2008 of 27 (000s) mt; low in 2015 of 0.6 (000s) mt) (Table 5.7; Figure 5.61.2).

Estimates of January 1 biomass were fairly stable through 2000, varying from 28-67 (000s) mt, then fluctuated at a higher level through 2012 (time-series high of 544 (000s) mt in 2002). A peak in 2010 of 309 (000s) mt was followed by rapid decline to 3.4 (000s) mt in 2013. Jan 1 biomass has varied in recent years and was 7 (000s) mt in 2017 (Table 5.8, Figure 5.61.1).

Total Stock Abundance and Recruitment

The base model estimates of total stock abundance and Age 1 recruitment trended similarly, with total stock abundance varying between 5.8 and 18.3 million shrimp through 2001 and recruit abundance varying between 3.7 and 16.4 million for the same period (Table 5.7, Figure 5.61.2). Abundance was highest in 2002 (145 mil total shrimp and 143 mil recruits) with smaller peaks in 2006 and 2010. Abundance declined to a low of less than 1-million shrimp in 2013 in both indices (0.6 and 0.4 mil, respectively), well below the time series medians of 11.1 mil shrimp (total stock) and 9.3 mil recruits. In 2017, abundance was again very low (1.5 mil and 0.9 recruits) (Table 5.7, Figure 5.61.2).

Fishing Mortality
Estimates of F (average F, weighted by numbers of shrimp, "N-weighted") from ASAP exhibited four phases over the time series. From 1985-2001, F fluctuated a relatively high level between 0.30 and 1.65 (mean = 0.81, median = 0.72) with a peak in 1995 (1.65), well above the time series mean of 0.58 (Table 5.7, Figure 5.61.1). Then, F was generally lower from 2002-2009 (range 0.11-0.53, median = 0.27), with a low of 0.11 in 2002. From 2010-2013 F was higher again (range 0.46-1.05, median 0.65), and in the last year of the commercial fishery (2013) F was 0.46. In the RSA years (2014-2017) F ranged 0.001-0.08 (median = 0.03), reflecting the harvest moratorium; terminal year F was 0.08 (Table 5.7). Estimates of F-multi for the one fleet modeled followed similar trends in F at a higher level through the time series (range 0.01-3.3, mean = 0.89, median = 0.66,) (Figure 5.61.1).

Retrospective Analysis
The retrospective analysis of the base case showed that the ASAP estimates were stable as years were removed from the model (average Mohn's rho=-0.05, Table 5.8, Figure 5.62). The analysis indicated a retrospective pattern of overestimating F (Mohn's rho = 0.52) and underestimating exploitable biomass (Mohn's rho =-0.62) and age 1 recruits (Mohn's rho =-0.12), while biases in SSB, Jan 1 biomass, and total stock abundance were near zero (Table 5.8). Terminal year estimates for each time series were not consistently above or below the corresponding 2017 estimate.

5.3.3 Sensitivity Analysis

Results of twelve sensitivity runs were compared to results from the base model (Table 5.8). Alternative scenarios evaluated sensitivity of model estimates based on assumed natural mortality (Scenarios B-G), design-based versus model-based survey indices (Scenario H), importance of survey indices (Scenario I-K), underreporting of commercial landings (Scenario L), and catch CV (Scenario M). All model scenarios trended similarly with respect to biomass, abundance, and F over the times series but differed in scale in some scenarios (Figures 5.63, Figure 5.64, and Figure 5.65).

Estimates of SSB were similar in scale and highest for runs with age-varying natural mortality scaled from a base M=0.5 (time-constant or scaled by PPI; BASE and Scenario B) and age-constant natural mortality of 0.95 (time-constant or scaled by PPI; Scenarios F and G) (Table 5.8, Figure 5.63). SSB estimates were generally lowest for runs with age-constant natural mortality scaled from a base of M=0.5 (time-constant or scaled by PPI, or PPI & temperature; Scenarios C, D, and E, respectively). When catch CV=0.05 (Scenario M) or design-based indices were applied (Scenario H) SSB slightly higher estimates of SSB were obtained, whereas slightly lower SSB was estimated when NEFSC fall surveys were removed from the base model (Scenarios I-K). all models indicated that SSB remained at record lows from 2013 to 2017 in the 33-year time series.

Oscillations in Age 1 recruitment over the time series generally aligned for all model scenarios with the highest recruitment peaks observed in 2002, 2006, and 2010, and the lowest values in recent years of 2012, 2013, 2015, and 2017 (Figure 5.64). In the base case, recruitment peaked in 2002 while for most other runs it was highest in 2006. The magnitude of recruitment was larger in the base model with respect to other natural mortality scenarios due to the overall higher natural mortality assumption for the base case (Table 4.2, Table 4.3, Figure 5.64). Recruitment estimates varied minimally with removal of survey indices, changes to catch, and a lower catch CV, as compared to the base run (Scenarios H-M; Table 5.8, Figure 5.64). The use of design-based indices resulted in lower recruit abundance in recent years (2013+) as compared results from the model-based indices (Scenario H vs all other runs; Table 5.8, Figure 5.64).

Fishing mortality (average F N-weighted) estimates derived from the base model trended higher in earlier years and lower in more recent years as compared to other sensitivity runs (Table 5.8, Figure 5.65). Age-constant but time-varying (scaled by PPI) natural mortality using a base M=0.5 generated the highest F estimates over the time series, while age-varying but time-constant (base M=0.05) generated the lowest F estimates over the time series (Figure 5.65). Terminal year F was highest in the sensitivity run applying design-based indices (Scenario H; Table 5.8, Figure 5.65). F estimates were more variable over the time series in response to the removal of survey indices for ASAP than was observed with sensitivity runs for the length-based model.

The comparison of runs with design-based versus model-based survey indices indicated that the fit to the model was significantly improved using model-based indices (Scenario H vs. all others, Table 5.8). The lack fit with design-based indices was driven in large part by a poor fit to the catch age-composition (Table 5.8).

Fishery independent indices were dropped from the model in Scenarios I-K, where the ASMFC summer shrimp survey was retained but the NEFSC fall survey indices (Albatross and Bigelow) were sequentially removed (Table 4.1). Results indicated a better fit to the model with the NEFSC surveys removal; however, there were little changes in trend or magnitude of outputs or stock status, indicating that the additional surveys do not generally conflict with summer survey information (Table 5.8, Figure 5.63, Figure 5.64, Figure 5.65).

Increasing the commercial catch in 1985-2000 by 25% (Scenario L) resulted in increased biomass and abundance outputs and slightly lower F in terminal year estimates (Table 5.8, Figure 5.63, Figure 5.64, Figure 5.65). However, 25% was applied only for demonstration as there is no information on the level of misreporting during this earlier time period.

For a sensitivity run to examine the influence of the assumed catch CV on the model, catch CV was held constant at 0.05, to reflect the catch CV applied in the CSA model (Scenario M, Table 4.1). Catch CV in the base run reflected the three selectivity blocks applied for the one commercial fleet; 0.3 in 1985-2000, 0.25 in 2001-2013, and 0.1 in 2014-2017. Model results were very similar to the base, although error (RMSE) for indices and catch was higher with the sensitivity run (Table 5.8, Figure 5.63, Figure 5.64). F estimates for the catch CV=0.05 run were generally lower than with other model runs (Figure 5.65).

5.4 Traffic Light/Data Poor Approach

5.4.1 Traffic Light Approach

Fishery independent indices of total biomass and spawning biomass have remained at historic lows for the past six years (2012–2017) (Table 5.9). Recruitment has been low to extremely poor for seven consecutive years and reached time series lows in 2013 and 2017 (Table 5.9). The index of early life survival has been variable in recent years (Table 5.9). Despite a very high survival index for the 2015 year class, suggesting that an unusually high proportion of the eggs produced in 2015 persisted to age 1.5 shrimp, recruitment of that year class was weak. The survival index of the 2016 year class was very low, as was its recruitment. The predation pressure index had decreased in recent years (2013–2015); however, increased to a time series high in 2017 (Table 5.9). In general, the predation pressure index has been high since the late 1990s. Water temperatures were at, or near, record highs in 2012, cooler in 2014 and 2015, and high again in 2016 and 2017 (Table 5.9). There were no fishery dependent indices for 2014-2017 due to a fishery moratorium (Table 5.9).

Summer survey model-based indices and total biomass indices have remained below the 20th percentile during 2012–2017, with those six values being the lowest estimates on record (Table 5.10). Similarly, spawning biomass and harvestable biomass indices have remained below the 20th percentile during 2012–2017, and are also the lowest estimates on record (Table 5.11). Total, spawning, and harvestable biomass indices in 2017 were the lowest observed in the 34 years of survey.

Recruitment was below the 20th percentile in 2012, 2013, 2015, and 2017, with the lowest recruitment on record observed in 2017 and second lowest in 2013 (Table 5.11). In 2013, 2015, and 2017, the abundance of recruits was less than three shrimp per tow, as compared to the SPM of 382 shrimp per tow. Early life survival (to age 1.5) was at or below the 20th percentile for the 2012 and 2016 year classes, with survival of the 2012 year class the lowest on record and 2011 the second lowest (Table 5.11). Early life survival of the 2013 and 2015 year classes was above the SPM, but recruitment of those year classes was weak. The survival index for the 2015 year class was the highest on record, possibly reflecting favorable temperatures during the larval period; however the reliability of survival estimations may be compromised at such low population levels. The 2013–2014 year classes would be the target of a 2018 fishery.

No commercial catch occurred in 2014, 2015, 2016, or 2017 due to a harvest moratorium. In 2013, the last year prior to the moratorium, the catch rate was below the 20th percentile and a record low for the time series (Table 5.11).

Trends in the four environmental indicators suggest that conditions have not been favorable for northern shrimp in recent years (Table 5.12). Predation pressure has generally increased since the late 1990s. During 2010-2012, the PPI was above the 80th percentile; however during 2013-2015 it fluctuated around a lower level (Table 5.12). In 2016, predation pressure jumped to a time series high, attributable to an increased biomass index of spiny dogfish (*Squalus acanthias*) (unpub. data, NEFSC 2017). Sea surface and bottom temperatures were colder in 2015 than in prior years; however, temperatures in 2016 and 2017 warmed to around the 80th percentile of the time series. An overall rise in water temperature since the stable period is evident, with spring anomalies and summer bottom temperatures in offshore shrimp habitat at, or exceeding, the 80th percentile from 2011 to 2013, and again in 2016 (Table 5.12).

Taken together, the FTLA indicators demonstrate that the Gulf of Maine northern shrimp stock status continues to be very poor (Figures 5.66 – 5.76). Total biomass, spawning biomass and harvestable biomass have remained at unprecedented lows for six consecutive years (Figures 5.66 – 5.68). Recruitment of the 2011, 2012, 2014, and 2016 year classes were the weakest observed in the 34-year time series, although recruitment of the 2015 year class was marginally higher (Figure 5.69). The stock remains in a depleted condition. Protection of the 2013 and 2015 year classes may provide a foundation for stock recovery if these year classes survive to spawn successfully.

Accepted definitions of stock collapse include a population at 10% of un-fished biomass (Worm et al. 2009) or at 20% of B_{MSY} (Pinsky et al. 2011). Using summer survey biomass indices and the 1984–1993 "stable period" survey mean as a highly conservative proxy for un-fished biomass, the Gulf of Maine northern shrimp stock was considered collapsed during 2012 – 2015, slightly above this threshold in 2016, and collapsed in 2017. Using the stable period mean as a proxy for B_{MSY} instead (likely a more reasonable assumption), the stock has remained in a collapsed state since 2012.

5.4.2 Data Poor Quota Calculation

In 2017, 53 mt of quota was allocated for the winter sampling program, of which 32.6 mt was caught. The slope of the log of the exploitable biomass index from the ASMFC summer survey over the last three years was negative (Figure 5.77). The three data poor quota methods recommended a reduction in harvest relative to 2017 levels (Table 5.13). The average quota recommendation for the 2018 fishing season was 26.5 mt.

5.5 Model Comparisons

Comparing the output of the CSA, ASAP, and UME models is somewhat difficult, because all three models are structured differently, so quantities like recruitment, biomass, and F are not directly comparable.

Recruitment is the most different across the models (Figure 5.78). The CSA model defines recruits as individuals that will recruit to the fishery in that year; for northern shrimp, this represents individuals in the 16-22 mm range. ASAP defines recruitment as the number of age-1 shrimp in the population; the average size of age-1 shrimp in the summer survey is ~16 mm carapace length. The UME model defines recruitment as the number of shrimp in the 10-12 mm size bins that enter the population every year. The ASAP and UME models have much higher estimates of recruitment than the CSA model, which is reasonable, because the CSA model defines recruitment as an older component of the stock. In addition, the ASAP and UME models use an age/size-varying estimate of M with recruits experiencing the highest levels of M, while the CSA assumes recruits and post-recruits experience the same M. ASAP estimates of recruitment are higher than UME estimates, but of the same magnitude, and both models identify the same strong and weak year classes. All three models indicate recruitment has declined since 2010, and that several of the recent year classes have been very weak.

Total abundance for all three models is weighted towards recruitment, so differences in recruitment patterns and recruitment magnitude are also present in the total abundance differences. All three models use a slightly different time step as well: the CSA starts in August and uses an annual time step; the ASAP model starts in December and uses an annual time step; the UME model starts in December and uses a seasonal time step. As a result, the ASAP estimates of total abundance are most directly comparable to the Dec. 1 abundance estimates from the UME; they show very similar patterns and magnitudes, although the ASAP estimates are slightly higher (Figure 5.79). The CSA estimates of total abundance (recruits and post-recruits) are most comparable to the season 2 estimates of total abundance for shrimp greater than 16 mm in length from the UME model. The UME and CSA estimates of total summer abundance are similar in magnitude, and show generally similar trends (Figure 5.79). All three models show highs in abundance in 2006/2007 and 2010, followed by declines to low levels in recent years (with the exception of 2016, where the ASAP and the UME models showed higher abundance in the winter due to a relatively good year class).

Spawning stock biomass is calculated slightly differently between the ASAP and the UME model; the CSA does not calculate SSB. ASAP uses an age-based maturity curve where all three and four year old shrimp are assumed mature; the UME model uses the proportion female at length from the summer survey to calculate SSB. For the CSA model, exploitable biomass is a reasonable proxy for SSB, as the fishery primarily targets the spawning females, although it does include some males. CSA estimates of exploitable biomass and ASAP estimates of SSB are similar in terms of both trend and magnitude; the UME estimates of SSB are lower over the time-series (Figure 5.80). This may be a result of the differences in the maturity curve (shifted further to the right than the ASAP curve) and the time-step, which decrements the population due to both fishing and natural mortality before calculating SSB for that year. However, the trend is similar across all three models, with peaks in 1996, 2007, and declines to low levels since 2010.

Fishing mortality is estimated differently across the models as well. The CSA estimates a single annual F for recruits and post-recruits, while the ASAP and UME models estimate an annual or seasonal full F that is applied to each age or size class via a selectivity curve. To make the estimates of annual F more comparable across the models, an N-weighted average F is calculated for the ASAP and UME models. F is averaged over ages 3 and 4 for the ASAP model and for shrimp greater than 22mm carapace length in the UME model. All three models showed similar patterns in F, but the CSA was generally the lowest across the time series; the UME model was closer to the CSA estimates prior to 2000, and closer to the ASAP estimates after that (Figure 5.81). All three models estimate F to be at time-series lows since the moratorium was implemented in 2014.

Overall, the three models estimated similar patterns in F, abundance, and biomass, and were of approximately the same magnitude, although differences in model structure make direct comparisons complicated. All models agreed that the population has declined to low levels since 2010, and that recruitment in 6 of the last 7 years has been well below average. Despite low levels of F since 2014, abundance and SSB have not increased.

6 REFERENCE POINTS AND STOCK STATUS

6.1 Reference Points

Prior to the 2014 benchmark assessment, northern shrimp management used historical proxies to establish F targets and thresholds. Earlier efforts to develop model-based reference points resulted in values that were not consistent with estimates of F derived from the CSA model and suggested the stock could sustain levels of F and harvest much higher than had been estimated by the CSA model. In addition, uncertainty about natural mortality and the spawner-recruit relationship made model-based reference points and quota calculations less reliable. The historical proxy was chosen in part because the allowable catch and stock status determinations were not sensitive to assumptions about M.

The F_{target} was defined as the average F estimated by the CSA model during a period in the fishery when biomass and landings were considered stable (1985-1994). The $F_{threshold}$ was the maximum F estimated during this time period. The NSTC would use the target and threshold values to recommend a target catch level (TAC) for the fishery in the upcoming season.

The stock biomass threshold of $B_{Threshold}$ = 9,000 mt (19.8 million lbs) and limit of B_{Limit} = 6,000 mt (13.2 million lbs) were based on historical abundance estimates and response to fishing pressure.

However, this approach may no longer be appropriate for northern shrimp in the Gulf of Maine. There is strong evidence that recruitment strength is driven by both spawning stock size and environmental conditions, particularly temperature (Richards et al. 2012). Unfortunately, environmental conditions in the Gulf of Maine are currently in flux. Model-based reference points that assume equilibrium conditions and historical reference points calculated from a different temperature regime may not be appropriate for the future dynamics of this stock. As temperatures in the Gulf of Maine continue to rise, levels of F and biomass that were sustainable in the past may become unsustainable as the productivity of the stock declines.

The NSTC chose a projection-based approach to establishing reference points for this assessment. A length-based projection model in R was developed to project the population forward under various scenarios about recruitment, M, and F. The projection was repeated 1,000 times with stochastic draws of recruitment, initial abundance-at-size for non-recruits, and fishery selectivity parameters.

Recruitment was drawn from a log-normal distribution with a mean equal to recruitment from 2013-2017 (Figure 6.1). As a sensitivity analysis, a run was also conducted with recruitment drawn from a log-normal distribution with a mean equal to the time-series average of recruitment (Figure 6.1). Abundance-at-size for non-recruits in the first year of the projection (2018) was calculated by the UME model by applying season 2 M in 2017 to the 2017 season 2 abundance (F is zero during season 2); the mean and standard deviation of those estimates were used to create draws of initial abundance-at-size for non-recruits in the projections. The fishery selectivity parameters were drawn from the mean and standard deviation of the model-estimated selectivity parameters in the most recent selectivity block for the trap and trawl fisheries.

The population was projected forward under no F for 50 years to see where the population would stabilize under different conditions. This was done with an M equal to the time-series average, and with an M equal to the average of the last 5 years (Figure 6.2).

To develop catch recommendations, the population was projected forward 3 years, and the probability that SSB was above 2017 SSB was calculated. The allocation of F between the trap and trawl fisheries was set using the ratio catch for each fleet over the last 3 years of the open fishery (2011-2013); trap catch was 12% of trawl catch over that time period.

The assumptions about M and recruitment had the largest effects on the projection trajectories under no fishing (Figure 6.3). Projections conducted with M equal to the time series mean and recruitment drawn from the 2011-2017 mean indicated the population would grow under no fishing pressure and SSB would stabilize around 2,039 mt, less than the “stable period” mean (1985-1994) of 4,162 mt, but more than double the 2017 estimate of 709 mt. Using the time-series mean of recruitment resulted in an estimate of long-term SSB roughly equal to the “stable period” mean, at 4,142 mt. However, under higher natural mortality scenarios, with M equal to the average of the last five years, the population declined even under no fishing. Under recent recruitment, SSB stabilized at 384 mt, nearly half 2017 levels. Under time series average recruitment, SSB stabilized at 785 mt.

With short term projections, the M and recruitment scenarios had an impact on the effect of different F levels (Figure 6.4). For the high, recent M scenarios, even low levels of harvest (F=0 or F=status quo) caused a decline in SSB, regardless of the recruitment scenario. For the time-series average M scenarios, higher levels of harvest caused the population to decline from 2018 to 2019, but most harvest scenarios had a greater than 50% chance of being above SSB_{2017} in 2020 (Figure 6.4, Figure 6.5).

Under the recent recruitment/time-series average M scenario, an F rate of 0.22 for the trawl fleet and 0.09 for the trap fleet would result in an SSB in 2020 that has a 50% chance of being above the 2017 estimate of SSB (Figure 6.5, Table 6.1). This is equivalent to a quota of ~40mt for the trap fishery and 135 mt for the trawl fishery. Under the recent recruitment/recent, high M scenario, that same F rate results in an SSB with zero percent chance of being above SSB_{2017} (Figure 6.5, Table 6.2).

6.2 Stock Status

Overall, the northern shrimp stock in the Gulf of Maine is depleted relative to the stable period mean. Low recruitment and high natural mortality hinder stock recovery. Projections suggest the stock could recover to moderate levels under current recruitment levels, but not if natural mortality remains high. If M continues to increase, the likelihood of recovery is extremely low, even in the absence of fishing, although fishing would hasten the decline.

7 RESEARCH RECOMMENDATIONS AND TIMING OF NEXT ASSESSMENTS

The TC recommends the following research priorities to improve the sampling, modeling, and biological understanding of the northern shrimp species.

Fishery-Dependent Priorities

- Evaluate selectivity of shrimp by traps and trawls *(high priority, short term)*
- Continue sampling of the northern shrimp commercial fishery, including port, sea, and RSA sampling to confirm, and if necessary update, the length-frequency of the species and identify any bycatch in the fishery *(high priority, long term)*
- Conduct a study comparing the effectiveness of the compound grate versus the double-Nordmore grate *(moderate priority, short term)*

Fishery-Independent Priorities

- Continuing sampling through summer shrimp survey despite the current low abundance of shrimp and the closure of the shrimp fishery in 2013 *(high priority, long term)*
- Explore ways to sample age 1 and younger shrimp *(moderate priority, short term)*

Modeling/Quantitative Priorities

- Continue research to refine annual estimates of consumption by predators, and include in models as appropriate *(high priority, short term)*
- Investigate growth parameters for the UME length-based model and the feasibility of adding a spatial-temporal structure to the model framework *(moderate priority, long term)*

Life History, Biological, and Habitat Priorities

- Investigate application of newly developed direct ageing methods to ground truth assumed ages based on size and stage compositions *(high priority, long term)*
- Evaluate larval and adult survival and growth, including frequency of molting and variation in growth rates, as a function of environmental factors and population density *(high priority, long term)*
- Study the effects of oceanographic and climatic variation (i.e., North Atlantic Oscillation) on the cold water refuges for shrimp in the Gulf of Maine *(high priority, long term)*
- Explore the mechanisms behind the stock-recruitment and temperature relationship for Gulf of Maine northern shrimp *(high priority, long term)*

Timing of Assessment Updates and Next Benchmark Assessment

The NSTC recommends that the assessment be updated annually to incorporate the most up-to-date data on abundance and recruitment into management recommendations. A benchmark assessment should be considered in five years if improvements in the length-based model or significant changes in the population warrant it.

8 REFERENCES

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9 TABLES

Table 2.1 U.S. commercial landings (mt) of northern shrimp in the Gulf of Maine, by year (1958–1984, left) or by season (1985–2017, right). Landings by season include the previous December. Massachusetts landings are combined with New Hampshire landings in 2009 to preserve confidentiality. Landings in 2014 are from Maine cooperative sampling trip catches. Landings in 2015–2017 are from RSA catches.

Year	Maine	Mass.	New Hamp.	Total
1958	2.2	0.0	0.0	2.2
1959	5.5	2.3	0.0	7.8
1960	40.4	0.5	0.0	40.9
1961	30.5	0.3	0.0	30.8
1962	159.5	16.2	0.0	175.7
1963	244.3	10.4	0.0	254.7
1964	419.4	3.1	0.0	422.5
1965	941.3	8.0	0.0	949.3
1966	1,737.8	10.5	18.1	1,766.4
1967	3,141.2	10.0	20.0	3,171.2
1968	6,515.2	51.9	43.1	6,610.2
1969	10,993.1	1,773.1	58.1	12,824.3
1970	7,712.8	2,902.3	54.4	10,669.5
1971	8,354.8	2,724.0	50.8	11,129.6
1972	7,515.6	3,504.6	74.8	11,095.0
1973	5,476.6	3,868.2	59.9	9,404.7
1974	4,430.7	3,477.3	36.7	7,944.7
1975	3,177.2	2,080.0	29.4	5,286.6
1976	617.3	397.8	7.3	1,022.4
1977	142.1	236.9	2.2	381.2
1978	0.0	3.3	0.0	3.3
1979	32.8	405.9	0.0	438.7
1980	69.6	256.9	6.3	332.8
1981	530.0	539.4	4.5	1,073.9
1982	883.0	658.5	32.8	1,574.3
1983	1,029.2	508.2	36.5	1,573.9
1984	2,564.7	565.4	96.8	3,226.9

Season	Maine	Mass.	New Hamp.	Total
1985	2,946.4	968.8	216.7	4,131.9
1986	3,268.2	1,136.3	230.5	4,635.0
1987	3,680.2	1,427.9	157.9	5,266.0
1988	2,258.4	619.6	157.6	3,035.6
1989	2,384.0	699.9	231.5	3,315.4
1990	3,236.3	974.9	451.3	4,662.5
1991	2,488.6	814.6	282.1	3,585.3
1992	3,070.6	289.3	100.1	3,460.0
1993	1,492.5	292.8	357.6	2,142.9
1994	2,239.7	247.5	428.0	2,915.2
1995	5,013.7	670.1	772.8	6,456.6
1996	8,107.1	660.6	771.7	9,539.4
1997	6,086.9	366.4	666.2	7,119.5
1998	3,481.3	240.3	445.2	4,166.8
1999	1,573.2	75.7	217.0	1,865.9
2000	2,516.2	124.1	214.7	2,855.0
2001	1,075.2	49.4	206.4	1,331.0
2002	391.6	8.1	53.0	452.7
2003	1,203.7	27.7	113.0	1,344.4
2004	1,926.9	21.3	183.2	2,131.4
2005	2,270.2	49.6	290.3	2,610.1
2006	2,201.6	30.0	91.1	2,322.7
2007	4,469.3	27.5	382.9	4,879.7
2008	4,515.8	29.9	416.8	4,962.4
2009	2,315.7	MA & NH: 185.6		2,501.2
2010	5,721.4	35.1	506.8	6,263.3
2011	5,569.7	196.4	631.5	6,397.5
2012	2,219.9	77.8	187.8	2,485.4
2013	289.7	18.9	36.9	345.5
2014	0.3	0.0	0.0	0.3
2015	6.1	0.6	0.0	6.7
2016	11.5	0.0	1.8	13.3
2017	31.2	0.9	0.5	32.6

Table 2.2 Price per pound and value of U.S. commercial landings of northern shrimp in the Gulf of Maine, with inflation adjusted prices and value for 1985–2017. No shrimp were sold or purchased from cooperative winter sampling in 2014. 2015–2017 prices and value are from the RSA program.

Year	Price $/Lb	Value $
1958	0.32	1,532
1959	0.29	5,002
1960	0.23	20,714
1961	0.20	13,754
1962	0.15	57,382
1963	0.12	66,840
1964	0.12	112,528
1965	0.12	245,469
1966	0.14	549,466
1967	0.12	871,924
1968	0.11	1,611,425
1969	0.12	3,478,910
1970	0.20	4,697,418
1971	0.19	4,653,202
1972	0.19	4,586,484
1973	0.27	5,657,347
1974	0.32	5,577,465
1975	0.26	3,062,721
1976	0.34	764,094
1977	0.55	458,198
1978	0.24	1,758
1979	0.33	320,361
1980	0.65	478,883
1981	0.64	1,516,521
1982	0.60	2,079,109
1983	0.67	2,312,073
1984	0.49	3,474,351

Season	Price $/Lb	Value $	Price ($/Lb) 2017 dollars	Value ($) 2017 dollars
1985	0.44	3,984,562	1.01	9,200,373
1986	0.63	6,451,206	1.40	14,305,796
1987	1.10	12,740,581	2.40	27,862,903
1988	1.10	7,391,777	2.31	15,459,334
1989	0.98	7,177,659	1.96	14,326,043
1990	0.72	7,351,420	1.37	14,082,303
1991	0.91	7,208,838	1.64	12,962,943
1992	0.99	7,547,941	1.74	13,272,710
1993	1.07	5,038,053	1.82	8,598,200
1994	0.75	4,829,106	1.25	8,033,645
1995	0.90	12,828,030	1.45	20,639,831
1996	0.73	15,341,504	1.15	24,185,394
1997	0.79	12,355,871	1.21	18,991,931
1998	0.96	8,811,938	1.44	13,228,159
1999	0.91	3,762,043	1.35	5,553,367
2000	0.79	4,968,655	1.13	7,112,453
2001	0.86	2,534,095	1.19	3,491,878
2002	1.08	1,077,534	1.48	1,476,975
2003	0.87	2,590,916	1.16	3,438,133
2004	0.44	2,089,636	0.58	2,725,359
2005	0.57	3,261,648	0.72	4,143,134
2006	0.37	1,885,978	0.45	2,304,275
2007	0.38	4,087,120	0.45	4,841,053
2008	0.49	5,407,373	0.56	6,126,491
2009	0.40	2,216,411	0.46	2,536,578
2010	0.52	7,133,718	0.58	8,008,822
2011	0.75	10,625,533	0.83	11,706,442
2012	0.95	5,230,481	1.02	5,589,023
2013	1.81	1,375,788	1.90	1,447,246
2014		0		0
2015	3.49	51,282	3.62	53,240
2016	6.67	195,925	6.85	201,133
2017	6.30	452,379	6.30	452,379

* Inflation adjustment from US Dept. of Labor, Bureau of Labor Statistics, at http://www.bls.gov/data/inflation_calculator.htm accessed Oct. 20, 2017.

Table 2.3 Distribution of landings (metric tons) in the Gulf of Maine northern shrimp fishery by season, state and month.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
1985 Season, 166 days, Dec 1 - May 15								
Maine	335.7	851.8	1,095.5	525.1	116.8	21.5	0.0	2,946.4
Mass.	91.7	283.9	238.3	239.3	57.8	57.0	0.8	968.8
N.H.	67.0	86.2	50.4	11.6	1.3		0.2	216.7
Total	494.4	1,221.9	1,384.2	776.0	175.9	78.5	1.0	4,131.9
1986 Season, 196 days, Dec 1 - May 31, June 8-21								
Maine	346.9	747.8	1,405.3	415.4	104.2	149.2	99.4	3,268.2
Mass.	154.3	213.4	221.2	200.7	111.2	84.8	150.7	1,136.3
N.H.	57.7	75.9	70.8	14.2	1.3	0.0	10.6	230.5
Total	558.9	1,037.1	1,697.3	630.3	216.7	234.0	260.7	4,635.0
1987 Season, 182 days, Dec 1 - May 31								
Maine	485.9	906.2	1,192.7	672.9	287.6	127.9	7.0	3,680.2
Mass.	103.5	260.0	384.9	310.2	180.8	182.8	5.7	1,427.9
N.H.	18.4	53.6	62.8	15.7	7.3	0.0	0.1	157.9
Total	607.8	1,219.8	1,640.4	998.8	475.7	310.7	12.8	5,266.0
1988 Season, 183 days, Dec 1 - May 31								
Maine	339.7	793.9	788.1	243.6	24.6	67.3	1.2	2,258.4
Mass.	14.4	225.8	255.0	104.9	8.6	10.9	0.0	619.6
N.H.	13.0	72.6	53.7	14.9	0.3	0.0	3.1	157.6
Total	367.1	1,092.3	1,096.8	363.4	33.5	78.2	4.3	3,035.6
1989 Season, 182 days, Dec 1 - May 31								
Maine	353.6	770.5	700.6	246.4	218.7	94.2		2,384.0
Mass.	26.2	197.5	154.9	104.8	160.9	55.6		699.9
N.H.	28.5	106.9	77.0	15.4	3.7	0.0		231.5
Total	408.3	1,074.9	932.5	366.6	383.3	149.8	0.0	3,315.4
1990 Season, 182 days, Dec 1 - May 31								
Maine	512.4	778.4	509.8	638.7	514.1	282.8	0.1	3,236.3
Mass.	75.6	344.5	184.8	100.2	159.0	110.0	0.8	974.9
N.H.	111.3	191.7	116.2	30.7	1.4			451.3
Total	699.3	1,314.6	810.8	769.6	674.5	392.8	0.9	4,662.5
1991 Season, 182 days, Dec 1 - May 31								
Maine	238.3	509.2	884.1	455.0	251.8	148.2	2.0	2,488.6
Mass.	90.6	174.7	176.0	131.2	93.3	133.8	15.0	814.6
N.H.	107.3	104.4	33.8	27.8	7.8	1.0		282.1
Total	436.2	788.3	1,093.9	614.0	352.9	283.0	17.0	3,585.3
1992 Season, 153 days, Dec 15 - May 15								
Maine	181.2	881.0	1,295.0	462.6	163.6	87.2		3,070.6
Mass.	17.1	148.3	73.3	47.6	2.9		0.1	289.3
N.H.	33.4	47.0	11.9	6.8	1.0			100.1
Total	231.7	1,076.3	1,380.2	517.0	167.5	87.2	0.1	3,460.0

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
1993 Season, 138 days, Dec 14 - April 30								
Maine	101.0	369.1	597.1	297.5	127.8			1,492.5
Mass.	19.6	82.0	81.9	62.3	42.0	5.0		292.8
N.H.	33.5	85.4	101.8	77.0	59.9			357.6
Total	154.1	536.5	780.8	436.8	229.7	5.0	0.0	2,142.9
1994 Season, 122 days, Dec 15 - Apr 15								
Maine	171.5	647.8	972.1	399.6	48.7			2,239.7
Mass.	27.1	68.0	100.8	38.8	12.8			247.5
N.H.	117.2	124.3	128.7	49.6	8.2			428.0
Total	315.8	840.1	1,201.6	488.0	69.7	0.0	0.0	2,915.2
1995 Season, 128 days, Dec 1 - Apr 30, 1 day per week off								
Maine	747.3	1,392.9	1,336.0	912.1	625.4			5,013.7
Mass.	160.6	154.0	104.1	111.0	139.5		0.9	670.1
N.H.	210.2	186.8	118.3	158.5	99.0			772.8
Total	1,118.1	1,733.7	1,558.4	1,181.6	863.9	0.0	0.9	6,456.6
1996 Season, 152 days, Dec 1- May 31, 1 day per week off								
Maine	1,122.0	1,693.1	3,236.9	795.6	361.5	897.6	0.4	8,107.1
Mass.	167.9	106.7	190.7	67.2	66.5	60.3	1.3	660.6
N.H.	189.8	169.5	234.0	81.9	78.8	17.1	0.6	771.7
Total	1,479.7	1,969.3	3,661.6	944.7	506.8	975.0	2.3	9,539.4
1997 Season, 156 days, Dec 1- May 27, two 5-day and four 4-day blocks off								
Maine	1,178.0	1,095.8	1,749.3	758.4	766.8	538.2	0.4	6,086.9
Mass.	90.2	110.4	111.4	49.0	1.2	0.5	3.7	366.4
N.H.	185.6	104.1	140.1	108.4	85.8	42.2	0.0	666.2
Total	1,453.8	1,310.3	2,000.8	915.8	853.8	580.9	4.1	7,119.5
1998 Season, 105 days, Dec 8-May 22, weekends off except Mar 14-15, Dec 25-31 and Mar 16-31 c								
Maine	511.1	926.8	1,211.1	401.0	228.7	202.6		3,481.3
Mass.	49.1	73.3	88.6	14.0	15.3			240.3
N.H.	89.4	106.9	143.5	54.3	49.0	2.1		445.2
Total	649.6	1,107.0	1,443.2	469.3	293.0	204.7	0.0	4,166.8
1999 Season, 90 days, Dec 15 - May 25, weekends, Dec 24 - Jan 3, Jan 27-31, Feb 24-28, Mar 16-31, and Apr 29 - May 2								
Maine	79.9	192.7	599.3	247.9	205.3	248.1		1,573.2
Mass.	25.0	23.8	16.0	2.5	8.4			75.7
N.H.	46.5	63.2	52.2	10.0	36.5	8.6		217.0
Total	151.4	279.7	667.5	260.4	250.2	256.7	0.0	1,865.9
2000 Season, 51 days, Jan 17 - Mar 15, Sundays off								
Maine		759.9	1,534.4	221.9				2,516.2
Mass.		25.9	86.0	12.2				124.1
N.H.		40.6	133.7	40.4				214.7
Total	0.0	826.4	1,754.0	274.6	0.0	0.0	0.0	2,855.0

Table 2.3 continued Landings (mt) by season, state, and month. Landings in 2014 are from Maine cooperative sampling trip catches. Landings in 2015–2016 are from RSA catches.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
2001 Season, 83 days, Jan 9 - Apr 30, Mar 18 - Apr 16 off, experimental offshore fishery in May								
Maine		575.8	432.8	36.6	29.8	0.3		1,075.2
Mass.		38.5	9.0	1.9		0.002		49.4
N.H.		127.9	78.6	conf	conf			206.4
Total	0.0	742.2	520.3	38.4	29.8	0.3	0.0	1,331.0
2002 Season, 25 days, Feb 15 - Mar 11								
Maine			306.8	84.8				391.6
Mass.			8.1	conf				8.1
N.H.			38.6	14.4				53.0
Total	0.0	0.0	353.5	99.1	0.0	0.0	0.0	452.7
2003 Season, 38 days, Jan 15 - Feb 27, Fridays off								
Maine		534.7	668.0	0.4			0.6	1,203.7
Mass.		12.0	15.7					27.7
N.H.		30.9	82.1					113.0
Total	0.0	577.6	765.8	0.4	0.0	0.0	0.6	1,344.4
2004 Season, 40 days, Jan 19 - Mar 12, Saturdays and Sundays off								
Maine	1.8	526.2	945.1	446.4	4.7	2.7	0.04	1,926.9
Mass.		conf	21.3	conf				21.3
N.H.		27.3	94.8	61.1				183.2
Total	1.8	553.5	1,061.1	507.5	4.7	2.7	0.04	2,131.4
2005 Season, 70 days, Dec 19 - 30, Fri-Sat off, Jan 3 - Mar 25, Sat-Sun off								
Maine	75.0	377.9	894.7	922.6			0.01	2,270.2
Mass.	7.2	8.1	24.9	9.4				49.6
N.H.	17.3	53.5	175.4	44.1				290.3
Total	99.5	439.5	1,095.0	976.0	0.0	0.0	0.01	2,610.1
2006 Season, 140 days, Dec 12 - Apr 30								
Maine	144.2	691.6	896.9	350.8	118.0			2,201.6
Mass.	conf	conf	30.0	conf	conf			30.0
N.H.	3.4	27.9	9.6	50.3	conf			91.1
Total	147.6	719.5	936.5	401.1	118.0	0.0	0.0	2,322.7
2007 Season, 151 days, Dec 1 - Apr 30								
Maine	761.9	1,480.5	1,590.4	481.9	154.2	0.4	0.03	4,469.3
Mass.	conf	27.5	conf	conf				27.5
N.H.	52.5	222.6	81.6	26.1	conf			382.9
Total	814.4	1,730.6	1,672.0	508.1	154.2	0.4	0.03	4,879.7
2008 Season, 152 days, Dec 1 - Apr 30								
Maine	408.6	1,053.6	2,020.4	983.8	49.3		0.1	4,515.8
Mass.	conf	conf	15.4	14.5				29.9
N.H.	94.2	123.7	161.6	37.4	conf			416.8
Total	502.7	1,177.3	2,197.3	1,035.7	49.3	0.0	0.1	4,962.4

conf = Confidential data were combined with an adjacent month.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
2009 Season, 180 days, Dec 1 - May 29								
Maine	134.6	595.9	988.2	560.1	34.9	1.8	0.2	2,315.7
Mass.& NH	conf	112.9	72.6	conf	conf			185.6
Total	134.6	708.8	1,060.8	560.1	34.9	1.8	0.2	2,501.2
2010 Season, 156 days, Dec 1 - May 5								
Maine	264.1	1,689.2	2,956.0	524.3	254.4	33.0	0.4	5,721.44
Mass.	conf	16.9	18.2	conf	conf			35.1
N.H.	112.8	152.4	200.0	14.2	27.4	conf		506.8
Total	376.9	1,858.6	3,174.2	538.5	281.8	33.0	0.4	6,263.3
2011 Season, 90 days, Dec 1 - Feb 28								
Maine	722.7	2,572.2	2,274.3	0.5				5,569.7
Mass.	20.8	100.9	74.7					196.4
N.H.	93.1	304.0	234.4					631.46
Total	836.6	2,977.0	2,583.4	0.5	0.0	0.0	0.0	6,397.5
2012 Season, Trawling Mon,Wed,Fri, Jan 2- Feb 17 (21 days); Trapping Feb 1-17 (17 days)								
Maine	0.5	1,130.6	1,088.2	0.5				2,219.9
Mass.		58.4	19.4					77.8
N.H.		119.2	68.6					187.8
Total	0.5	1,308.2	1,176.2	0.5	0.0	0.0	0.0	2,485.4
2013 Season, Trawling 3 to 7 days/wk, Jan 23 - Apr 12 (54 days); Trapping 6 or 7 days/wk, Feb 5 - Apr 12 (62 days								
Maine		64.9	179.7	42.5	2.6			289.7
Mass.		5.3	8.9	4.7				18.9
N.H.		13.8	16.3	6.9	conf			36.9
Total	0.0	84.0	204.9	54.1	2.6	0.0	0.0	345.5
2014 Season Closed, 5 Maine trawl trips made to collect samples								
Maine		0.05	0.13	0.08				0.3
Mass.								0.0
N.H.								0.0
Total	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.3
2015 Season, Limited research fishery for data collection only								
Maine		0.2	3.7	2.3				6.1
Mass.		0.1	0.1	0.3				0.6
N.H.		0.0	0.0	0.0				0.0
Total	0.0	0.3	3.8	2.6	0.0	0.0	0.0	6.7
2016 Season, Limited research fishery for data collection only								
Maine		1.5	3.7	6.3	0.01			11.5
Mass.								0.0
N.H.		0.4	1.2	0.3				1.8
Total	0.0	1.9	4.9	6.5	0.01	0.0	0.0	13.3

2014-2017 research fishery data include some discards.

Table 2.3 continued Landings (mt) by season, state, and month. Landings in 2017 are from RSA catches.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
2017 Season, Limited research fishery for data collection only								
Maine		4.8	19.2	7.2				31.2
Mass.		0.4	0.4	0.0				0.9
N.H.		0.2	0.3	0.0				0.5
Total	0.0	5.4	19.9	7.2	0.0	0.0	0.0	32.6

2014-2017 research fishery data include some discards.

Table 2.4 Distribution of landings (metric tons) in the Maine northern shrimp fishery by season, gear type, and month. Landings in 2014 are from Maine cooperative sampling trip catches. Landings in 2015–2017 are from RSA catches.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total	% of total
2000 Season, 51 days, Jan 17 - Mar 15, Sundays off									
Trawl		731.1	1,354.8	163.6				2,249.47	89%
Trap		28.9	179.6	58.3				266.7	11%
Total	0.0	759.9	1,534.4	221.9	0.0	0.0	0.0	2,516.2	
2001 Season, 83 days, Jan 9 - Apr 30, Mar 18 - Apr 16 off, experimental offshore fishery in May									
Trawl		533.0	360.1	30.9	29.8	0.3		954.0	89%
Trap		42.9	72.6	5.7				121.2	11%
Total	0.0	575.8	432.8	36.6	29.8	0.3	0.0	1,075.2	
2002 Season, 25 days, Feb 15 - Mar 1									
Trawl			263.6	77.2				340.8	87%
Trap			43.2	7.6				50.8	13%
Total	0.0	0.0	306.8	84.8	0.0	0.0	0.0	391.6	
2003 Season, 38 days, Jan 15 - Feb 27, Fridays off									
Trawl		467.2	518.8	0.4			0.6	987.0	82%
Trap		67.5	149.2					216.7	18%
Total	0.0	534.7	668.0	0.4	0.0	0.0	0.6	1,203.7	
2004 Season, 40 days, Jan 19 - Mar 12, Saturdays and Sundays off									
Trawl	1.8	514.0	905.5	430.0	4.7	2.7	0.04	1858.7	96%
Trap		12.2	39.5	16.5				68.1	4%
Total	1.8	526.2	945.1	446.4	4.7	2.7	0.04	1926.9	
2005 Season, 70 days, Dec 19 - 30, Fri-Sat off, Jan 3 - Mar 25, Sat-Sun off									
Trawl	75.0	377.9	770.6	663.6			0.01	1887.1	83%
Trap		conf	124.0	259.0				383.1	17%
Total	75.0	377.9	894.7	922.6	0.0	0.0	0.01	2270.2	
2006 Season, 140 days, Dec 12 - Apr 30									
Trawl	144.2	675.0	733.8	256.9	118.0			1928.0	88%
Trap	conf	16.6	163.1	93.9	conf			273.6	12%
Total	144.2	691.6	896.9	350.8	118.0	0.0	0.0	2201.6	
2007 Season, 151 days, Dec 1 - Apr 30									
Trawl	761.9	1,443.3	1,275.6	362.1	143.6	0.4	0.0	3,986.9	89%
Trap	conf	37.2	314.7	119.8	10.6			482.4	11%
Total	761.9	1,480.5	1,590.4	481.9	154.2	0.4	0.0	4,469.3	
2008 Season, 152 days, Dec 1 - Apr 3									
Trawl	408.6	989.6	1,680.8	603.4	42.6		0.1	3,725.0	82%
Trap	conf	64.0	339.6	380.4	6.7			790.7	18%
Total	408.6	1,053.6	2,020.4	983.8	49.3	0.0	0.1	4,515.8	

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total	% of total
2009 Season, 180 days, Dec 1 - May 29									
Trawl	134.6	579.7	780.9	405.4	33.6	1.8	0.2	1,936.3	84%
Trap	conf	16.2	207.3	154.7	1.3			379.4	16%
Total	134.6	595.9	988.2	560.1	34.9	1.8	0.2	2,315.7	
2010 Season, 156 days, Dec 1 - May 5									
Trawl	264.1	1,495.2	2,132.6	338.3	254.4	33.0	0.4	4,517.9	79%
Trap	conf	194.1	823.4	186.0	conf			1,203.5	21%
Total	264.1	1,689.2	2,956.0	524.3	254.4	33.0	0.4	5,721.4	
2011 Season, 90 days, Dec 1 - Feb 28									
Trawl	720.8	2,194.5	1,728.5	0.5				4,644.4	83%
Trap	1.9	377.7	545.8					925.3	17%
Total	722.7	2,572.2	2,274.3	0.5	0.0	0.0	0.0	5,569.7	
2012 Season, Trawling Mon,Wed,Fri, Jan 2- Feb 17 (21 days); Trapping Feb 1-17 (17 days)									
Trawl	0.5	1,130.6	895.2	0.5				2,026.8	91%
Trap			193.1					193.1	9%
Total	0.5	1,130.6	1,088.2	0.5	0.0	0.0	0.0	2,219.9	
2013 Season, Trawl 2-7 days/wk, Jan 23-Apr 12 (54 days); Trap 6-7 days/wk, Feb 5-Apr 12 (62 days									
Trawl		64.9	164.5	37.5	2.6			269.5	93%
Trap			15.2	4.9	conf			20.2	7%
Total	0.0	64.9	179.7	42.5	2.6	0.0	0.0	289.7	
2014 Season Closed, 5 Maine trawl trips to collect samples									
Trawl		0.0	0.1	0.1				0.3	100%
Trap								0.0	
Total	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.3	
2015 Season, Limited research fishery for data collection									
Trawl		0.2	3.4	2.0				5.6	92%
Trap		0.0	0.3	0.2				0.5	8%
Total	0.0	0.2	3.7	2.3	0.0	0.0	0.0	6.1	
2016 Season, Limited research fishery for data collection									
Trawl		1.4	1.9	4.1				7.4	64%
Trap		0.1	1.8	2.2	0.01			4.1	36%
Total	0.0	1.5	3.7	6.3	0.01	0.0	0.0	11.5	
2017 Season, Limited research fishery for data collection									
Trawl		4.7	14.0	5.4				24.1	77%
Trap		0.1	5.2	1.8				7.1	23%
Total	0.0	4.8	19.2	7.2	0.00	0.0	0.0	31.2	

conf = Confidential data were combined with an adjacent month.

Table 2.5 **Discards of shrimp in kgs from Northeast Pelagic Observer Program observed trips by target species and year. Totals include both Northern shrimp and "unknown" shrimp that could not be identified to species by the observer.**

Target Species	2004	2005	2006	2007	2008	2009	2010	2011	2012
HERRING, ATLANTIC	0.7	90.9	7.3	24.5				2.4	40.8
GROUNDFISH, NK	12.9	8.5	5.8	6.8	4.5		11.3		2
HAKE, SILVER	0.1	0.7	14.3	8.2		0.05	1.1		0.9
SHRIMP, PANDALID	0.3		22.7		0.05		0.5		
COD	1.9	2.9	1.5	0.4		1	0.9	4.9	1.4
SHRIMP, NK				13.6					
HADDOCK		0.5	5.4			0.1			
FLOUNDER, NK	0.05	4.5			1				
FLOUNDER, YELLOWTAIL		0.9		2.5	1.4				
FLOUNDER, WINTER		3.6		0.6	0.2				
MONKFISH						2.7	0.3		
FLOUNDER, WITCH	1.1	0.9		0.05		1		0.05	0.2
POLLOCK	0.1	0.05		0.1	0.05	0.4		2.4	
FLOUNDER, AM. PLAICE						0.9	0.1		
FISH, NK									0.5
HERRING, NK	0.2								
LOBSTER, AMERICAN	0.1								
QUAHOG, OCEAN		0.05							
HAKE, WHITE						0.05			
HAGFISH, ATLANTIC					0.05				
Grand Total (kg)	17.5	113.6	56.9	56.8	7.3	6.2	14.2	9.8	45.7
Number of Trips with Shrimp	33	92	33	35	10	25	13	22	19
Total Trips Observed*	1,040	2,072	862	965	1,234	1,282	864	891	1,026

*Trips that landed in MA, NH, or ME and used trawl, dredge, or pot/trap gear

Table 2.6 Distribution of fishing effort (number of trips) in the Gulf of Maine northern shrimp fishery by season, state, and month.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
1985 Season, 166 days, Dec 1 - May 15								
Maine	552	1,438	1,979	1,198	260	35		5,462
Mass.	127	269	224	231	92	73		1,016
N.H.	118	135	78	26	22			379
Total	797	1,842	2,281	1,455	374	108	0	6,857
1986 Season, 183 days, Dec 1 - May 31								
Maine	590	1,309	2,798	831	224	133	68	5,953
Mass.	128	235	225	320	194	133	159	1,394
N.H.	156	163	165	51	3		17	555
Total	874	1,707	3,188	1,202	421	266	244	7,902
1987 Season, 182 days, Dec 1 - May 31								
Maine	993	2,373	3,073	2,241	617	340	16	9,653
Mass.	325	354	414	426	283	317	164	2,283
N.H.	67	164	175	95	28		32	561
Total	1,385	2,891	3,662	2,762	928	657	212	12,497
1988 Season, 183 days, Dec 1 - May 31								
Maine	972	2,183	2,720	1,231	193	122		7,421
Mass.	28	326	426	315	26	57		1,178
N.H.	72	231	236	99	3			641
Total	1,072	2,740	3,382	1,645	222	179	0	9,240
1989 Season, 182 days, Dec 1 - May 31								
Maine	958	2,479	2,332	936	249	84		7,038
Mass.	103	479	402	254	297	102		1,637
N.H.	120	369	312	69	16			886
Total	1,181	3,327	3,046	1,259	562	186	0	9,561
1990 Season, 182 days, Dec 1 - May 31								
Maine	1,036	1,710	1,529	1,986	897	238		7,396
Mass.	147	459	273	202	175	118		1,374
N.H.	178	363	284	157	6			988
Total	1,361	2,532	2,086	2,345	1,078	356	0	9,758
1991 Season, 182 days, Dec 1 - May 31								
Maine	568	1,286	2,070	1,050	438	139		5,551
Mass.	264	416	401	231	154	147		1,613
N.H.	279	285	135	82	22	1		804
Total	1,111	1,987	2,606	1,363	614	287	0	7,968
1992 Season, 153 days, Dec 15 - May 15								
Maine	411	1,966	2,700	1,222	318	141		6,758
Mass.	59	337	145	101	41			683
N.H.	96	153	76	29	3			357
Total	566	2,456	2,921	1,352	362	141	0	7,798

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
1993 Season, 138 days, Dec 14 - April 30								
Maine	249	1,102	1,777	1,032	227			4,387
Mass.	60	200	250	185	72			767
N.H.	76	246	275	256	151			1,004
Total	385	1,548	2,302	1,473	450	0	0	6,158
1994 Season, 122 days, Dec 15 - Apr 15								
Maine	265	1,340	1,889	1,065	122			4,681
Mass.	58	152	147	83	15			455
N.H.	169	228	266	173	18			854
Total	492	1,720	2,302	1,321	155	0	0	5,990
1995 Season, 128 days, Dec 1 - Apr 30, 1 day per week off								
Maine	879	2,341	2,641	1,337	694			7,892
Mass.	145	385	275	157	109			1,071
N.H.	189	331	279	359	344			1,502
Total	1,213	3,057	3,195	1,853	1,147	0	0	10,465
1996 Season, 152 days, Dec 1- May 31, 1 day per week off								
Maine	1,341	2,030	3,190	1,461	444	457		8,923
Mass.	299	248	325	269	106	126		1,373
N.H.	331	311	389	248	155	61		1,495
Total	1,971	2,589	3,904	1,978	705	644	0	11,79
1997 Season, 156 days, Dec 1- May 31, two 5-day and four 4-day blocks off								
Maine	1,674	1,753	2,737	1,178	793	530		8,665
Mass.	184	226	245	114	7	1		777
N.H.	277	245	301	218	189	62		1,292
Total	2,135	2,224	3,283	1,510	989	593	0	10,734
1998 Season, 152 days, Dec 1- May 31, 1 day per week off								
Maine	852	1,548	1,653	725	346	189		5,313
Mass.	94	200	148	70	3	1		515
N.H.	141	216	182	134	83	22		778
Total	1,087	1,964	1,983	929	432	212	0	6,606
1999 Season, 152 days, Dec 1- May 31, 1 day per week off								
Maine	190	556	1,125	553	324	172		2,920
Mass.	39	57	71	9	40			216
N.H.	82	192	213	44	123	21		675
Total	311	805	1,409	606	487	193	0	3,811
2000 Season, 51 days, Jan 17 - Mar 15, Sundays off								
Maine		897	2,494	647				4,038
Mass.		33	117	32	1			183
N.H.		45	201	87				333
Total	0	975	2,812	766	1	0	0	4,554

Table 2.6 continued Trips by season, state, and month. 2014 data are Maine cooperative sampling trips; 2015–2016 data are RSA trips.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
2001 Season, 83 days, Jan 9 - Apr 30, Mar 18 - Apr 15 off, experimental offshore fishery in May								
Maine		1,683	1,551	177	43	6		3,460
Mass.		111	48	10		1		170
N.H.		303	200	conf	conf			503
Total	0	2,097	1,799	187	43	7	0	4,133
2002 Season, 25 days, Feb 15 - Mar 11								
Maine			799	299				1,098
Mass.			31	conf				31
N.H.			119	56				175
Total	0	0	949	355	0	0	0	1,304
2003 Season, 38 days, Jan 15 - Feb 27, Fridays off								
Maine		1114	1,582	1			2	2,699
Mass.		41	50					91
N.H.		81	151					232
Total	0	1,236	1,783	1	0	0	2	3,022
2004 Season, 40days, Jan 19 - Mar 12, Saturdays and Sundays off								
Maine	7	647	1,197	482	13	14	6	2,366
Mass.		conf	56	conf				56
N.H.		46	147	66				259
Total	7	693	1,400	548	13	14	6	2,681
2005 Season, 70 days, Dec 19 - 30, Fri-Sat off, Jan 3 - Mar 25, Sat-Sun off								
Maine	140	667	1,305	1,255	0	0	1	3,368
Mass.	15	18	49	23				105
N.H.	24	76	216	77				393
Total	179	761	1,570	1,355	0	0	1	3,866
2006 Season, 140 days, Dec 12 - Apr 30								
Maine	148	585	947	530	101			2,311
Mass.	conf	conf	58	conf	conf			58
N.H.	5	23	19	62	conf			109
Total	153	608	1,024	592	101	0	0	2,478
2007 Season, 151 days, Dec 1 - Apr 30								
Maine	437	1,102	1,514	669	136	1	3	3,862
Mass.	conf	45	conf	conf				45
N.H.	26	115	71	44	conf			256
Total	463	1,262	1,585	713	136	1	3	4,163
2008 Season, 152 days, Dec 1 - Apr 30								
Maine	418	1,291	2,076	1,286	102	0	9	5,182
Mass.	conf	conf	25	13				38
N.H.	63	141	125	38	conf			367
Total	481	1,432	2,226	1,337	102	0	9	5,587

conf = Confidential data were combined with an adjacent month.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
2009 Season, 180 days, Dec 1 - May 29								
Maine	134	785	1,122	739	47	5	1	2,833
Mass.& NH	conf	107	62	conf	conf			169
Total	134	892	1,184	739	47	5	1	3,002
2010 Season, 156 days, Dec 1 - May 5								
Maine	241	1,562	2,602	914	194	29	1	5,543
Mass.	conf	26	23	conf	conf			49
N.H.	55	127	151	21	56	conf		410
Total	296	1,715	2,776	935	250	29	1	6,002
2011 Season, 90 days, Dec 1 - Feb 28								
Maine	599	2,880	2,875	1				6,355
Mass.	28	92	73	0	0			193
N.H.	108	241	198					547
Total	735	3,213	3,146	1	0	0	0	7,095
2012 Season, Trawling Mon,Wed,Fri, Jan 2- Feb 17 (21 days); Trapping Feb 1-17 (17 days)								
Maine	1	1,305	2,014	1				3,321
Mass.		74	43					117
N.H.		129	99					228
Total	1	1,508	2,156	1	0	0	0	3,666
2013 Season, Trawl 2-7 days/wk, Jan 23-Apr 12 (54 days); Trap 6-7 days/wk, Feb 5-Apr 12 (62 days)								
Maine		202	889	260	22			1,373
Mass.		9	28	19	0			56
N.H.		20	73	27	conf			120
Total	0	231	990	306	22	0	0	1,549
2014 Season Closed, 5 Maine trawl trips made to collect samples								
Maine		1	2	2				5
Mass.								0
N.H.								0
Total	0	1	2	2	0	0	0	5
2015 Season Closed, Limited research fishery for data collection only								
Maine		1	24	20				45
Mass.		1	2	2				5
N.H.								0
Total	0	2	26	22	0	0	0	50
2016 Season Closed, Limited research fishery for data collection only								
Maine		8	21	31	3			63
Mass.								0
N.H.		1	2	2				5
Total	0	9	23	33	3	0	0	68

Table 2.6 continued Trips by season, state, and month. 2017 data are RSA trips.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total
2017 Season, Limited research fishery for data collection only								
Maine		15	73	51				139
Mass.		3	3	1				7
N.H.		3	4	0				7
Total	0	21	80	52	0	0	0	153

Table 2.7 Distribution of fishing trips in the Maine northern shrimp fishery by season, gear type, and month. 2014 data are cooperative sampling trips; 2015–2017 data are RSA trips.

	Dec	Jan	Feb	Mar	Apr	May	Other	Season Total	%
2000									
Trawl		818	2,073	462				3,353	97%
Trap		79	421	185				685	20%
Total	0	897	2,494	647	0	0	0	4,038	
2001									
Trawl		1,500	1,214	112	43	6		2,875	83%
Trap		183	337	65				585	17%
Total	0	1,683	1,551	177	43	6	0	3,460	
2002									
Trawl			595	236				831	76%
Trap			204	63				267	24%
Total	0	0	799	299	0	0	0	1,098	
2003									
Trawl		850	1,081	1			2	1,934	72%
Trap		264	501					765	28%
Total	0	1,114	1,582	1	0	0	2	2,699	
2004									
Trawl	7	566	965	382	13	14	6	1,953	83%
Trap		81	232	100				413	17%
Total	7	647	1,197	482	13	14	6	2,366	
2005									
Trawl	140	667	953	778			1	2,539	75%
Trap		conf	352	477				829	25%
Total	140	667	1,305	1,255	0	0	1	3,368	
2006									
Trawl	148	490	563	273	101			1,575	68%
Trap	conf	95	384	257	conf			736	32%
Total	148	585	947	530	101	0	0	2,311	
2007									
Trawl	437	977	921	349	119	1	3	2,807	73%
Trap	conf	125	593	320	17			1,055	27%
Total	437	1,102	1,514	669	136	1	3	3,862	
2008									
Trawl	418	1,062	1,393	661	51	0	9	3,594	69%
Trap	conf	229	683	625	51			1,588	31%
Total	418	1,291	2,076	1,286	102	0	9	5,182	
2009									
Trawl	134	705	673	381	32	5	1	1,931	68%
Trap	conf	80	449	358	15			902	32%
Total	134	785	1,122	739	47	5	1	2,833	
2010									
Trawl	241	1,231	1,520	450	194	29	1	3,666	66%
Trap	conf	331	1,082	464	conf			1,877	34%
Total	241	1,562	2,602	914	194	29	1	5,543	
2011									
Trawl	577	2,068	1,692	1				4,338	68%
Trap	22	812	1,183					2,017	32%
Total	599	2,880	2,875	1	0	0	0	6,355	
2012									
Trawl	1	1,305	1,046	1				2,353	71%
Trap			968					968	29%
Total	1	1,305	2,014	1	0	0	0	3,321	
2013									
Trawl		202	607	158	22			989	72%
Trap		0	282	102	conf			384	28%
Total	0	202	889	260	22	0	0	1,373	
2014									
Trawl		1	2	2				5	100%
Trap								0	0%
Total	0	1	2	2	0	0	0	5	
2015									
Trawl		1	8	5				14	31%
Trap		0	16	15				31	69%
Total	0	1	24	20	0	0	0	45	
2016									
Trawl		3	3	9				15	24%
Trap		5	18	22	3			48	76%
Total	0	8	21	31	3	0	0	63	
2017									
Trawl		12	29	22				63	45%
Trap		3	44	29				76	55%
Total	0	15	73	51	0	0	0	139	

conf = Small amounts of confidential trap data were combined with trawl data for that month.

Table 2.8 Total weight of the northern shrimp catches that were sampled (mt), number of samples and interviews collected, total weight of the samples (kg), and numbers of northern shrimp (*P. borealis*) measured, by fishing season, from Gulf of Maine northern shrimp port sampling.

Fishing Season	Catches sampled (mt)	Number of samples	Sample wts (kg)	Numbers measured
1985	42.09	66	65.3	6,032
1986	37.52	72	76.3	6,415
1987	33.83	81	67.2	5,699
1988	41.33	94	79.4	6,393
1989	60.47	106	102.6	8,885
1990	56.24	98	86.5	8,132
1991	120.93	215	174.7	15,058
1992	73.58	162	128.5	10,225
1993	61.42	160	147.1	12,852
1994	78.17	165	132.1	12,221
1995	98.66	131	143.8	14,270
1996	243.70	243	293.8	28,320
1997	251.69	323	351.2	35,033
1998	150.73	227	249.5	23,916
1999	130.60	222	196.1	22,529
2000	112.82	130	121.2	11,458
2001	53.54	146	140.5	14,714
2002	31.28	58	49.4	5,243
2003	63.57	128	121.5	11,805
2004	114.99	113	107.1	10,972
2005	166.22	214	209.9	19,539
2006	171.49	162	176.5	16,218
2007	301.78	207	222.4	25,409
2008	237.43	243	258.6	26,181
2009	130.49	152	152.2	12,804
2010	324.59	266	296.9	25,393
2011	272.52	286	328.1	30,590
2012	278.10	311	370.0	39,748
2013	39.01	115	124.2	11,370

Table 2.9 Estimated numbers of vessels in the Gulf of Maine northern shrimp fishery by fishing season and state. 2014 data are from the Maine cooperative sampling program. 2015–2017 data are for the RSA.

Season	Maine			Massachusetts	New Hampshire	Total
	Trawl	Trap	Total			
1980			15-20	15-20		30-40
1981			~75	~20-25		~100
1982			>75	~20-25		>100
1983			~164	~25	~5-8	~197
1984			239	43	6	288
1985			~231	~40	~17	~300
1986						~300
1987			289	39	17	345
1988			~290	~70	~30	~390
1989			~230	~50	~30	~310
1990			~220			~250
1991			~200	~30	~20	~250
1992			~259	~50	16	~325
1993			192	52	29	273
1994			178	40	29	247
1995						
1996			275	43	29	347
1997			238	32	41	311
1998			195	33	32	260
1999			181	27	30	238
2000	207	68	265	17	27	304
2001	174	60	234	19	27	275
2002	117	52	168	7	23	198
2003	142	49	191	12	22	222
2004	114	56	170	7	15	192
2005	102	64	166	9	22	197
2006	68	62	129	4	11	144
2007	97	84	179	3	15	196
2008	121	94	215	4	15	234
2009	80	78	158	12 (MA and NH combined)		170
2010	124	112	235	6	15	256
2011	172	143	311	12	19	342
2012	164	132	295	15	17	327
2013	110	72	182	13	14	208
2014	1	0	1	0	0	1
2015	3	5	8	1	0	9
2016	3	2	5	0	1	6
2017	8	5	13	1	1	15

Note that some boats reported both trapping and trawling, and some landed in more than one state.

Table 2.10 **Gulf of Maine northern shrimp commercial catch rates by season. Mean CPUE in pounds/hour towing is from Maine trawler port sampling. Mean catch in pounds/trip is from NMFS weigh-out and logbook data for all gears for all states. Trawl pounds/trip is from logbook data for all trawl trips for all states. Moratorium implemented for 2014 – 2017 seasons. 1 lb = 2.2 kg.**

Season	**Maine Trawl Catch (kg) per Tow-Hour**			**GOM Catch (kg) per Trip**	**GOM Trawl Catch (kg) per Trip**
	Inshore (<55F)	Offshore (>55F)	Combined		
1985	-		102	603	
1986	-		57	587	
1987	-		*na*	421	
1988	-		43	329	
1989	-		75	347	
1990	-		58	478	
1991	43	69	64	450	
1992	60	42	53	444	
1993	37	59	42	348	
1994	63	68	64	487	
1995	78	93	88	617	
1996	154	92	114	809	
1997	93	87	88	663	
1998	72	68	70	631	
1999	67	67	67	490	
2000	127	102	123	627	669
2001	45	61	49	322	341
2002	101	41	88	347	387
2003	79	98	83	445	500
2004	164	141	159	795	910
2005	107	96	103	675	733
2006	259	156	226	937	1,185
2007	241	216	230	1,172	1,415
2008	159	148	156	888	1,043
2009	181	143	168	833	1,010
2010	193	161	182	1,044	1,227
2011	152	197	158	902	1,078
2012	185	142	181	678	850
2013	54	35	50	223	279

Table 3.1 **Biomass indices (stratified arithmetic mean kg per tow) of northern shrimp collected during NEFSC fall surveys, by vessel. The survey vessel and gear changed in 2009. No conversion factors are available for northern shrimp.**

Year	FRV *Albatross IV* Biomass index	Year	FRV *Albatross IV* Biomass index	NOAA Ship *Henry B. Bigelow* Biomass index
1968	3.2	2003	1.08	
1969	2.7	2004	1.58	
1970	3.7	2005	2.77	
1971	3.0	2006	6.64	
1972	3.3	2007	4.13	
1973	1.9	2008	3.05	
1974	0.8	2009		7.8
1975	0.9	2010		5.0
1976	0.6	2011		5.6
1977	0.2	2012		2.8
1978	0.4	2013		1.2
1979	0.5	2014		1.9
1980	0.5	2015		0.7
1981	1.5	2016		0.5
1982	0.3	2017		0.7
1983	1.0			
1984	1.90			
1985	1.60			
1986	2.50			
1987	1.70			
1988	1.20			
1989	1.81			
1990	2.04			
1991	0.44			
1992	0.41			
1993	1.85			
1994	2.24			
1995	1.22			
1996	0.90			
1997	1.12			
1998	1.99			
1999	2.32			
2000	1.28			
2001	0.63			
2002	1.70			

Table 3.2: **Biomass indices (stratified geometric mean kg per tow) of northern shrimp collected during the Maine - New Hampshire inshore trawl surveys by year, regions 1–4 (NH to Schoodic Pt, Maine) and depths 3–4 (> 35 fa.), with coefficients of variation (CVs) and number of tows (n).**

	Spring			Fall		
	kg/tow	CV	n	kg/tow	CV	n
2003	**4.2**	0.07	40	**1.9**	0.15	33
2004	**3.9**	0.06	42	**1.5**	0.18	38
2005	**7.8**	0.05	40	**3.6**	0.14	25
2006	**11.0**	0.07	46	**2.1**	0.16	38
2007	**10.2**	0.08	43	**4.0**	0.09	45
2008	**15.4**	0.05	45	**3.6**	0.16	37
2009	**9.7**	0.06	45	**2.8**	0.08	41
2010	**15.0**	0.05	48	(samples lost)		
2011	**17.9**	0.04	50	**4.2**	0.09	32
2012	**7.5**	0.06	50	**1.9**	0.09	42
2013	**1.7**	0.20	46	**0.6**	0.21	45
2014	**2.1**	0.08	47	**0.3**	0.20	43
2015	**1.7**	0.09	52	**0.3**	0.21	37
2016	**2.2**	0.07	48	**0.4**	0.23	39
***2017**	**2.1**	0.09	52	**0.4**	0.28	39

* Fall 2017 data are preliminary.

Table 3.3 **Stratified geometric mean number (abundance) and weight (biomass, kg) per tow and derived indices of northern shrimp from summer shrimp surveys (strata 1, 3, 5, 6, 7 and 8). Recruit index is abundance of presumed age 1.5 shrimp. Other derived indices are described in text. YC=year class, EPI=egg production index. The model-based index is described in the text.**

Year	N Tows	Total Abundance	Total Biomass	Recruit Index	Spawner Biomass	EPI Millions	YC Survival Index	>22 mm Number	>22 mm Weight (kg)	Model Index	Model CV
1984	37	1,152	10.5	18	3.6	0.72		316	3.4	0.936	0.177
1985	44	1,825	17.7	332	5.7	1.19	496	1,169	11.5	1.468	0.169
1986	40	1,695	19.6	358	7.2	1.48	287	860	10.0	1.147	0.162
1987	41	1,533	15.4	342	6.2	1.25	559	854	9.5	0.831	0.169
1988	41	1,269	12.8	828	2.5	0.52	222	298	3.4	1.235	0.185
1989	43	1,884	17.0	276	5.0	1.01	274	564	6.1	1.236	0.164
1990	43	1,623	18.1	142	6.0	1.25	476	1,127	12.0	1.122	0.178
1991	43	1,256	11.7	482	6.5	1.34	226	657	8.0	0.818	0.184
1992	45	955	9.4	282	4.3	0.85	565	397	4.8	0.470	0.173
1993	46	1,157	9.1	757	2.2	0.44	431	250	2.8	1.168	0.190
1994	43	984	8.7	368	2.3	0.46	664	243	2.7	1.020	0.183
1995	35	1,449	13.3	292	6.2	1.27	506	628	7.0	0.976	0.159
1996	32	776	8.8	232	3.1	0.63	294	358	4.0	0.781	0.159
1997	40	762	7.7	374	2.3	0.48	212	245	2.8	0.852	0.151
1998	35	583	6.3	134	1.8	0.35	239	170	1.9	0.555	0.139
1999	42	398	5.8	114	1.5	0.31	1,294	174	1.9	0.605	0.141
2000	35	808	6.4	450	2.9	0.58	57	283	3.2	0.762	0.147
2001	36	451	4.3	18	1.7	0.31	1,992	146	1.5	0.280	0.148
2002	38	1,445	9.2	1,164	2.8	0.54	35	261	2.9	1.032	0.144
2003	37	564	5.5	11	2.0	0.34	527	173	1.7	0.733	0.145
2004	35	887	10.3	286	3.1	0.63	5,155	519	5.3	1.135	0.166
2005	46	3,661	23.4	1,752	9.2	1.89	589	871	10.3	2.272	0.131
2006	29	9,998	66.0	374	28.4	5.58	15	2,773	29.9	4.353	0.177
2007	43	887	11.5	28	3.4	0.67	91	412	4.1	1.567	0.145
2008	38	1,737	16.8	506	5.9	1.22	828	995	10.8	1.660	0.157
2009	49	1,627	15.4	555	6.4	1.29	391	702	8.5	1.673	0.138
2010	49	1,373	13.9	475	3.9	0.79	34	413	4.8	1.488	0.142
2011	47	830	8.6	44	3.0	0.57	8	316	3.2	0.924	0.135
2012	49	138	2.5	7	0.7	0.15	2	81	0.9	0.251	0.133
2013	40	27	1.0	1	0.2	0.05	779	24	0.3	0.061	0.147
2014	46	139	1.7	116	0.3	0.04	58	16	0.2	0.197	0.150
2015	32	58	1.3	3	0.4	0.08	5,291	38	0.4	0.060	0.182
2016	41	332	3.8	226	1.1	0.23	16	103	1.2	0.252	0.123
2017	45	26	0.9	0.1	0.1	0.03		13	0.2	0.080	0.249
Mean	41	1303	11.6	334	4.2	0.84	707	484	5.3	1.000	0.160
Median	41	970	9	284	3	1	343	316	3	0.930	0.158
1984-93	42	1,435	14.1	382	4.9	1.01	393	649	7.1	1.043	0.175
Median	43	1,401	14.1	337	5.4	1.10	431	611	7.0	1.134	0.175

Table 4.1 **ASAP base model and sensitivity runs descriptions , based on alternative M assumptions (Scenarios B-G), metric and importance of survey indices (Scenarios H-K), under-reporting of commercial landings (Scenario L), and coefficient of variation on commercial catch (Scenario M). "X" represents scenario applied, constant M assumed when blank.**

Model Scenario	Natural mortality assumption			Additional adjustment to inputs from BASE
	Base M	Age-varying	Time-varying (scaled by PPI)	
BASE	0.5	X	X	NA
B	0.5	X		NA
C	0.5		X	NA
D	0.5		PPI with temperature adjustment (see Section 1.1.3)	NA
E	0.5			NA
F	0.95		X	NA
G	0.95			NA
H	0.5	X	X	Design-based estimators for all survey indices (see Figure 3.4)
I	0.5	X	X	Remove Albatross index
J	0.5	X	X	Remove Bigelow index
K	0.5	X	X	Remove Albatross & Bigelow indices
L	0.5	X	X	Commercial catch scaled up 25% 1985-2000 (to reflect change in reporting in 2001, see Section 5.3.3)
M	0.5	X	X	Catch CV = 0.05 (as applied in base CSA model, see Section 4.1)

Table 4.2 **Time-varying and age-varying natural mortality estimates for Gulf of Maine northern shrimp ASAP base run.**

	Age 1	Age 2	Age 3	Age 4+
1985	1.59	1.26	0.40	1.27
1986	1.62	1.28	0.40	1.29
1987	1.03	0.81	0.26	0.82
1988	1.34	1.06	0.33	1.07
1989	1.38	1.09	0.34	1.10
1990	1.68	1.33	0.42	1.34
1991	1.33	1.05	0.33	1.06
1992	1.29	1.02	0.32	1.03
1993	1.25	0.99	0.31	1.00
1994	0.93	0.74	0.23	0.75
1995	1.70	1.34	0.42	1.35
1996	1.50	1.19	0.37	1.20
1997	1.00	0.79	0.25	0.80
1998	1.24	0.98	0.31	0.99
1999	1.96	1.55	0.49	1.56
2000	2.16	1.71	0.54	1.72
2001	1.92	1.52	0.48	1.53
2002	3.47	2.74	0.86	2.77
2003	2.76	2.19	0.69	2.20
2004	1.30	1.02	0.32	1.03
2005	1.25	0.99	0.31	1.00
2006	1.76	1.39	0.44	1.41
2007	1.87	1.48	0.47	1.49
2008	2.25	1.78	0.56	1.79
2009	1.97	1.56	0.49	1.57
2010	2.99	2.37	0.75	2.39
2011	3.06	2.42	0.76	2.44
2012	3.07	2.43	0.77	2.45
2013	2.04	1.62	0.51	1.63
2014	2.54	2.01	0.63	2.02
2015	2.21	1.75	0.55	1.76
2016	4.03	3.19	1.01	3.22
2017	2.52	1.99	0.63	2.01

Table 4.3 **Gulf of Maine northern shrimp age compositions (in millions of shrimp for 1985-2013 and thousands for 2014-2017) and effective sample sizes (ESS) for commercial fleet catch applied in ASAP model.**

	Commercial catch				
	Age 1	Age 2	Age 3	Age 4+	ESS
1985	9.8	53.2	51.4	237.2	46
1986	52.4	0.0	275.5	31.7	53
1987	40.4	49.5	0.0	325.3	83
1988	8.4	56.1	152.6	0.0	57
1989	81.8	5.8	94.2	114.0	64
1990	0.0	145.2	139.8	152.3	65
1991	59.2	47.5	168.0	45.0	53
1992	38.1	5.0	50.0	169.5	52
1993	29.6	44.6	47.8	56.2	41
1994	65.5	37.2	133.3	23.7	40
1995	108.1	316.3	171.7	22.5	70
1996	115.2	251.3	483.2	15.7	79
1997	181.8	53.2	101.6	347.1	72
1998	75.5	110.6	150.5	23.1	44
1999	19.9	63.1	116.8	2.8	25
2000	11.3	28.7	115.8	86.6	30
2001	41.4	8.8	60.4	31.6	28
2002	0.0	32.3	0.5	11.1	9
2003	34.2	0.0	83.3	10.6	20
2004	0.0	193.3	0.0	28.1	18
2005	26.8	0.0	205.1	2.2	26
2006	26.5	41.0	0.0	135.8	17
2007	33.8	140.4	331.3	42.2	28
2008	0.0	48.8	385.6	48.3	37
2009	16.0	0.0	8.7	182.3	20
2010	58.0	98.5	0.0	370.3	40
2011	44.6	142.6	417.7	0.0	47
2012	7.6	46.8	192.8	20.2	24
2013	0.0	1.1	7.7	22.4	10
2014	0.0	0.3	1.7	15.6	10
2015	420.6	0.2	40.2	173.5	10
2016	8.3	1068.7	14.8	58.6	10
2017	400.0	0.0	2106.7	0.0	10

Table 4.4 Gulf of Maine northern shrimp age compositions (in numbers of shrimp per tow for Summer and numbers per tow x 100 for Fall) and effective sample sizes (ESS) for the surveys used in the ASAP model.

	ASMFC Summer Shrimp Survey					NEFSC Fall Albatross Survey					NEFSC Fall Bigelow Survey				
	Age 1	Age 2	Age 3	Age 4+	ESS	Age 1	Age 2	Age 3	Age 4+	ESS	Age 1	Age 2	Age 3	Age 4+	ESS
1985	315.2	0.0	1398.7	108.5	44	0	0	0	0	0	0	0	0	0	0
1986	319.7	474.4	0.0	900.9	40	0	0	0	0	0	0	0	0	0	0
1987	345.5	277.6	909.8	0.0	41	0	0	0	0	0	0	0	0	0	0
1988	826.7	115.5	146.1	180.9	41	0	0	0	0	0	0	0	0	0	0
1989	348.4	1002.4	422.4	109.5	43	0	0	0	0	0	0	0	0	0	0
1990	132.7	319.3	915.5	255.7	43	0	0	0	0	0	0	0	0	0	0
1991	514.9	116.1	168.4	456.0	43	13.0	3.1	4.1	11.5	10	0	0	0	0	0
1992	272.1	310.3	213.1	159.7	45	1.8	6.3	4.5	6.5	10	0	0	0	0	0
1993	754.5	223.1	149.5	29.3	46	75.6	10.6	13.8	4.5	10	0	0	0	0	0
1994	325.2	474.8	111.6	72.2	43	33.4	44.5	16.7	14.3	10	0	0	0	0	0
1995	286.5	556.1	467.9	138.1	35	5.6	11.4	41.4	0.8	10	0	0	0	0	0
1996	232.3	184.5	215.2	143.8	32	2.2	5.2	12.7	19.5	10	0	0	0	0	0
1997	377.7	130.8	164.5	88.9	40	20.6	12.7	8.3	11.7	10	0	0	0	0	0
1998	94.6	305.6	144.6	38.0	35	21.1	50.2	20.0	6.1	10	0	0	0	0	0
1999	113.5	144.3	76.4	63.5	42	22.8	55.1	26.8	10.8	10	0	0	0	0	0
2000	450.8	82.0	187.8	86.7	35	49.0	11.5	16.3	19.3	10	0	0	0	0	0
2001	43.3	308.1	36.7	63.0	36	2.8	29.0	7.3	7.7	10	0	0	0	0	0
2002	1135.6	48.1	224.0	37.7	38	48.0	2.9	16.1	1.7	10	0	0	0	0	0
2003	28.7	491.2	19.6	24.7	37	0.4	29.0	5.2	5.2	10	0	0	0	0	0
2004	294.7	0.0	569.7	22.3	35	28.8	3.4	52.8	2.2	10	0	0	0	0	0
2005	1732.2	1088.0	27.0	814.0	46	161.4	56.9	14.7	51.8	10	0	0	0	0	0
2006	462.8	6903.6	2402.7	226.6	29	52.4	196.6	104.7	15.1	10	0	0	0	0	0
2007	0.6	164.7	718.0	3.3	43	8.7	50.5	164.0	17.2	10	0	0	0	0	0
2008	522.3	0.0	700.4	519.2	38	24.6	6.9	54.0	65.3	10	0	0	0	0	0
2009	548.9	485.8	0.0	591.7	49	0	0	0	0	0	72.9	41.5	44.0	241.3	10
2010	519.5	518.3	335.0	0.0	49	0	0	0	0	0	47.3	54.0	72.5	6.1	10
2011	0.0	433.8	325.6	70.8	47	0	0	0	0	0	9.1	34.4	50.5	61.4	10
2012	10.5	54.2	28.3	44.9	49	0	0	0	0	0	1.9	19.8	12.7	13.9	10
2013	0.0	4.2	12.7	10.5	50	0	0	0	0	0	0.6	2.5	5.2	3.7	10
2014	124.3	0.0	0.0	14.4	50	0	0	0	0	0	15.9	2.7	3.9	3.4	10
2015	0.0	51.6	0.0	6.7	50	0	0	0	0	0	1.5	10.4	0.2	0.6	10
2016	225.8	0.0	105.7	0.0	50	0	0	0	0	0	3.4	0.9	4.3	0.5	10
2017	0.0	16.7	0.0	9.3	50	0	0	0	0	0	0	0	0	0	0

Table 4.5 **Weights at age applied for Gulf of Maine northern shrimp estimated from NORMSEP analysis and length-weight predictions from ASMFC summer shrimp survey data.**

	Age 1	Age 2	Age 3	Age 4+
1985	0.0031	0.0060	0.0094	0.0136
1986	0.0026	0.0064	0.0103	0.0116
1987	0.0029	0.0064	0.0107	0.0126
1988	0.0031	0.0064	0.0107	0.0126
1989	0.0031	0.0064	0.0103	0.0136
1990	0.0029	0.0064	0.0098	0.0131
1991	0.0031	0.0069	0.0107	0.0126
1992	0.0031	0.0064	0.0112	0.0141
1993	0.0029	0.0073	0.0116	0.0147
1994	0.0031	0.0064	0.0112	0.0126
1995	0.0029	0.0060	0.0107	0.0126
1996	0.0031	0.0057	0.0103	0.0126
1997	0.0026	0.0060	0.0103	0.0131
1998	0.0026	0.0057	0.0098	0.0136
1999	0.0031	0.0064	0.0107	0.0121
2000	0.0031	0.0069	0.0107	0.0126
2001	0.0043	0.0064	0.0107	0.0116
2002	0.0037	0.0049	0.0107	0.0136
2003	0.0040	0.0064	0.0116	0.0121
2004	0.0031	0.0060	0.0098	0.0136
2005	0.0029	0.0060	0.0094	0.0121
2006	0.0031	0.0057	0.0107	0.0136
2007	0.0031	0.0049	0.0082	0.0147
2008	0.0034	0.0060	0.0082	0.0121
2009	0.0029	0.0064	0.0103	0.0126
2010	0.0034	0.0064	0.0126	0.0126
2011	0.0031	0.0049	0.0082	0.0116
2012	0.0034	0.0064	0.0098	0.0116
2013	0.0031	0.0057	0.0107	0.0126
2014	0.0040	0.0060	0.0103	0.0136
2015	0.0031	0.0077	0.0103	0.0141
2016	0.0040	0.0060	0.0116	0.0126
2017	0.0031	0.0069	0.0103	0.0126

Table 5.1 **Profile over M for CSA model. All CSA models used model-based survey indices. PCA is an exploratory run using a composite predation and temperature index to scale M.**

		Constant M		Time-varying M					
Component		M=0.5	M=0.95	0.3*PPI	0.4*PPI	0.5*PPI	0.6*PPI	0.95* PPI	PCA
Shrimp survey	Recruits	-25.2	57.2	-13.9	-19.1	-26.4	-20.7	131.7	-30.0
Shrimp survey	Post-recruits	-17.6	66.1	-22.1	-22.5	-21.4	-1.9	100.3	-24.9
Fall_Albatross	Rcrt + Post-R	-1.3	13.4	-8.3	-7.6	-5.8	-4.5	10.2	-5.7
Fall_Bigelow	Rcrt + Post-R	1.9	3.5	-0.7	-1.3	-1.9	-0.2	4.3	-2.7
Catch	Rcrt + Post-R	-98.8	-98.9	-98.6	-98.6	-98.5	-98.9	-98.9	-101.8
	NLL	-141.1	41.3	-143.6	-149.0	-154.2	-126.2	147.5	-165.0

Table 5.2 **Goodness of fit statistics for final CSA model using PPI-scaled M with average M=0.5.**

Component	GOF CV	NLL	Estimate	Mohn's rho
Recruits	0.29	-26.4	Recruits	0.14
Post-recruits	0.34	-21.4	PostRecruits	0.11
Fall Albatross	0.51	-5.8	F	-0.09
Fall Bigelow	0.60	-1.9	Total B	0.13
Catch	0.01	-98.5		
Total		-154.2		

Table 5.3a Likelihood components for final CSA model (series 1) with varying likelihood weights (lambda) (series 2-7).

	Lambda for	series 1	series 2	series 3	series 4	series 5	series 6	series 7
	Shrimp survey	1	2	3	5	1	1	1
	Fall survey	1	1	1	1	0	0 Alb 1 Big	1
	Catch	1	0.5	0.5	0.5	0.5	1	0.01
Component								
Shrimp survey	Recruits	-26.4	-55.6	-84.7	-144.2	-27.6	-27.2	-32.9
Shrimp survey	Post-recruits	-21.4	-45.5	-69.7	-118.9	-23.0	-23.1	-26.2
Fall_Albatross	Rcrt + Post-R	-5.8	-3.5	-2.7	-2.1	0.0	0.0	-6.1
Fall_Bigelow	Rcrt + Post-R	-1.9	-1.7	-1.7	-1.7	0.0	-1.9	-2.7
Catch	Rcrt + Post-R	-98.5	-48.2	-46.9	-42.9	-49.2	-98.7	3.2
	NLL	-154.2	-154.6	-205.7	-309.8	-99.8	-150.8	-64.6

Table 5.3b Mohn's rho calculated for CSA model outputs with varying likelihood weights.

Lambda for	series 1	series 2	series 3	series 4	series 5	series 6	series 7
Shrimp survey	1	2	3	5	1	1	1
Fall survey	1	1	1	1	0	0 Alb 1 Big	1
Catch	1	0.5	0.5	0.5	0.5	1	0.01
Recruits	0.14	0.14	0.14	0.14	0.15	0.14	0.06
Post-recruits	0.11	0.12	0.13	0.13	0.14	0.11	0.04
Exploitable B	0.13	0.14	0.14	0.14	0.15	0.13	0.06
F	-0.09	-0.10	-0.10	-0.10	-0.10	-0.08	-0.10

Table 5.4. Population estimates from the CSA model.

	F	Recruits (billions of shrimp)	Post-recruits (billions of shrimp)	Exploitable Biomass (mt)
1985	0.26	1.01	0.93	14,395.9
1986	0.26	1.08	0.95	17,114.5
1987	0.39	0.68	0.97	14,863.2
1988	0.27	0.37	0.66	9,379.7
1989	0.26	0.90	0.62	9,707.4
1990	0.35	0.79	0.86	12,488.1
1991	0.35	0.47	0.93	13,185.5
1992	0.38	0.37	0.64	9,430.4
1993	0.30	0.32	0.46	6,877.5
1994	0.24	0.82	0.47	7,638.5
1995	0.49	1.07	0.90	13,709.9
1996	0.77	1.19	0.76	15,359.8
1997	0.85	0.91	0.56	11,521.8
1998	0.51	0.67	0.41	7,497.3
1999	0.27	0.61	0.42	7,236.9
2000	0.37	0.53	0.55	8,616.7
2001	0.22	0.51	0.44	6,863.4
2002	0.09	0.26	0.42	5,199.0
2003	0.12	1.23	0.40	8,500.9
2004	0.23	0.65	0.64	9,073.9
2005	0.16	0.99	0.72	13,745.9
2006	0.07	2.05	1.38	23,011.8
2007	0.18	2.31	2.20	32,475.9
2008	0.22	1.09	1.93	24,661.5
2009	0.11	1.15	1.59	24,012.4
2010	0.31	1.11	1.38	21,483.7
2011	0.54	0.95	1.11	15,702.0
2012	0.45	0.54	0.54	7,864.2
2013	0.13	0.12	0.29	3,838.3
2014	0.00	0.04	0.13	1,884.3
2015	0.00	0.18	0.08	1,448.4
2016	0.01	0.04	0.13	1,616.6
2017	0.01	0.18	0.11	1,956.2
2018		0.05	0.10	1,467.0
Median	0.26	0.68	0.63	9,405.0
Mean	0.28	0.74	0.73	11,289.1

Table 5.5. Population estimates from the base run of the UME model.

Year	Average F (N-Weighted)	Recruitment (Billions of shrimp)	Total Abundance (Billions of shrimp)	Spawning Stock Biomass (mt)	Total Biomass (mt)
1984	0.35	3.51	7.8	4,414.1	19,726.1
1985	0.26	5.86	9.2	4,038.9	22,990.1
1986	0.34	3.48	6.4	5,339.7	20,039.4
1987	0.56	3.32	5.3	5,008.6	15,974.1
1988	0.31	8.96	11.2	4,204.9	19,369.1
1989	0.41	3.32	7.0	4,835.3	19,083.7
1990	0.46	3.07	5.6	2,890.3	17,237.6
1991	0.45	4.41	6.1	3,431.2	14,302.4
1992	0.52	3.43	5.5	4,114.8	13,409.6
1993	0.35	9.20	11.2	3,320.1	17,381.6
1994	0.33	3.86	7.8	4,433.9	19,151.6
1995	0.40	5.04	8.9	6,458.0	24,192.9
1996	0.70	2.87	5.5	5,242.8	18,269.5
1997	0.91	4.10	5.8	3,867.8	13,834.2
1998	0.76	3.25	5.6	3,269.5	13,258.6
1999	0.41	3.55	5.6	2,915.3	13,149.7
2000	1.04	14.24	15.6	2,696.1	18,701.6
2001	0.90	2.88	5.2	1,709.6	10,857.6
2002	0.10	99.39	100.6	2,993.9	82,725.4
2003	0.55	4.35	8.9	2,079.4	18,564.1
2004	0.41	5.82	7.1	1,207.2	11,967.5
2005	0.45	17.24	19.7	3,331.0	23,885.5
2006	0.26	28.51	35.1	4,639.2	45,871.2
2007	0.54	7.55	15.7	6,900.0	39,323.3
2008	0.31	18.64	22.8	4,162.2	39,015.4
2009	0.18	17.20	21.1	7,065.9	34,045.6
2010	0.63	39.01	43.3	5,816.2	51,415.5
2011	1.64	6.46	9.9	2,800.1	19,642.1
2012	1.15	1.66	2.6	1,222.5	6,547.2
2013	0.29	2.31	2.6	710.2	3,544.4
2014	0.00	6.56	7.0	859.5	7,108.7
2015	0.01	1.52	2.3	725.5	4,163.4
2016	0.01	16.18	16.6	674.8	14,837.1
2017	0.03	2.05	2.6	709.5	3,683.9
Median	0.41	4.38	7.45	3,381.1	18,416.8
Mean	0.47	10.67	13.33	3,473.2	21,096.2

Table 5.6. Model fit diagnostics for the base case and sensitivity runs of the UME model.

Model Scenario		**BASE**	**B**	**C**	**D**	**E**	**F**	**G**
Natural mortality assumption	Length-varying	X	X		X			
	Time-varying (PPI)	X		X	PPI & temp		X	
	Base M	0.5	0.5	0.5	0.5	0.5	0.95	0.95
Other adjustment to inputs from BASE		NA	NA	NA	NA	NA	NA	NA
objective function and components	objective function	19,470.70	19,536.90	19,425.80	19,477.00	19,527.60	19,426.80	19,590.10
	catch total	-90.47	-66.77	-87.38	-81.67	-63.79	-95.37	-79.20
	index fit total	62.26	119.82	82.40	32.84	123.15	63.71	136.07
	catch length comp	12,655.78	12,702.23	12,652.32	12,645.27	12,674.73	12,642.32	12,713.31
	index length comp	6,654.97	6,630.90	6,648.37	6,666.61	6,644.80	6,666.75	6,687.75
	recruit deviations	188.18	150.76	130.10	213.92	148.76	149.38	132.15
RMSE	Mixed fleet catch	0.99	3.37	1.75	1.51	3.70	0.78	2.16
	Trawl catch	1.24	1.79	0.91	1.74	1.83	0.86	1.47
	Trap catch	0.03	0.01	0.02	0.05	0.01	0.04	0.01
	index - Summer Suvey	6.30	8.71	7.36	4.76	8.93	6.88	9.80
	index - NEFSC	3.65	4.84	3.83	3.40	4.82	3.08	4.70
Terminal year (2017) estimates	SSB (mt)	709.5	2,088.8	1,126.4	642.6	2,299.1	719.9	3,081.0
	Jan 1 biomass (mt)	3,683.9	8,126.8	2,624.6	3,833.1	4,513.1	4,405.6	11,428.3
	Expl. biomass (mt)	674.6	2,100.5	1,095.9	550.4	2,355.0	439.1	2,595.8
	Total stock (millions)	2,553.1	4,618.1	743.6	2,778.2	1,098.3	2,141.4	4,527.0
	Recruits (millions)	2,049.0	3,315.8	292.5	2,277.4	379.5	1,225.9	2,423.0
	F ave N-weighted	0.03	0.01	0.02	0.03	0.01	0.03	0.01
Retrospective Mohn's rho, 5-yr peel to 2013	rho SSB	0.06	0.10	0.14	0.11	0.19	0.09	-0.02
	rho recruits	-0.01	0.21	0.06	0.08	0.18	-0.02	-0.06
	rho F ave N-weighted	0.02	-0.10	-0.02	0.02	-0.08	0.07	-0.11

Table 5.6 (cont.) Model fit diagnostics for the base case and sensitivity runs of the UME model.

Model Scenario		**BASE**	**H**	**I**	**J**	**K**
Natural mortality assumption	Age-varying	X	X	X	X	X
	Time-varying (PPI)	X	X	X	X	X
	Base M	0.5	0.5	0.5	0.5	0.5
Other adjustment to inputs from BASE		NA	Design-based indices	Summer index only	Catch scaled up 25% prior to 2001	Catch CV = 0.05 (CSA)
objective function and components	objective function	19,470.70	19,568.40	16,658.00	19,479.20	19,445.20
	catch total	-90.47	-87.91	-92.97	-86.81	-147.75
	index fit total	62.26	146.44	48.53	71.96	76.25
	catch length comp	12,655.78	12,647.65	12,641.32	12,660.22	12,665.88
	index length comp	6,654.97	6,656.92	3,884.40	6,653.90	6,659.83
	recruit deviations	188.18	205.31	176.77	179.93	190.96
RMSE	Mixed fleet catch	0.99	1.08	0.97	1.45	0.31
	Trawl catch	1.24	1.42	0.97	1.24	0.28
	Trap catch	0.03	0.05	0.03	0.02	0.01
	index - Summer Suvey	6.30	11.85	6.63	6.56	6.81
	index - NEFSC	3.65	3.04		4.00	4.00
Terminal year (2017) estimates	SSB (mt)	709.5	556.6	717.6	789.1	777.5
	Jan 1 biomass (mt)	3,683.9	2,968.9	3,624.1	4,082.0	3,987.3
	Expl. biomass (mt)	674.6	483.9	708.7	753.8	744.5
	Total stock (millions)	2,553.1	1,926.4	2,520.9	2,827.7	2,748.2
	Recruits (millions)	2,049.0	1,475.6	2,036.4	2,269.3	2,204.2
	F ave N-weighted	0.03	0.04	0.03	0.03	0.03
Retrospective Mohn's rho, 5-yr peel to 2013	rho SSB	0.06	0.10	0.05	0.06	0.03
	rho Recruitment	-0.01	0.01	-0.05	-0.01	-0.03
	rho F ave N-weighted	0.02	0.00	0.07	0.02	0.05

Table 5.6 (cont.) Model fit diagnostics for the base case and sensitivity runs of the UME model.

Model Scenario		**BASE**	**L**	**M**	**N**	**O**	**P**	**Q**
Natural mortality assumption	Age-varying	X	X	X	X	X	X	X
	Time-varying (PPI)	X	X	X	X	X	X	X
	Base M	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Other adjustment to inputs from BASE		NA	2 Growth Regimes, pre/post-2000	2 Growth Regimes, temp based	2 Growth Regimes, size based	Deviations from B-H S-R curve	Env data as recr dev index (mean R)	Env data as recr dev index (B-H R)
objective function and components	objective function	19,470.70	19,402.00	19,434.90	19,440.80	19,539.10	19,228.90	19,246.10
	catch total	-90.47	-91.11	-88.78	-89.98	-90.52	-91.51	-91.74
	index fit total	62.26	59.95	63.28	58.21	53.96	30.79	30.34
	catch length comp	12,655.78	12,630.84	12,626.93	12,632.26	12,659.94	12,641.40	12,642.14
	index length comp	6,654.97	6,633.41	6,639.01	6,643.72	6,662.26	6,618.91	6,624.14
	recruit deviations	188.18	168.93	194.45	196.60	253.44	0.00	0.00
RMSE	Mixed fleet catch	0.99	1.20	0.85	0.94	0.89	1.26	1.24
	Trawl catch	1.24	0.98	1.55	1.33	1.31	0.89	0.88
	Trap catch	0.03	0.03	0.03	0.03	0.04	0.01	0.01
	index - Summer Suvey	6.30	6.39	6.25	6.11	5.75	4.77	4.73
	index - NEFSC	3.65	3.38	3.77	3.59	3.70	3.24	3.25
Terminal year (2017) estimates	SSB (mt)	709.5	732.9	754.2	772.6	527.9	539.9	527.4
	Jan 1 biomass (mt)	3,683.9	3,752.8	3,590.8	3,715.6	3,342.5	2,059.1	2,040.8
	Expl. biomass (mt)	674.6	636.9	731.6	737.0	520.6	521.7	511.1
	Total stock (millions)	2,553.1	2,570.5	2,402.5	2,487.1	2,530.3	665.0	675.8
	Recruits (millions)	2,049.0	2,079.6	1,922.9	1,995.8	2,107.5	160.8	179.5
	F ave N-weighted	0.03	0.03	0.03	0.03	0.04	0.04	0.04
Retrospective Mohn's rho, 5-yr peel to 2013	rho SSB	0.06	0.02	0.07	0.16	0.27	0.18	0.14
	rho Recruitment	-0.01	-0.02	0.03	0.05	-0.18	-0.03	-0.06
	rho F ave N-weighted	0.02	0.03	-0.01	0.00	0.18	0.03	0.03

Table 5.7 Population estimates from the base run of the ASAP model.

Year	F (N-weighted)	Recruits (billions of shrimp)	Total Abundance (billions of shrimp)	Exploitable Biomass (mt)	Spawning Stock Biomass (mt)
1985	0.39	5.71	10.6	15,444	19,512
1986	0.42	7.86	10.5	11,963	16,377
1987	1.50	4.84	7.2	9,074.9	10,089.8
1988	0.48	9.28	11.7	5,631.9	8,195.2
1989	0.41	10.08	13.3	8,147.4	9,870.1
1990	0.68	3.70	7.3	8,947.7	12,097.5
1991	0.72	4.11	5.8	7,539.3	10,910.8
1992	1.00	4.87	6.5	6,108.2	6,822.0
1993	0.57	9.29	11.1	4,539.5	5,818.8
1994	0.73	11.89	15.1	6,182.4	7,383.9
1995	1.65	8.41	14.4	10,324.7	15,215.6
1996	0.81	5.40	8.0	7,303.4	12,212.7
1997	1.45	6.64	8.6	7,073.2	8,734.8
1998	1.28	7.34	10.3	5,142.2	6,508.1
1999	0.30	7.98	10.9	6,194.1	9,591.0
2000	0.79	16.37	18.3	7,994.5	9,131.3
2001	0.66	10.20	12.4	3,926.7	3,865.3
2002	0.11	143.67	145.6	6,244.1	5,357.2
2003	0.53	25.80	30.5	4,610.6	2,963.3
2004	0.36	8.70	10.8	4,091.1	5,329.4
2005	0.31	40.12	43.3	7,610.4	8,443.9
2006	0.20	48.40	61.1	15,107.5	14,397.2
2007	0.32	9.58	21.2	24,149.8	30,900.3
2008	0.23	26.49	31.2	26,761.1	31,948.1
2009	0.22	59.18	63.3	16,441.9	15,718.8
2010	0.62	72.20	81.4	12,282.8	11,157.3
2011	0.68	19.53	24.1	6,968.4	8,128.7
2012	1.05	2.25	3.7	4,417.3	5,244.8
2013	0.46	0.37	0.6	1,344.6	1,626.3
2014	0.00	10.06	10.2	818.3	732.4
2015	0.02	2.26	3.1	594.9	287.4
2016	0.01	29.35	29.7	1,545.5	1,686.1
2017	0.08	0.89	1.5	887.5	740.6
Median	0.47	8.99	11.0	7,020.8	8,589.4
Mean	0.58	19.18	22.5	8,042.8	9,606.0

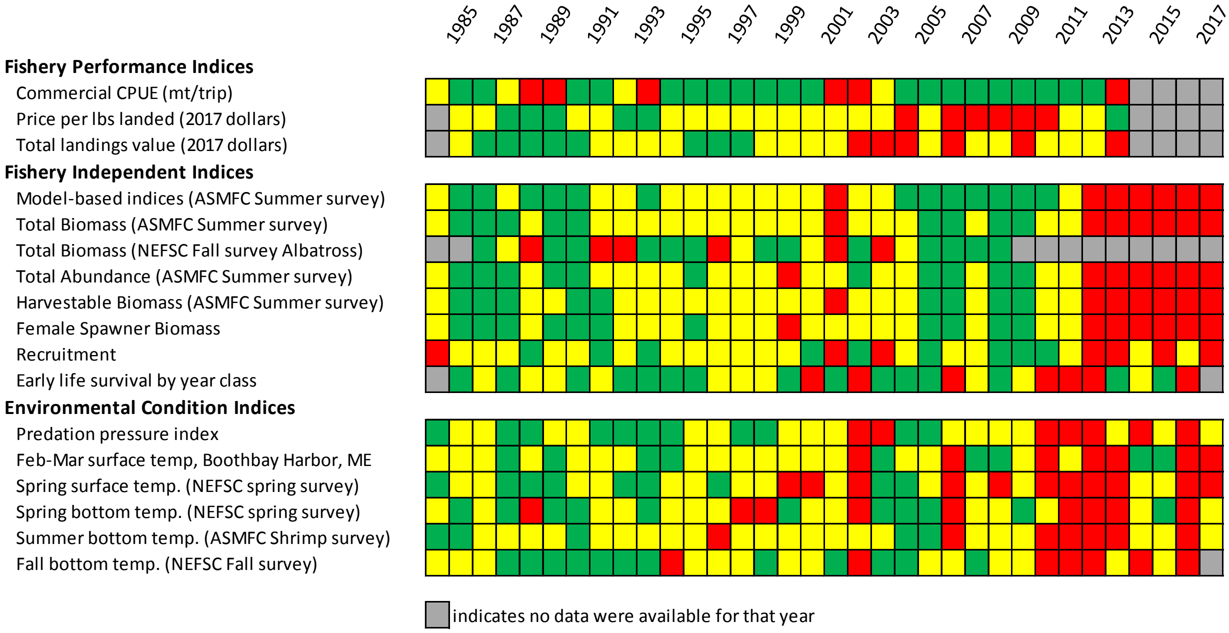
Table 5.8 ASAP model diagnostics, terminal year (2017) model estimates, and Mohn's rho retrospective biases for model base case and all sensitivity runs (Scenarios B-M). Diagnostics include objective function value (OB) and contribution to the OB by components and root mean square error (RMSE) of the standardized residuals. Terminal year estimates and Mohn's rho are given for SSB, Jan 1 and exploitable biomass, stock and recruit (age-1) abundances, and F.

Model Scenario		**BASE**	**B**	**C**	**D**	**E**	**F**	**G**
Natural mortality assumption	Age-varying	X	X					
	Time-varying (PPI)	X		X	PPI & temp		X	
	Base M	0.5	0.5	0.5	0.5	0.5	0.95	0.95
Other adjustment to inputs from BASE		NA	NA	NA	NA	NA	NA	NA
objective function and components	objective function	3,497	3,456	3,449	3,431	3,789	3,759	3,477
	catch total	-29.35	-32.81	-27.84	-34.71	-39.11	-46.04	-27.43
	index fit total	-6.48	-4.18	-13.60	-18.26	6.98	-2.42	-0.36
	catch age comp	1,547	1,547	1,539	1,545	1,565	1,563	1,540
	index age comp	1,944	1,909	1,914	1,903	2,218	2,212	1,929
	recruit deviations	40.8	37.5	36.6	35.4	38.2	33.0	36.0
RMSE	catch fleet / total catch	1.04	0.93	1.08	0.87	1.04	0.81	1.10
	discards fleet 1	0	0	0	0	0	0	0
	index - albatross	1.53	1.81	1.68	1.63	1.89	1.56	1.80
	index - bigelow	0.98	1.07	1.06	1.00	1.17	0.98	1.11
	index - summer surv	1.90	1.75	1.67	1.63	1.86	1.95	1.81
	index total	1.68	1.70	1.61	1.57	1.80	1.72	1.74
	recruitment devs	2.54	2.46	2.44	2.41	2.48	2.34	2.42
Terminal year (2017) estimates	SSB (000s) mt	0.74	1.69	0.73	0.84	1.39	1.01	1.53
	Jan 1 biomass (000s) mt	7.08	5.08	2.41	2.36	3.28	3.02	7.63
	Expl. biomass (000s) mt	0.89	2.29	0.91	1.13	1.85	1.33	1.70
	Total stock (millions)	1.47	0.71	0.35	0.31	0.42	0.44	1.23
	Age 1 (millions)	0.89	0.14	0.07	0.04	0.05	0.12	0.40
	F ave N-weighted	0.08	0.02	0.05	0.04	0.02	0.04	0.02
Retrospective Mohn's rho, 3-yr peel to 2014	rho SSB	-0.03	-0.07	0.19	-0.21	-0.02	0.00	0.18
	rho Jan 1 biomass	-0.02	0.27	0.34	0.21	0.29	0.10	0.47
	rho expl biomass	-0.62	-0.60	-0.44	-0.72	-0.55	-0.54	-0.47
	rho total stock	-0.06	0.29	0.33	0.28	0.35	0.09	0.46
	rho Age 1	-0.12	0.20	0.18	0.20	0.29	0.01	0.35
	rho F ave N-weighted	0.52	0.40	0.02	0.70	0.29	0.21	0.08

Table 5.8 Continued

Model Scenario		BASE	H	I	J	K	L	M
Natural mortality assumption	Age-varying	X	X	X	X	X	X	X
	Time-varying (PPI)	X	X	X	X	X	X	X
	Base M	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Other adjustment to inputs from BASE		NA	Design-based indices	Remove Albatross index	Remove Bigelow index	Summer index only	Catch scaled up 25% prior to 2001	Catch CV = 0.05 (CSA)
objective function and components	objective function	3,497	3,765	3,266	3,402	3,171	3,491	3,472
	catch total	-29.35	-35.60	-28.71	-30.45	-29.93	-32.96	-97.60
	index fit total	-6.48	236.0	-12.02	-4.01	-9.38	-5.46	5.43
	catch age comp	1,547	1,571	1,528	1,544	1,524	1,547	1,565
	index age comp	1,944	1,940	1,739	1,851	1,646	1,942	1,954
	recruit deviations	40.8	54.2	40.1	41.4	40.8	40.0	44.6
RMSE	catch fleet / total catch	1.04	1.02	1.06	1.01	1.02	0.93	0.28
	discards fleet 1	0	0	0	0	0	0	0
	index - albatross	1.53	3.40	NA	1.53	NA	1.54	1.53
	index - bigelow	0.98	3.76	0.96	NA	NA	1.00	1.04
	index - summer surv	1.90	3.00	1.77	1.90	1.77	1.91	2.07
	index total	1.68	3.25	1.65	1.76	1.77	1.69	1.79
	recruitment devs	2.54	2.84	2.52	2.55	2.54	2.52	2.63
Terminal year (2017) estimates	SSB (000s) mt	0.74	0.41	0.68	0.73	0.66	0.89	1.01
	Jan 1 biomass (000s) mt	7.08	3.20	6.59	7.15	6.65	8.38	8.96
	Expl. biomass (000s) mt	0.89	0.49	0.80	0.89	0.80	1.08	1.24
	Total stock (millions)	1.47	0.60	1.37	1.48	1.38	1.73	1.83
	Age 1 (millions)	0.89	0.30	0.83	0.89	0.83	1.04	1.09
	F ave N-weighted	0.08	0.14	0.08	0.08	0.09	0.06	0.06
Retrospective Mohn's rho, 3-yr peel to 2014	rho SSB	-0.03	-0.16	-0.06	0.00	-0.02	-0.02	0.09
	rho Jan 1 biomass	-0.02	0.25	-0.03	-0.01	-0.02	-0.02	0.06
	rho expl biomass	-0.62	-0.70	-0.64	-0.59	-0.61	-0.61	-0.53
	rho total stock	-0.06	0.21	-0.07	-0.05	-0.06	-0.06	0.02
	rho Age 1	-0.12	0.14	-0.13	-0.11	-0.12	-0.12	-0.04
	rho F ave N-weighted	0.52	0.87	0.57	0.45	0.49	0.50	0.33

Table 5.9 Traffic light analysis results. Red indicates unfavorable conditions or status, yellow indicates intermediate values, and green indicates favorable conditions or status.



		1985		1987		1989		1991		1993		1995		1997		1999		2001		2003		2005		2007		2009		2011		2013		2015		2017
Fishery Performance Indices																																		
Commercial CPUE (mt/trip)	🟨	🟩	🟩	🟨	🟥	🟥	🟩	🟩	🟨	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	⬜	⬜	⬜	⬜
Price per lbs landed (2017 dollars)	⬜	🟨	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	⬜	⬜	⬜	⬜
Total landings value (2017 dollars)	⬜	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟨	🟥	🟨	🟨	🟥	🟨	🟨	🟨	🟥	⬜	⬜	⬜	⬜
Fishery Independent Indices																																		
Model-based indices (ASMFC Summer survey)	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥
Total Biomass (ASMFC Summer survey)	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥
Total Biomass (NEFSC Fall survey Albatross)	⬜	⬜	🟩	🟨	🟥	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟥	🟨	🟩	🟩	🟨	🟥	🟩	🟥	🟨	🟩	🟩	🟩	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Total Abundance (ASMFC Summer survey)	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟥	🟨	🟨	🟩	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥
Harvestable Biomass (ASMFC Summer survey)	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥
Female Spawner Biomass	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥
Recruitment	🟥	🟨	🟨	🟨	🟩	🟨	🟨	🟩	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟥	🟩	🟥	🟨	🟩	🟨	🟨	🟩	🟩	🟩	🟨	🟥	🟥	🟨	🟥	🟨	🟥
Early life survival by year class	⬜	🟩	🟨	🟩	🟨	🟨	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟥	🟩	🟥	🟩	🟩	🟩	🟥	🟨	🟩	🟨	🟥	🟥	🟥	🟩	🟨	🟩	🟥	⬜
Environmental Condition Indices																																		
Predation pressure index	🟩	🟨	🟨	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟥	🟥	🟩	🟩	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟨	🟥	🟨	🟥	🟨
Feb-Mar surface temp, Boothbay Harbor, ME	🟨	🟨	🟨	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩	🟨	🟨	🟥	🟩	🟩	🟨	🟥	🟨	🟥	🟥	🟩	🟩	🟥	🟥
Spring surface temp. (NEFSC spring survey)	🟩	🟨	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟨	🟩	🟨	🟨	🟥	🟥	🟨	🟥	🟩	🟩	🟨	🟥	🟨	🟥	🟨	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥
Spring bottom temp. (NEFSC spring survey)	🟨	🟩	🟨	🟩	🟥	🟩	🟩	🟨	🟨	🟩	🟨	🟨	🟨	🟥	🟥	🟩	🟨	🟨	🟥	🟩	🟩	🟩	🟥	🟨	🟨	🟩	🟨	🟥	🟥	🟥	🟨	🟩	🟥	🟨
Summer bottom temp. (ASMFC Shrimp survey)	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟨
Fall bottom temp. (NEFSC Fall survey)	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟨	🟨	🟨	🟩	🟨	🟨	🟩	🟥	🟩	🟩	🟨	🟨	🟩	🟨	🟨	🟥	🟥	🟥	🟨	🟥	🟨	🟥	⬜

⬜ indicates no data were available for that year

Table 5.10 **Annual indicator values for fishery performance indices used in the traffic light analysis for GOM northern shrimp. Colors indicate status relative to reference levels, where: RED = at or below 20th percentile of the time series; YELLOW = between 20th percentile and the stable period (1985-1994) mean (SPM); and GREEN = at or above the SPM. Stipple indicates no data. Fishery values from 2014-2017 represent RSA effort and landings.**

Fishery Performance Indices

Fishing Season	Number trips (states & gears combined)	Commercial CPUE (mt/trip)	Price per lb landed (2017 dollars)	Total landings value (2017 dollars)
1984	6,912	0.43		
1985	6,857	0.60	$1.01	$9,200,373
1986	7,902	0.59	$1.40	$14,305,796
1987	12,497	0.42	$2.40	$27,862,903
1988	9,240	0.33	$2.31	$15,459,334
1989	9,561	0.35	$1.96	$14,326,043
1990	9,758	0.48	$1.37	$14,082,303
1991	7,968	0.45	$1.64	$12,962,943
1992	7,798	0.44	$1.74	$13,272,710
1993	6,158	0.35	$1.82	$8,598,200
1994	5,990	0.49	$1.25	$8,033,645
1995	10,465	0.62	$1.45	$20,639,831
1996	11,791	0.81	$1.15	$24,185,394
1997	10,734	0.66	$1.21	$18,991,931
1998	6,606	0.63	$1.44	$13,228,159
1999	3,811	0.49	$1.35	$5,553,367
2000	4,554	0.63	$1.13	$7,112,453
2001	4,133	0.32	$1.19	$3,491,878
2002	1,304	0.35	$1.48	$1,476,975
2003	3,022	0.44	$1.16	$3,438,133
2004	2,681	0.79	$0.58	$2,725,359
2005	3,866	0.68	$0.72	$4,143,134
2006	2,478	0.94	$0.45	$2,304,275
2007	4,163	1.17	$0.45	$4,841,053
2008	5,587	0.89	$0.56	$6,126,491
2009	3,002	0.83	$0.46	$2,536,578
2010	5,979	1.03	$0.58	$8,008,822
2011	7,095	0.90	$0.83	$11,706,442
2012	3,648	0.68	$1.02	$5,589,023
2013	1,322	0.23	$1.90	$1,447,246
2014	5		-	-
2015	50		$3.62	$53,240
2016	68		$6.85	$201,133
2017	153		$6.30	$452,379
1984-2013 mean	**6,229**	**0.60**	**$1.24**	**$9,850,027**
2014-2017 mean	**69**	**na**	**$5.59**	**$235,584**
Stable period mean: 1985-1994	8,373	0.45	$1.69	$13,810,425
20th percentile of 1984-2013	3,523	0.41	$0.66	$3,470,380

Table 5.11 Annual indicator values for fishery independent indices used in the traffic light analysis for GOM northern shrimp. Colors indicate status relative to reference levels, where: RED = at or below 20th percentile of the time series; YELLOW = between 20th percentile and the stable period (1985-1994) mean (SPM); and GREEN = at or above the SPM.

Fishery Independent Indices

Survey	Model-based Survey Indices			Total Biomass (kg/tow)		
	ASMFC Summer	NEFSC Fall Albatross	NEFSC Fall Bigelow	ASMFC Summer	NEFSC Fall Albatross	NEFSC Fall Bigelow
1984	🟨 0.94			🟨 10.5		
1985	🟩 1.47			🟩 17.7		
1986	🟩 1.15	🟩 0.68		🟩 19.6	🟩 2.5	
1987	🟨 0.83	🟥 0.40		🟩 15.4	🟨 1.4	
1988	🟩 1.24	🟥 0.34		🟨 12.8	🟥 1.1	
1989	🟩 1.24	🟩 0.78		🟩 17.0	🟩 2.0	
1990	🟩 1.12	🟩 0.59		🟩 18.1	🟩 1.7	
1991	🟨 0.82	🟥 0.32		🟨 11.7	🟥 0.8	
1992	🟨 0.47	🟥 0.19		🟨 9.4	🟥 0.6	
1993	🟩 1.17	🟩 1.04		🟨 9.1	🟩 1.7	
1994	🟨 1.02	🟩 1.09		🟨 8.7	🟩 2.2	
1995	🟨 0.98	🟩 0.59		🟨 13.3	🟩 1.6	
1996	🟨 0.78	🟥 0.40		🟨 8.8	🟥 1.1	
1997	🟨 0.85	🟨 0.53		🟨 7.7	🟨 1.2	
1998	🟨 0.55	🟩 0.97		🟨 6.3	🟩 2.2	
1999	🟨 0.61	🟩 1.21		🟨 5.8	🟩 2.2	
2000	🟨 0.76	🟩 0.96		🟨 6.4	🟨 1.4	
2001	🟥 0.28	🟨 0.50		🟥 4.3	🟥 0.6	
2002	🟨 1.03	🟨 0.69		🟨 9.2	🟩 1.7	
2003	🟨 0.73	🟨 0.40		🟨 5.5	🟥 1.0	
2004	🟩 1.14	🟩 0.88		🟨 10.3	🟨 1.4	
2005	🟩 2.27	🟩 2.85		🟩 23.4	🟩 2.6	
2006	🟩 4.35	🟩 3.69		🟩 66.0	🟩 7.5	
2007	🟩 1.57	🟩 2.41		🟨 11.5	🟩 4.1	
2008	🟩 1.66	🟩 1.51		🟩 16.8	🟩 3.4	
2009	🟩 1.67		🟩 3.56	🟩 15.4		🟩 7.8
2010	🟩 1.49		🟩 1.80	🟨 13.9		🟩 5.0
2011	🟨 0.92		🟩 1.55	🟨 8.6		🟩 5.6
2012	🟥 0.25		🟩 0.48	🟥 2.5		🟩 121.6
2013	🟥 0.06		🟥 0.13	🟥 1.0		🟩 1.2
2014	🟥 0.20		🟩 0.26	🟥 1.7		🟩 1.9
2015	🟥 0.06		🟥 0.13	🟥 1.3		🟥 0.7
2016	🟥 0.25		🟥 0.09	🟥 3.8		🟥 0.5
2017	🟥 0.08			🟥 0.9		
1984-2013 mean	**1.11**	**1.00**	**1.50**	**12.9**	**2.0**	**28.2**
2014-2017 mean	**0.15**	**na**	**0.16**	**1.9**	**na**	**1.1**
Stable period mean: 1985-1994	**1.04**	**0.54**	**na**	**14.1**	**1.5**	**na**
20th percentile of 1984-2017	**0.39**	**0.40**	**0.13**	**5.0**	**1.1**	**0.9**

Table 5.11 Continued

Fishery Independent Indices (continued)					
	Harvestable Biom. >22 mm CL (kg/tow)	Spawner Biomass (kg/tow)	Total Abundance (#/tow)	Recruitment (age 1.5) (#/tow)	Early life survival by year class
Survey			ASMFC Summer		
1984	3.4	3.6	1,151.9	18.4	
1985	11.5	5.7	1,825.4	332.2	496.3
1986	10.0	7.2	1,694.7	358.1	286.7
1987	9.5	6.2	1,532.8	342.0	558.7
1988	3.4	2.5	1,268.8	827.9	221.8
1989	6.1	5.0	1,883.6	276.3	274.2
1990	12.0	6.0	1,623.2	141.7	476.3
1991	8.0	6.5	1,255.9	482.1	225.8
1992	4.8	4.3	955.1	281.6	565.4
1993	2.8	2.2	1,156.9	756.6	430.5
1994	2.7	2.3	984.1	368.1	664.3
1995	7.0	6.2	1,448.6	292.1	505.6
1996	4.0	3.1	775.6	231.9	294.4
1997	2.8	2.3	761.6	373.8	211.6
1998	1.9	1.8	582.8	134.0	239.0
1999	1.9	1.5	398.1	113.7	1,294.5
2000	3.2	2.9	807.6	450.3	56.7
2001	1.5	1.7	451.3	17.6	1,991.9
2002	2.9	2.8	1,445.5	1,164.5	34.5
2003	1.7	2.0	564.2	10.7	527.3
2004	5.3	3.1	886.7	286.4	5,154.6
2005	10.3	9.2	3,661.1	1,752.5	589.5
2006	29.9	28.4	9,997.6	374.3	14.9
2007	4.1	3.4	886.6	28.3	90.7
2008	10.8	5.9	1,737.0	505.7	827.5
2009	8.5	6.4	1,627.3	554.5	390.6
2010	4.8	3.9	1,372.7	474.7	33.8
2011	3.2	3.0	830.1	43.7	8.5
2012	0.9	0.7	137.9	6.7	1.6
2013	0.3	0.2	27.4	0.9	779.0
2014	0.2	0.3	138.7	116.2	58.3
2015	0.4	0.4	58.3	2.7	5,290.9
2016	1.2	1.1	331.5	225.8	15.7
2017	0.2	0.1	26.0	0.1	
1984-2013 mean	**6.0**	**4.7**	**1,457.7**	**366.7**	**594.7**
2014-2017 mean	**0.5**	**0.5**	**138.6**	**86.2**	**1,788.3**
Stable period mean: 1985-1994	**7.1**	**4.9**	**1,434.8**	**381.7**	**392.8**
20th percentile of 1984-2017	**1.6**	**1.6**	**430.0**	**24.3**	**57.0**

Table 5.12 **Annual indicator values for environmental condition indices used in the traffic light analysis for GOM northern shrimp. Colors indicate status relative to reference levels, where: RED = at or above the 80th percentile of the time series; YELLOW = between 80th percentile and the stable period (1985-1994) mean (SPM); and GREEN = at or below the SPM.**

Environmental Condition Indices

	Predation Pressure Index	Summer bottom temp.	Fall bottom temp.	Spring bottom temp.	Feb-Mar surface temp.	Spring surface temp.
Survey	NEFSC Fall	ASMFC Summer	NEFSC Fall	NEFSC Spring	Boothbay Hbr, ME	NEFSC Spring
1984	434.3	4.14	0.8	0.6	2.9	-0.1
1985	597.8	4.05	0.6	0.1	2.8	0.1
1986	608.1	6.26	0.7	1.2	2.6	0.8
1987	387.8	6.00	0.0	0.0	1.8	-0.6
1988	503.1	6.48	-0.1	1.3	2.7	-0.2
1989	520.4	5.57	-0.3	-0.1	1.9	-0.6
1990	631.3	3.55	0.1	0.2	2.6	0.0
1991	501.8	6.10	0.1	0.5	3.4	0.6
1992	486.7	6.33	-0.2	0.6	3.2	-0.9
1993	470.1	5.81	-0.3	-0.8	1.2	-0.7
1994	351.9	6.76	1.3	0.6	1.8	0.2
1995	638.5	6.55	0.5	0.8	3.3	0.1
1996	564.8	7.10	1.1	1.0	3.3	-0.2
1997	378.1	6.82	0.5	1.4	3.7	0.0
1998	466.6	6.35	-0.4	1.3	2.9	0.5
1999	738.7	6.06	0.6	0.3	2.9	0.9
2000	813.7	6.71	0.7	1.1	3.1	0.9
2001	723.3	6.53	0.1	0.7	2.9	0.4
2002	1,305.8	7.05	1.3	1.3	4.1	1.2
2003	1,040.8	5.60	-0.1	-0.2	2.4	-0.6
2004	487.8	4.73	-1.1	-0.8	3.0	-0.9
2005	471.3	4.93	0.5	0.1	3.0	0.2
2006	663.5	7.11	1.2	1.3	5.5	0.9
2007	704.7	5.90	-0.3	0.5	2.0	0.0
2008	846.3	5.87	0.4	0.5	2.3	1.2
2009	740.6	6.01	0.7	0.4	2.6	0.4
2010	1,126.5	7.39	1.7	0.9	4.1	1.7
2011	1,150.4	7.71	1.4	2.3	2.9	0.9
2012	1,156.6	7.86	2.0	2.0	5.5	1.9
2013	769.3	7.12	1.2	1.3	3.9	1.8
2014	955.1	6.23	1.4	0.5	2.2	0.5
2015	832.2	5.80	0.3	0.1	1.4	0.1
2016	1,518.4	7.20	2.0	1.4	4.1	1.7
2017	948.2	6.90		1.0	3.8	0.9
1984-2013 mean	**676.0**	**6.15**	**0.5**	**0.7**	**3.0**	**0.3**
2014-2017 mean	**1,063.5**	**6.53**	**1.2**	**0.8**	**2.9**	**0.8**
Stable period mean: 1985-1994	**514.2**	**5.43**	**0.1**	**0.4**	**2.4**	**-0.1**
80th percentile of 1984-2017	**950.9**	**7.07**	**1.3**	**1.3**	**3.8**	**0.9**

Table 5.13 Quota recommendation from the data-poor method. Quota recommendations are constrained so that catch does not increase or decrease more than 20% from the previous year's catch.

Method	Quota (mt)
GB slope	19.9
I-slope 1	27.5
SBT1	21.9
Average of unconstrained	23.1
Average of constrained	26.5

Table 6.1. Short term harvest projections for the UME model under different F scenarios for the average M scenario.

Model	Year	Trawl F	Trap F	Trawl TAC	Trap TAC	p(SSB > SSB_{2017})
M=Time series mean, R=Recent recruitment	2018	0	0	0 mt (0 lbs)	0 mt (0 lbs)	22%
	2019			0 mt (0 lbs)	0 mt (0 lbs)	100%
	2020			0 mt (0 lbs)	0 mt (0 lbs)	100%
	2018	0.02	0	10.7 mt (23,643 lbs)	1 mt (2,148 lbs)	17%
	2019			13.2 mt (29,005 lbs)	1.3 mt (2,857 lbs)	100%
	2020			15.2 mt (33,611 lbs)	1.4 mt (3,093 lbs)	100%
	2018	0.08	0.01	52 mt (114,714 lbs)	4.7 mt (10,433 lbs)	8%
	2019			62 mt (136,730 lbs)	5.9 mt (13,079 lbs)	100%
	2020			69 mt (152,137 lbs)	6.2 mt (13,754 lbs)	100%
	2018	0.23	0.03	130.2 mt (287,008 lbs)	11.8 mt (26,041 lbs)	1%
	2019			141.1 mt (311,078 lbs)	13.5 mt (29,871 lbs)	76%
	2020			153.1 mt (337,627 lbs)	13.4 mt (29,546 lbs)	69%
	2018	0.51	0.06	267.4 mt (589,567 lbs)	23.8 mt (52,415 lbs)	0%
	2019			241.1 mt (531,570 lbs)	21.8 mt (48,020 lbs)	0%
	2020			248.6 mt (547,987 lbs)	20 mt (44,183 lbs)	8%
	2018	0.85	0.1	395.8 mt (872,560 lbs)	34.7 mt (76,547 lbs)	0%
	2019			298.9 mt (659,010 lbs)	25.6 mt (56,454 lbs)	0%
	2020			314.2 mt (692,716 lbs)	21.7 mt (47,899 lbs)	1%
	2018	1.7	0.2	611.7 mt (1,348,485 lbs)	52.1 mt (114,885 lbs)	0%
	2019			326.8 mt (720,396 lbs)	23.2 mt (51,248 lbs)	0%
	2020			395.6 mt (872,076 lbs)	20.5 mt (45,291 lbs)	0%

Table 6.2. Short term harvest projections for the UME model under different F scenarios for the high M scenario.

Model	Year	Trawl F	Trap F	Trawl TAC	Trap TAC	p(SSB > SSB_{2017})
M=Recent M, R=Time series mean	2018	0	0	0 mt (0 lbs)	0 mt (0 lbs)	3%
	2019			0 mt (0 lbs)	0 mt (0 lbs)	39%
	2020			0 mt (0 lbs)	0 mt (0 lbs)	6%
	2018	0.02	0	10.2 mt (22,449 lbs)	0.9 mt (2,024 lbs)	3%
	2019			10 mt (22,097 lbs)	1 mt (2,153 lbs)	30%
	2020			9 mt (19,760 lbs)	0.8 mt (1,820 lbs)	5%
	2018	0.08	0.01	49.6 mt (109,400 lbs)	4.5 mt (9,969 lbs)	1%
	2019			46.2 mt (101,957 lbs)	4.6 mt (10,054 lbs)	4%
	2020			40.3 mt (88,875 lbs)	3.6 mt (7,997 lbs)	2%
	2018	0.23	0.03	124.6 mt (274,633 lbs)	11.2 mt (24,751 lbs)	0%
	2019			106 mt (233,642 lbs)	10.1 mt (22,319 lbs)	0%
	2020			89.8 mt (197,983 lbs)	7.7 mt (16,880 lbs)	0%
	2018	0.51	0.06	254.9 mt (561,939 lbs)	22.6 mt (49,800 lbs)	0%
	2019			181.2 mt (399,548 lbs)	16.7 mt (36,725 lbs)	0%
	2020			148.9 mt (328,294 lbs)	11.6 mt (25,519 lbs)	0%
	2018	0.85	0.1	382 mt (842,216 lbs)	32.9 mt (72,559 lbs)	0%
	2019			223.2 mt (492,013 lbs)	19.5 mt (42,950 lbs)	0%
	2020			182.6 mt (402,621 lbs)	12.3 mt (27,031 lbs)	0%
	2018	1.7	0.2	589.9 mt (1,300,613 lbs)	49 mt (107,991 lbs)	0%
	2019			239.1 mt (527,186 lbs)	17.5 mt (38,645 lbs)	0%
	2020			230.3 mt (507,697 lbs)	11.5 mt (25,278 lbs)	0%

10 FIGURES

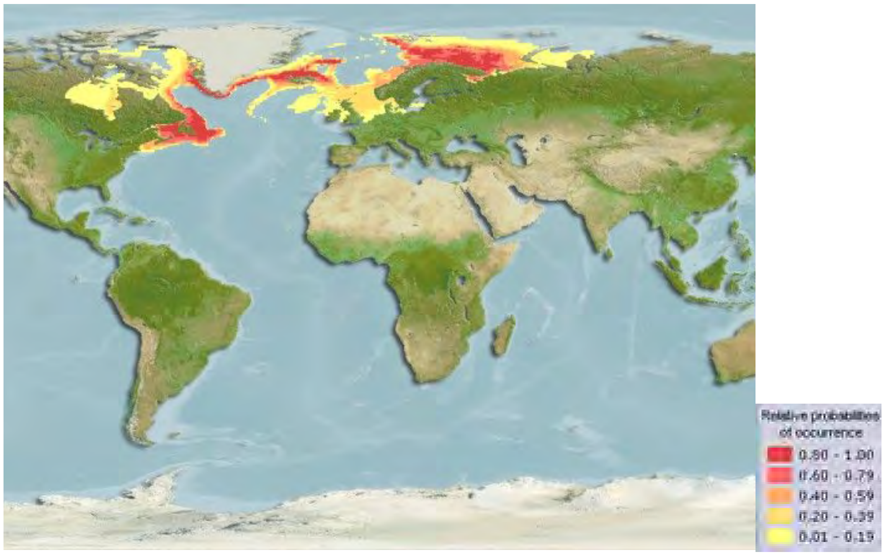


Figure 1.1 Range distribution of northern shrimp with relative probabilities of occurrence. (www.aquamaps.org)

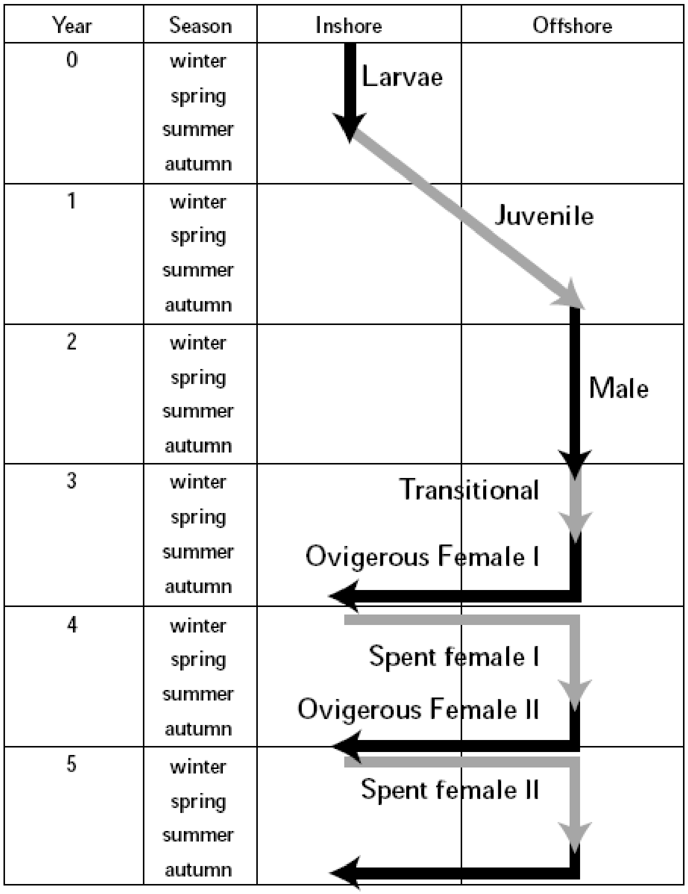


Figure 1.2 Life cycle of northern shrimp in the Gulf of Maine (Clark et al. 2000)

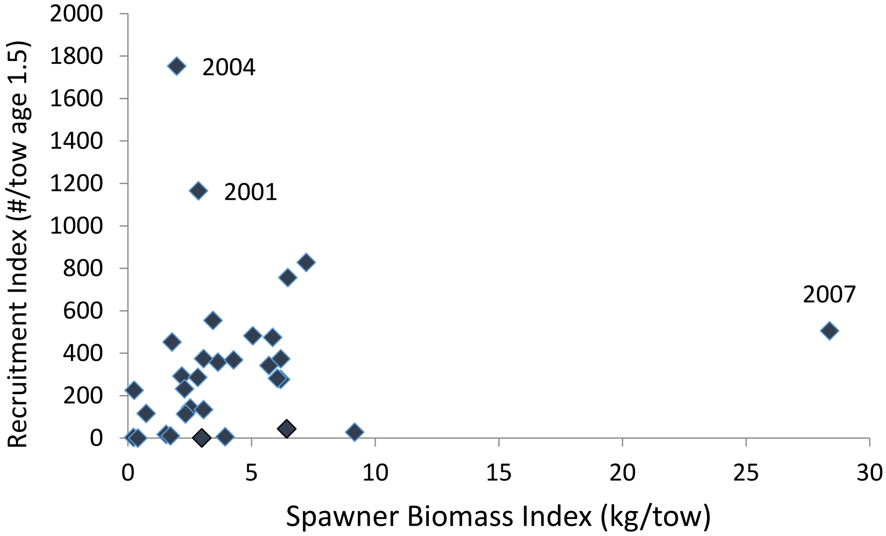


Figure 1.3 **Relationship between summer survey index of Gulf of Maine female northern shrimp biomass the summer before spawning to age 1.5 abundance two years later. Year labels indicate the assumed age 1.5 year class.**

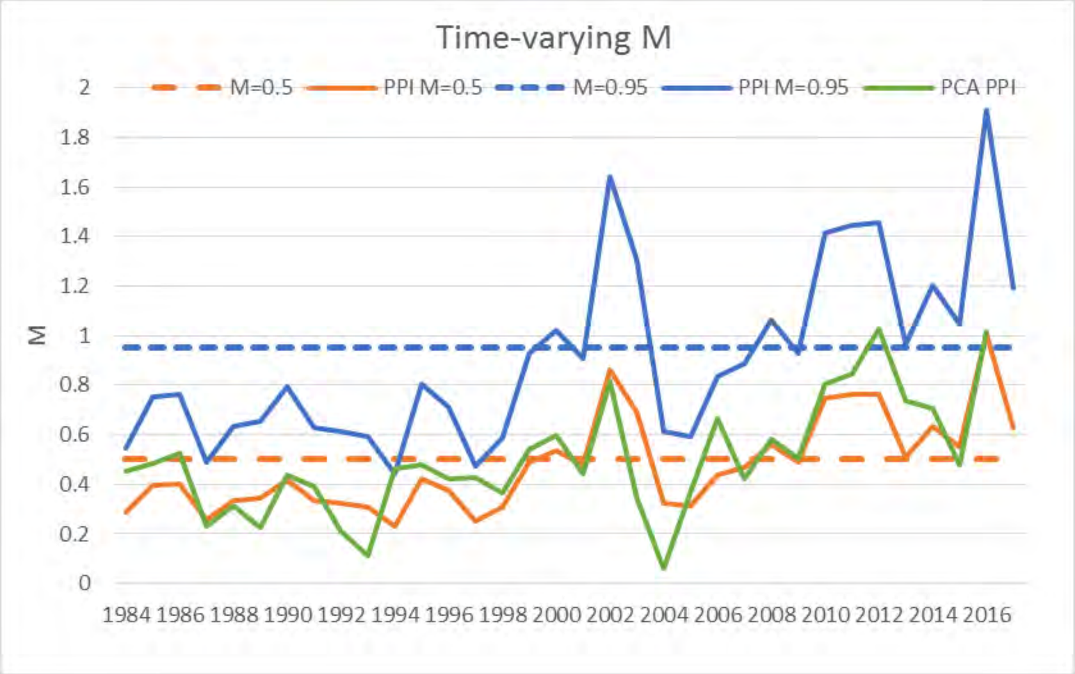


Figure 1.4 **Scaling of time-varying M scenarios over the time series.**

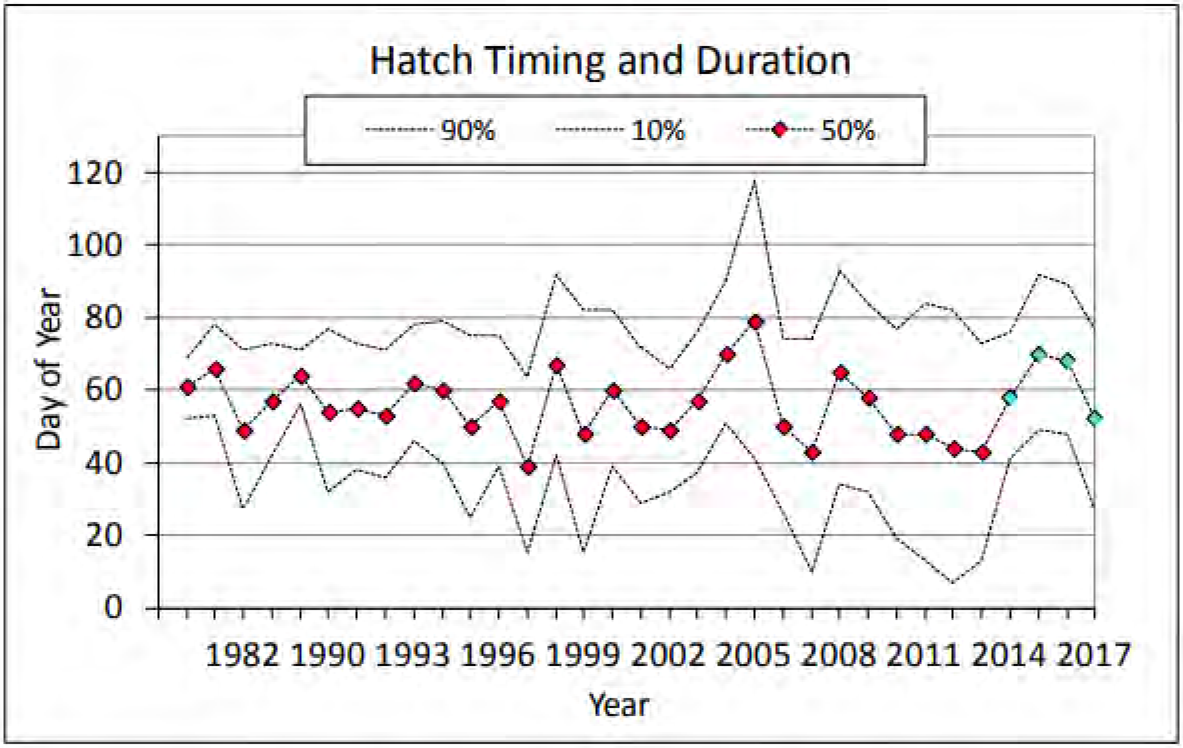


Figure 1.5 **Timing and duration of the hatch period for northern shrimp in the Gulf of Maine. Turquoise points indicate winter sampling done by the states while the fishery was closed.**

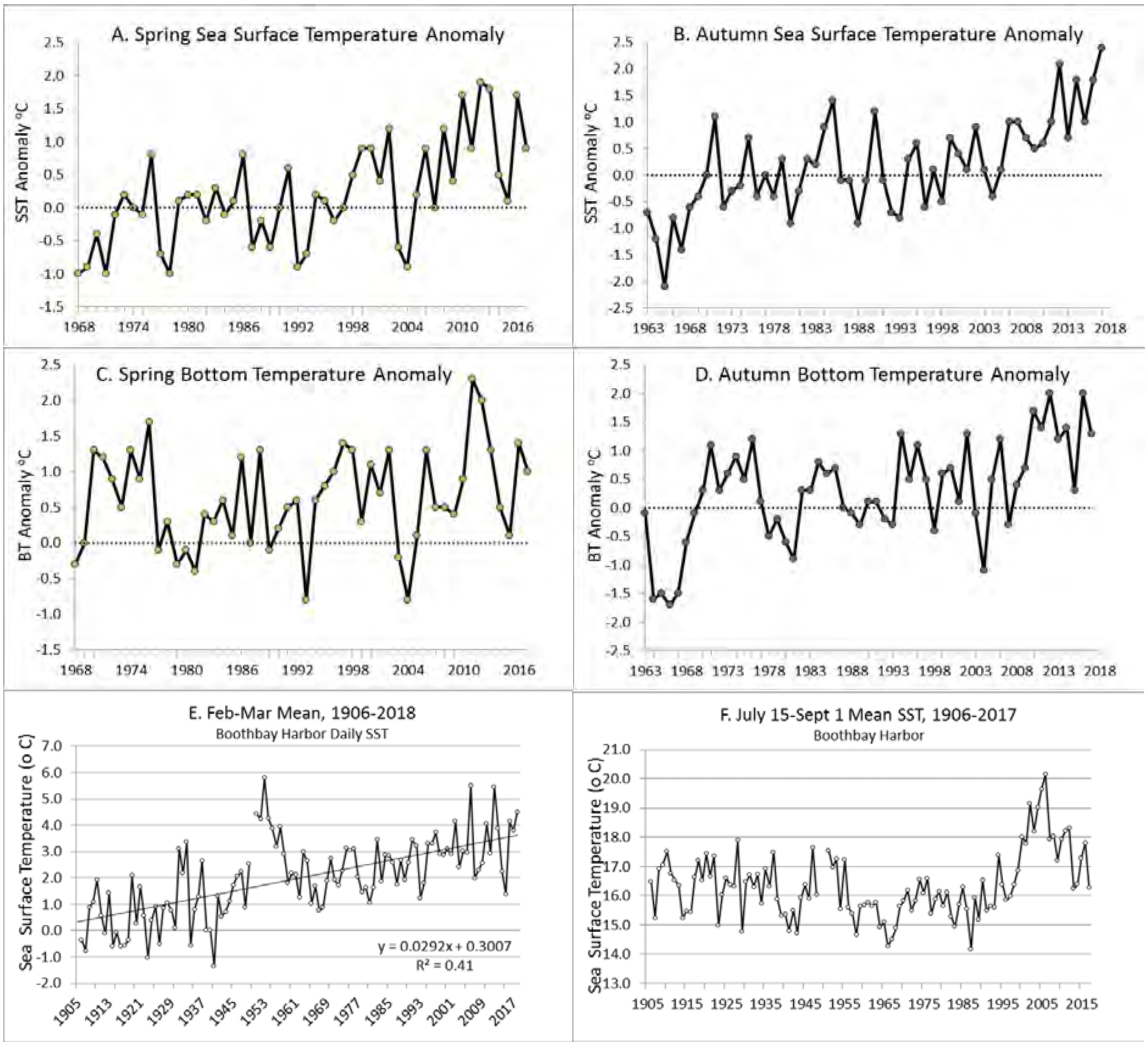


Figure 1.6 Ocean temperature anomalies in the Gulf of Maine. (A) spring and (B) autumn sea surface temperature anomalies in shrimp offshore habitat areas from NEFSC trawl surveys, 1968-2017 (through 2016 autumn temperatures). (C) spring and (D) autumn bottom temperature anomalies in shrimp offshore habitat areas from NEFSC trawl survey, 1968-2017 (through 2016 for autumn temperatures). (E-F) average sea surface temperature during (E) February-March and (F) July 15-September 1 at Boothbay Harbor, Maine, 1906-2917.

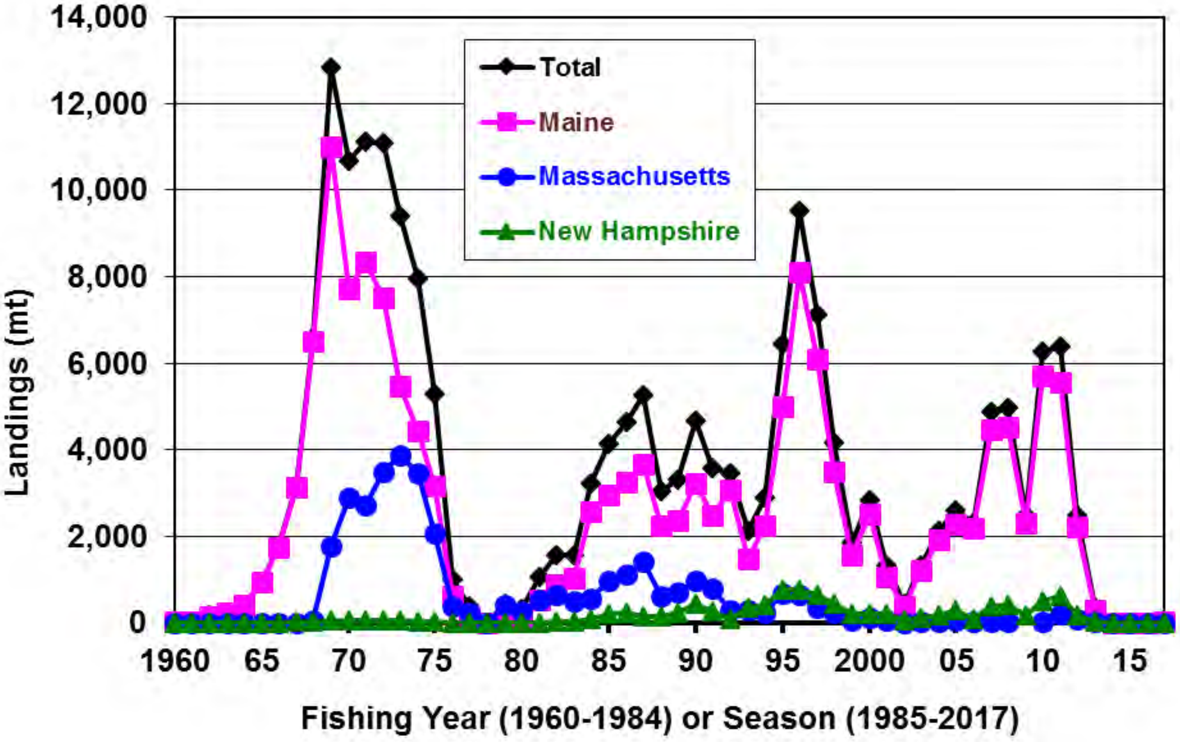


Figure 2.1 U.S. commercial landings (mt) of northern shrimp in the Gulf of Maine, by season and state. Massachusetts landings are combined with New Hampshire landings in 2009 to preserve confidentiality. Landings in 2014 are from Maine cooperative sampling trip catches. Landings in 2015 - 2017 are from the RSA program catches.

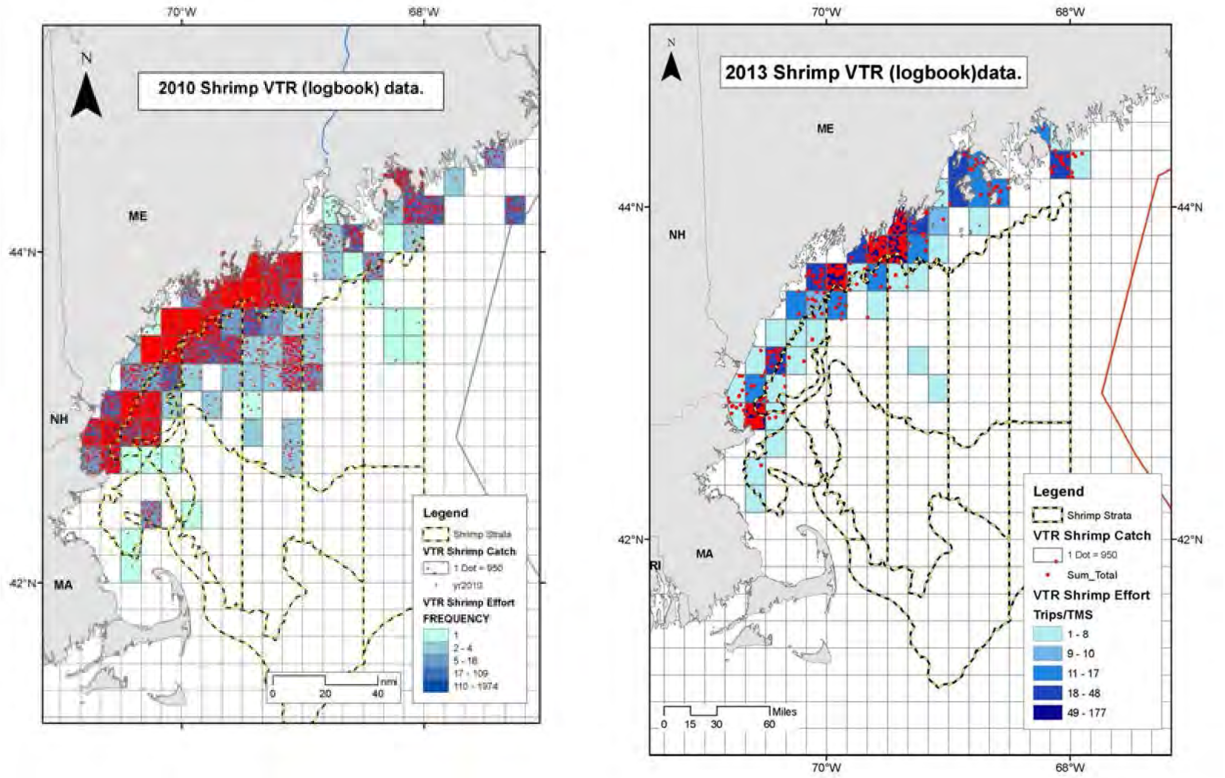


Figure 2.2 Pounds caught and numbers of trips during the 2010 (left) and 2013 (right) northern shrimp fishing seasons by 10-minute-square. Each red dot represents 950 lbs caught; locations of dots within squares are random and do not reflect the actual location of the catch. Number of trips is indicated by the blue palette for the squares. From preliminary state and federal harvester logbook (VTR) data.

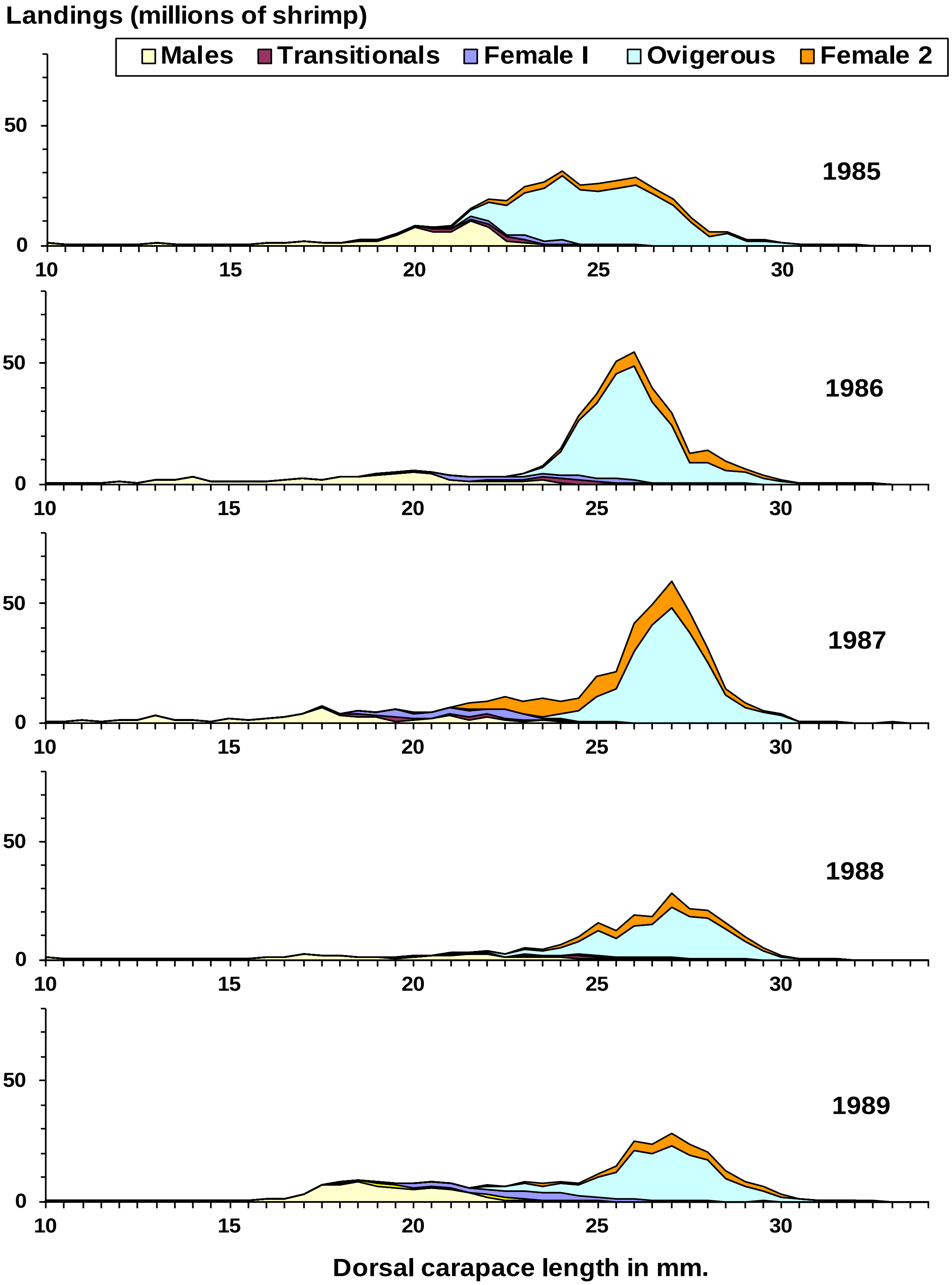


Figure 2.3 Gulf of Maine northern shrimp landings in estimated numbers of shrimp, by length, development stage, and fishing season.

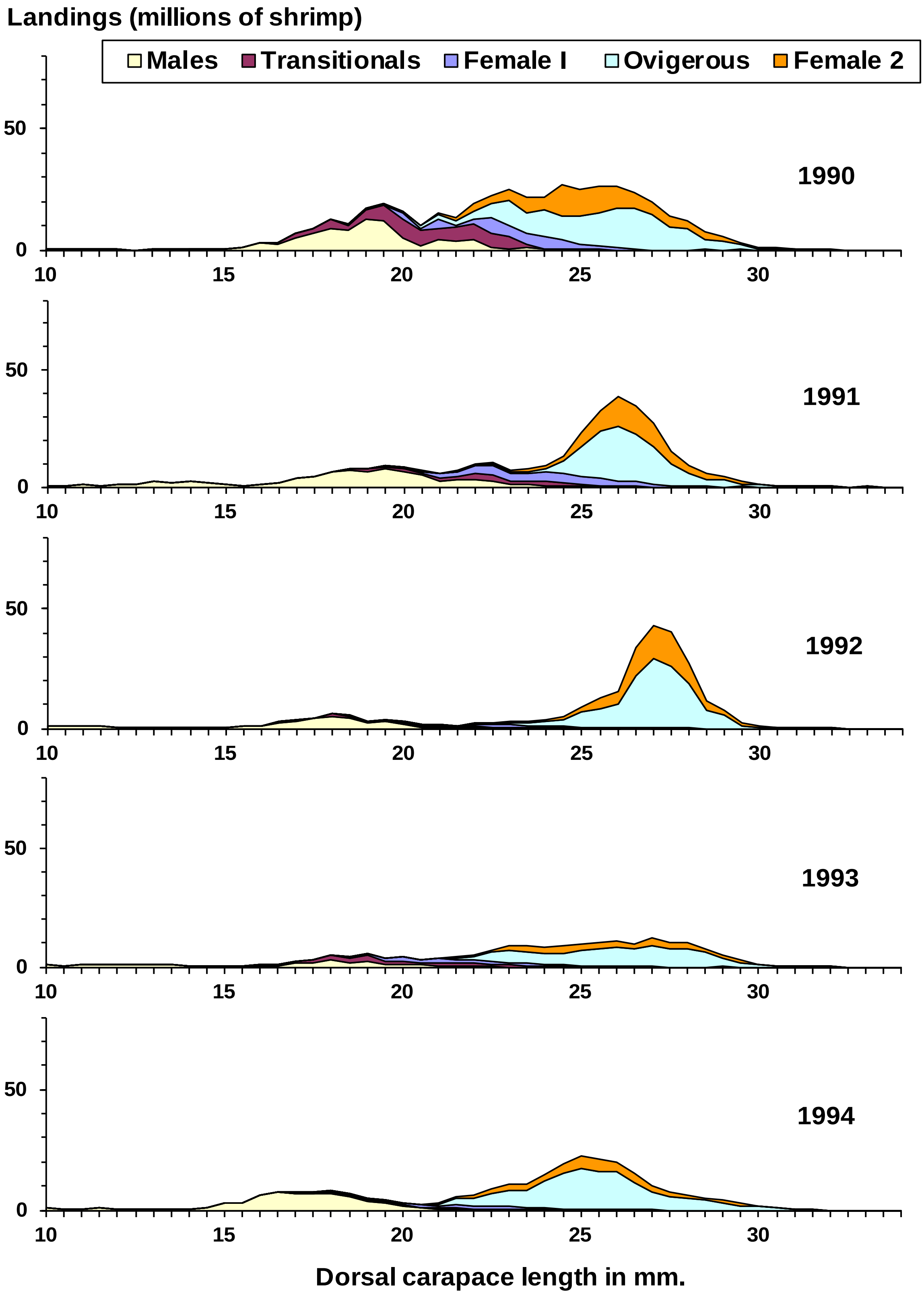


Figure 2.3 continued Landings in estimated numbers of shrimp.

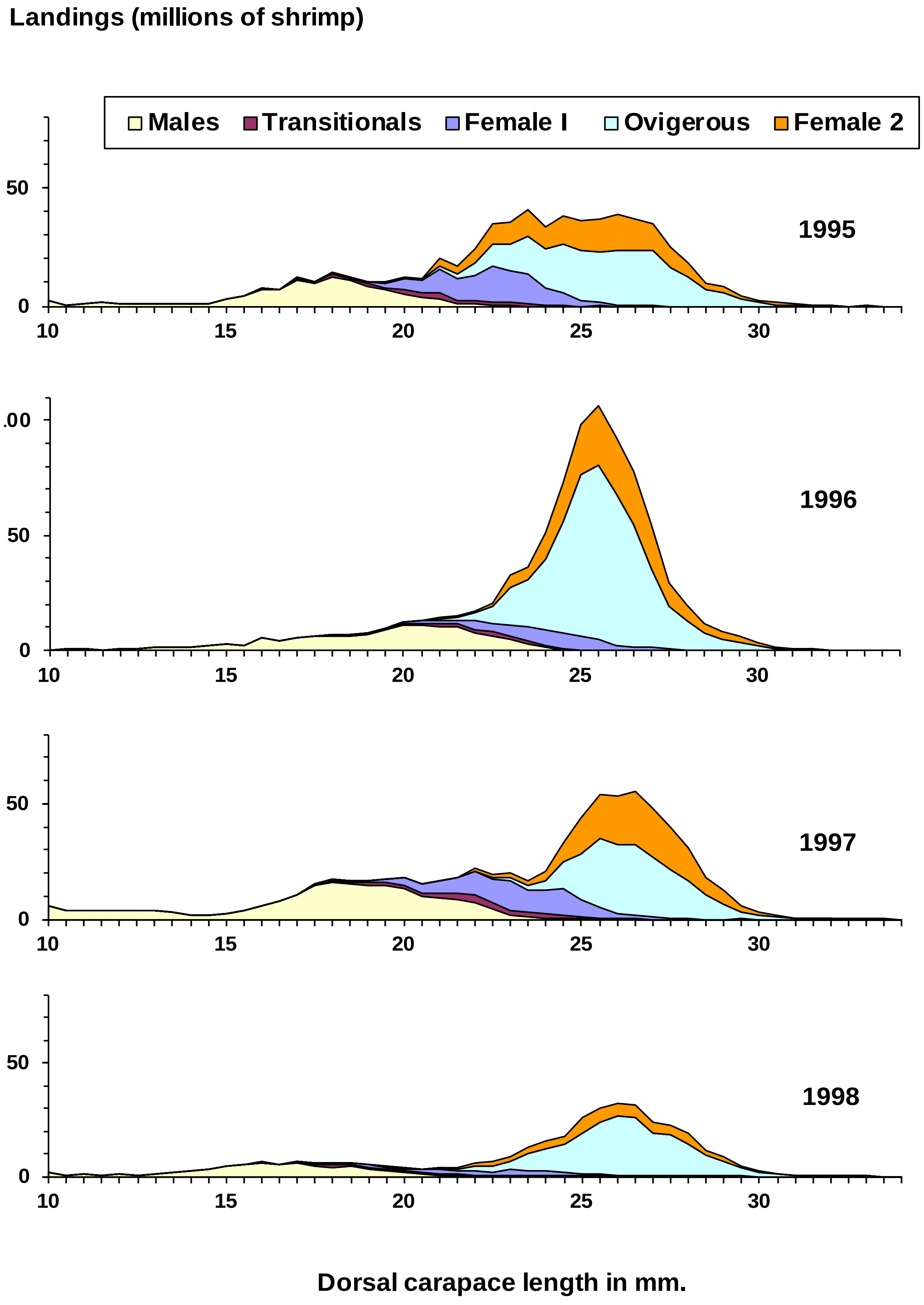


Figure 2.3 continued Landings in estimated numbers of shrimp.

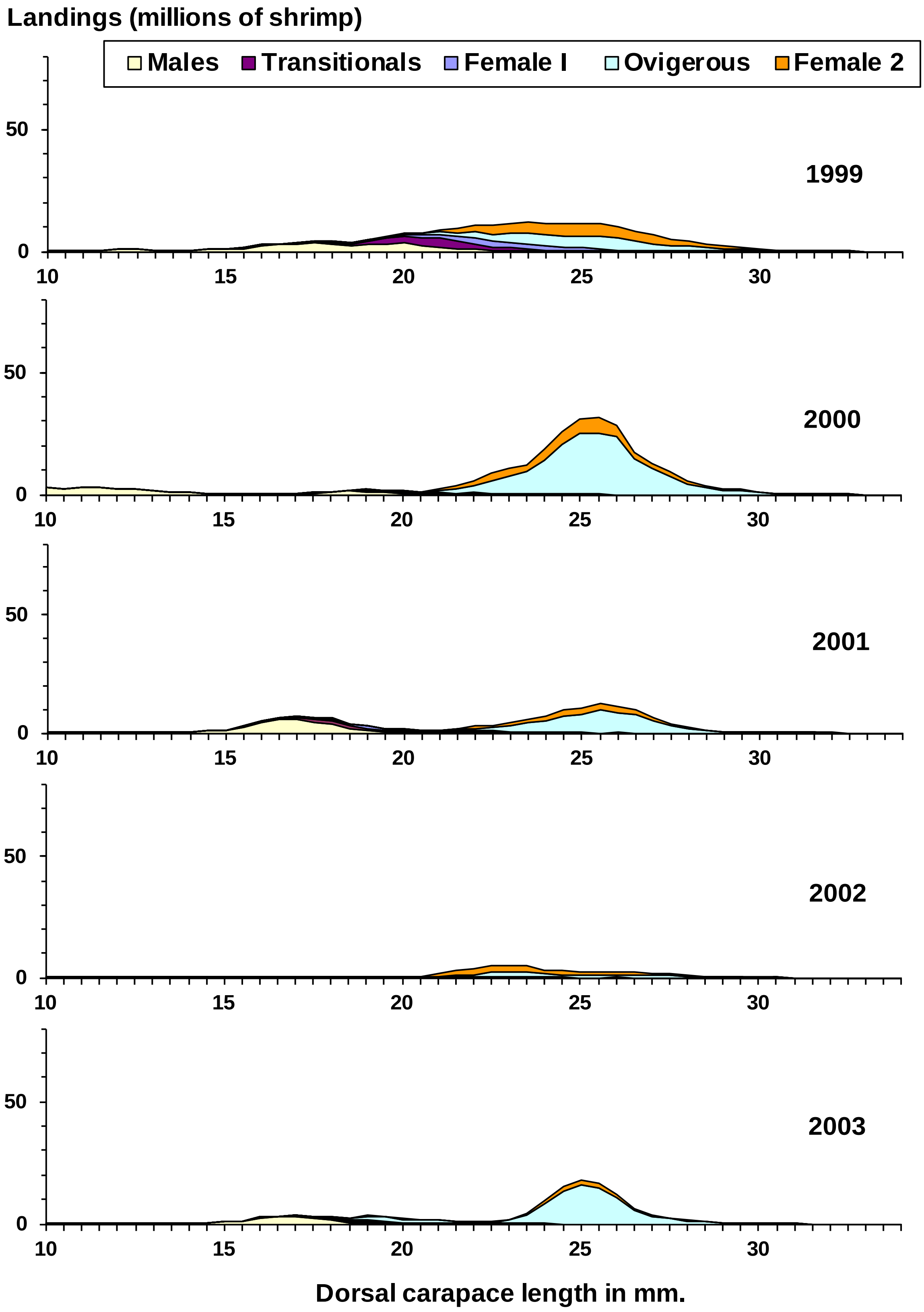


Figure 2.3 continued Landings in estimated numbers of shrimp.

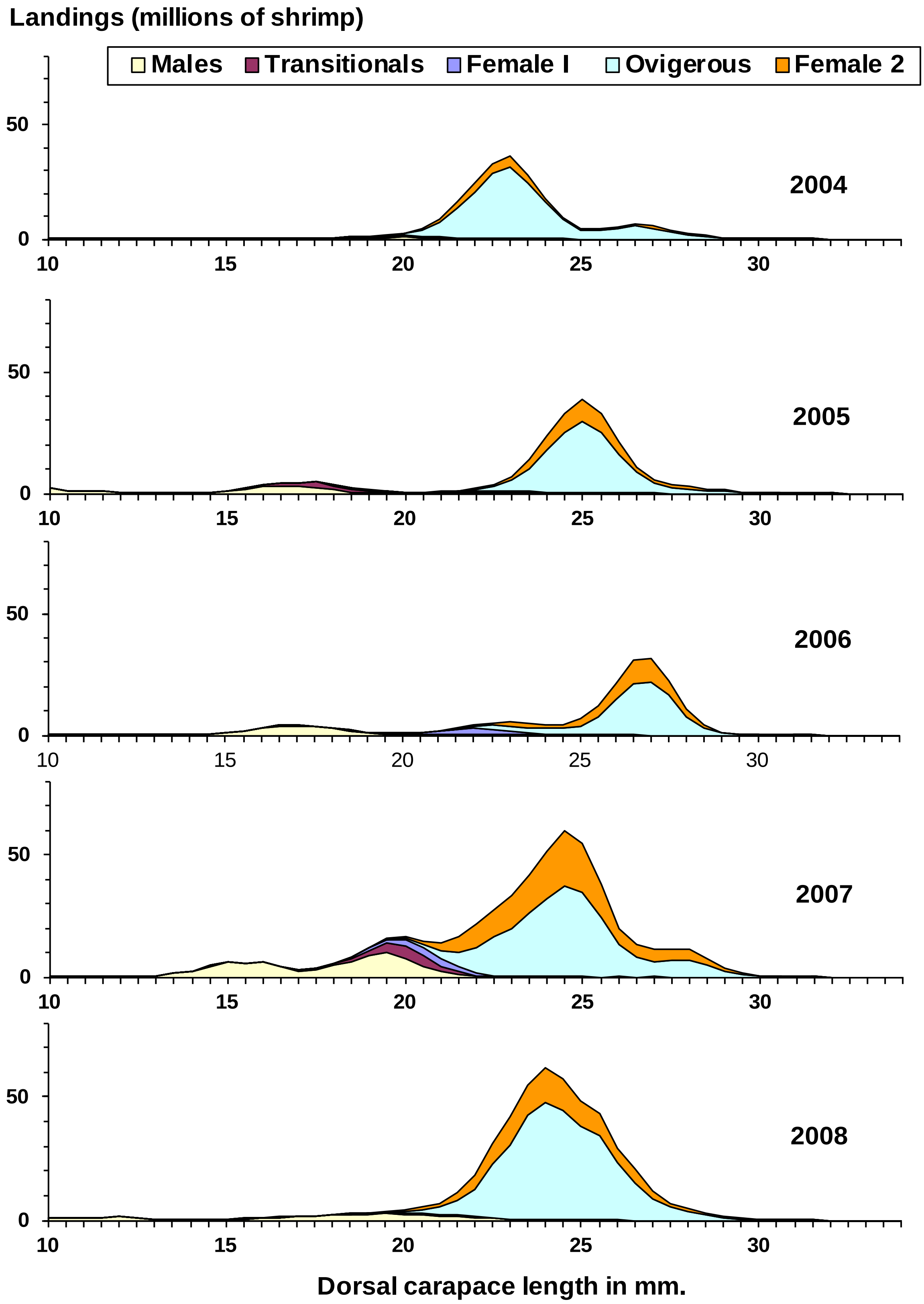


Figure 2.3 continued Landings in estimated numbers of shrimp.

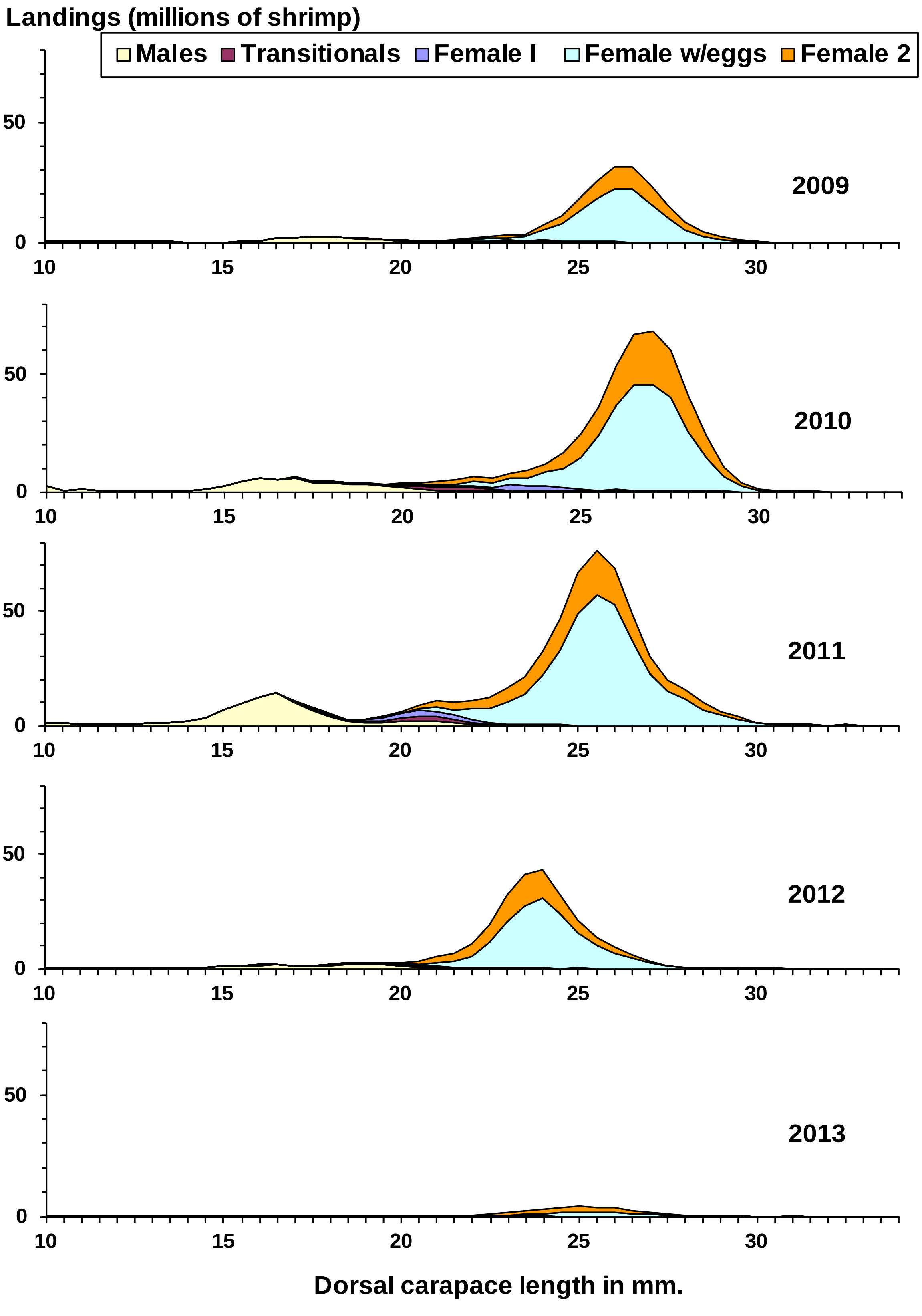


Figure 2.3 continued Landings in estimated numbers of shrimp.

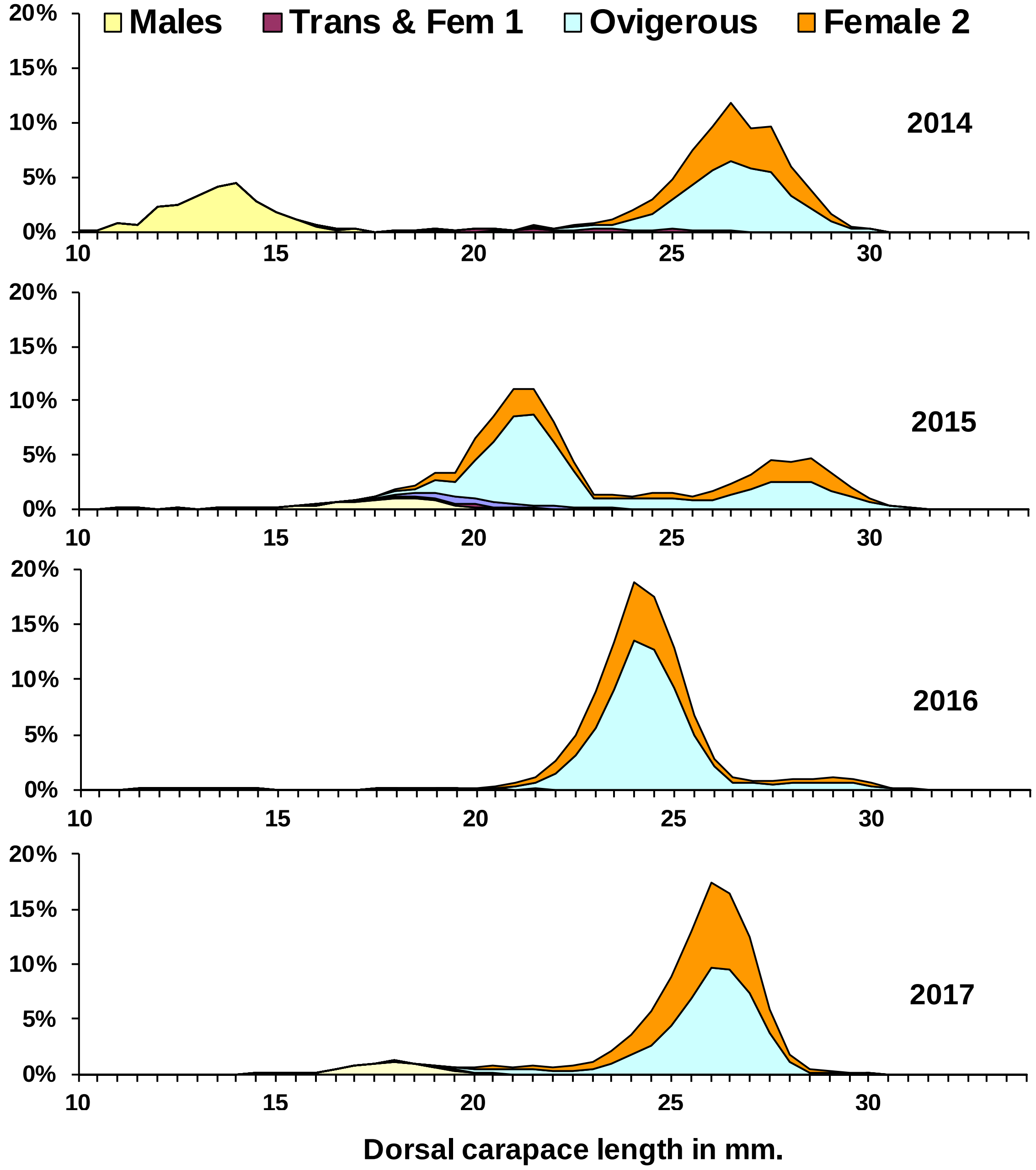
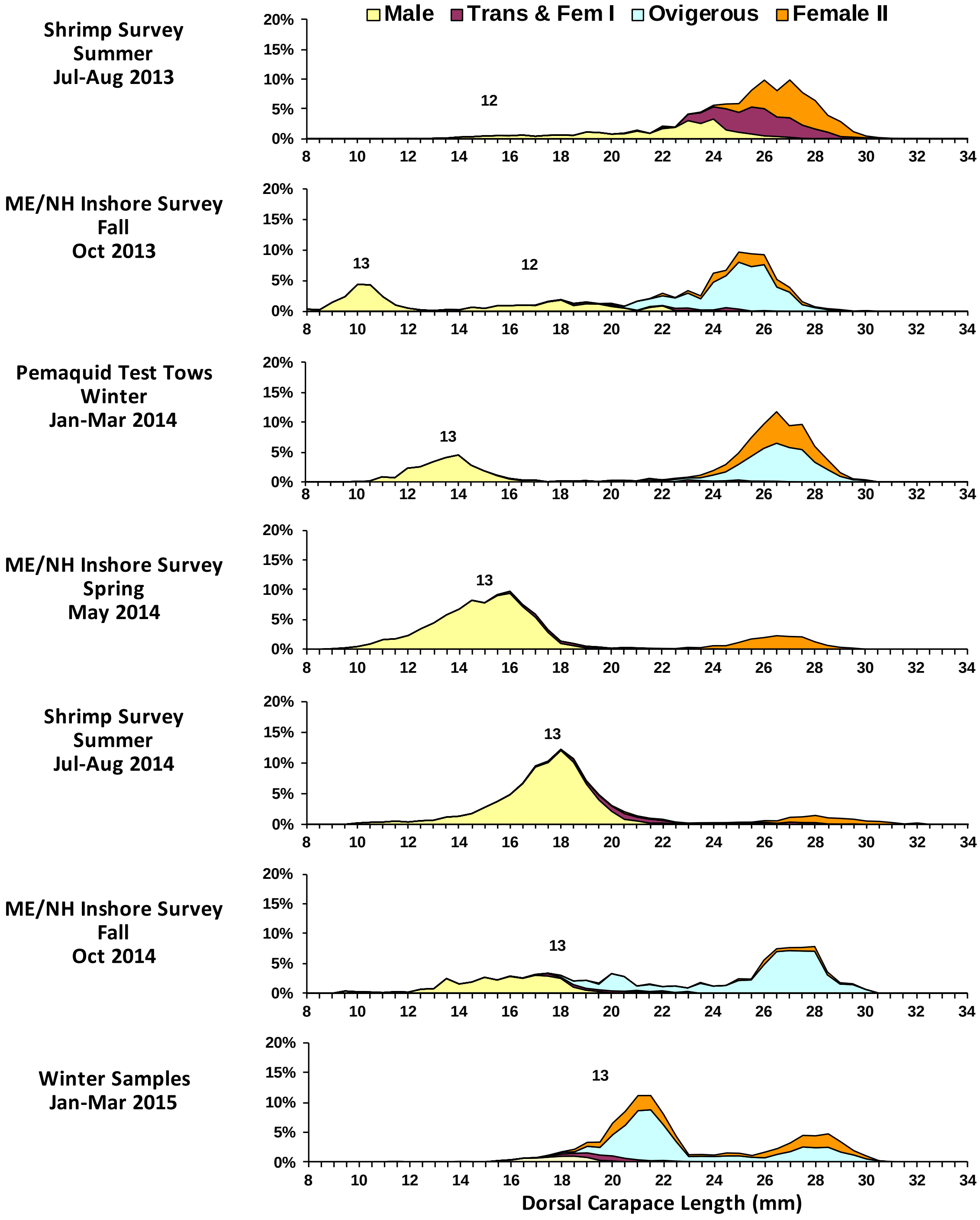


Figure 2.3 continued Landings in estimated numbers of shrimp, expressed as percentages. 2014 data are from Maine cooperative winter sampling catches. 2015–2017 data are from the Gulf of Maine RSA program. See Hunter (2014, 2016), Whitmore et al. 2015, and Hunter et al. 2017 for details.



Continued on next page

Figure 2.4 Northern shrimp relative size-sex-stage frequencies from 2013–2017 Gulf of Maine surveys and sampling programs. Two-digit years denote the mode of assumed 2012–2015 year classes.

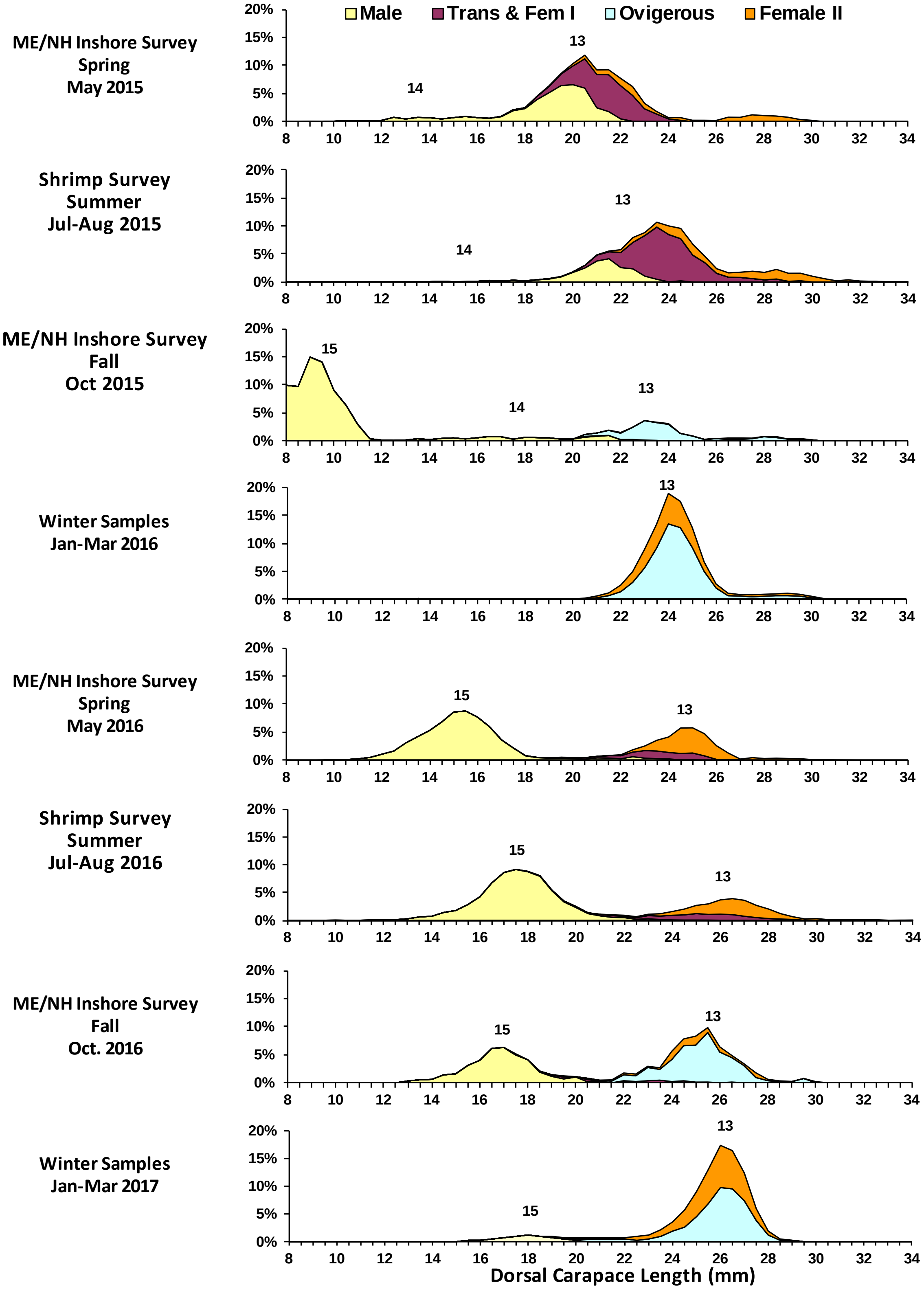


Figure 2.4 Continued

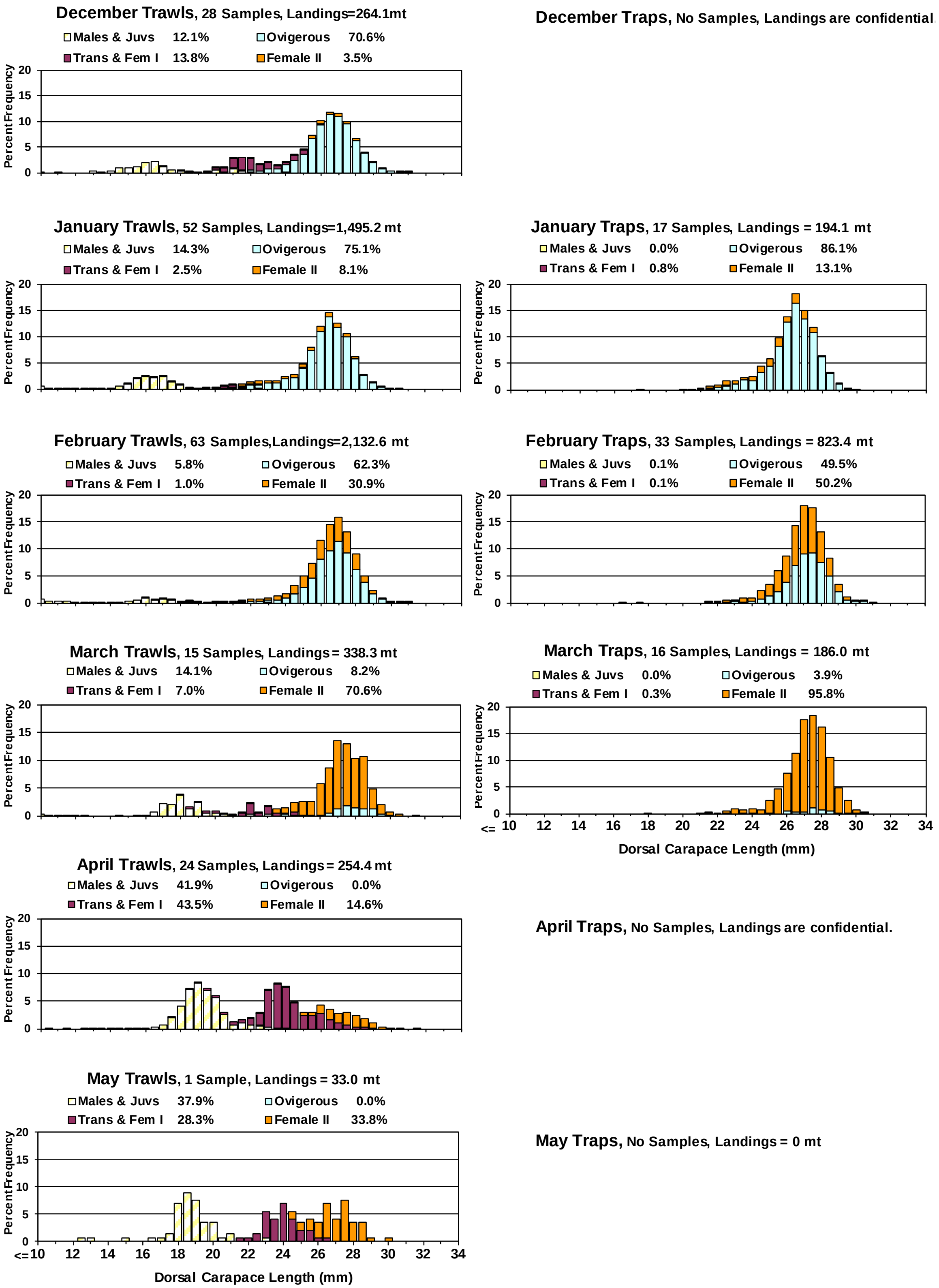
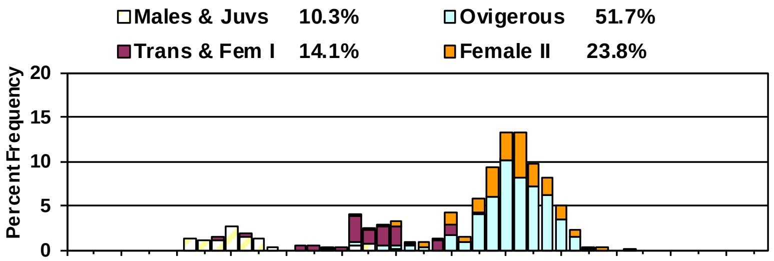
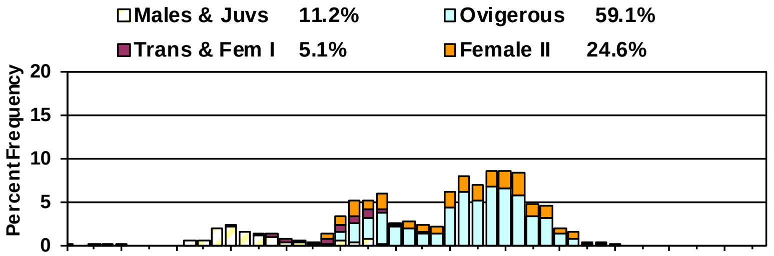


Figure 2.5 Maine northern shrimp size-sex-stage relative frequency distributions from the 2010 season by month for trawls (left) and traps (right).

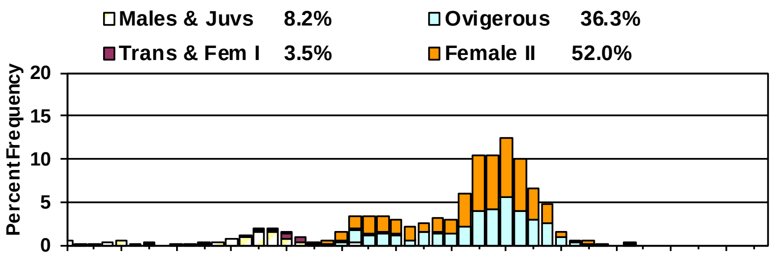
December, 0 MA, 3 NH Samples, Landings = 112.8 mt



January, 3 MA, 3 NH Samples, Landings = 169.4 mt

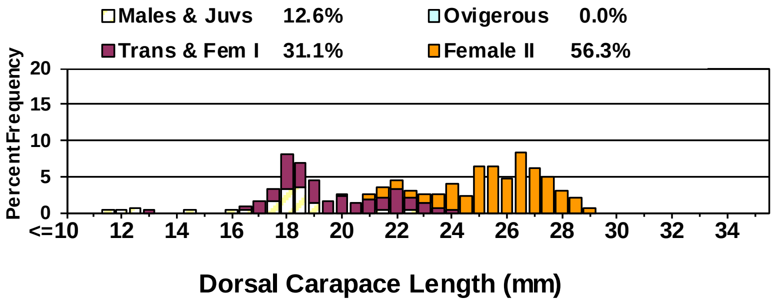


February, 3 MA, 3 NH Samples, Landings = 218.2 mt



March, No Samples, Landings = 14.2 mt

April, 0 MA, 2 NH Samples, Landings = 27.4 mt



May, No Samples, Landings are Confidential.

Figure 2.6 Northern shrimp size-sex-stage relative frequency distributions from the 2010 season by month for Massachusetts and New Hampshire combined.

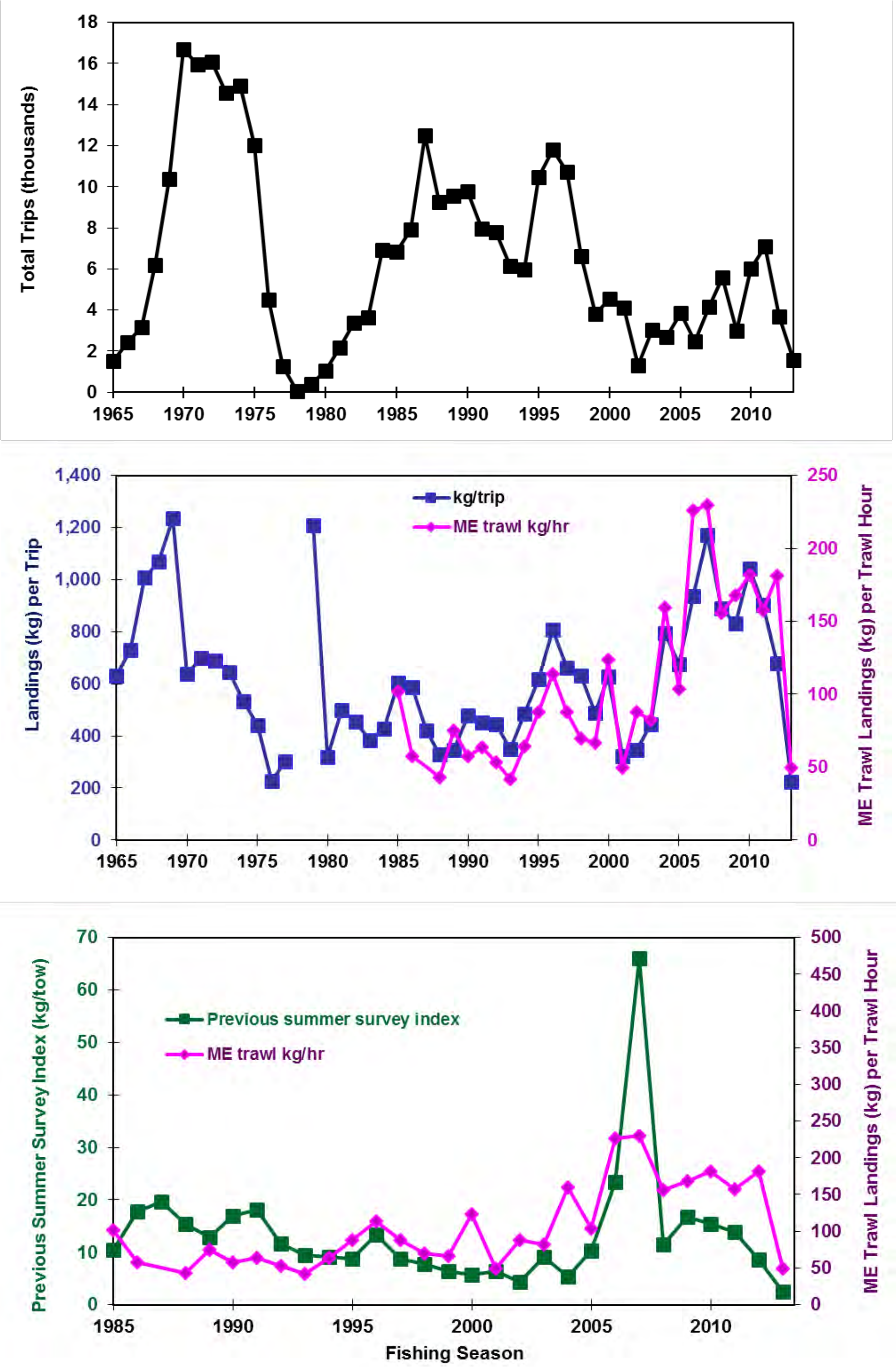


Figure 2.7 Nominal fishing effort (trips) in the Gulf of Maine northern shrimp fishery by season (top), catch per unit effort in kg/trip and Maine trawl kg/hr (middle), and Maine trawl kg/hr and the previous summer shrimp survey index (bottom).

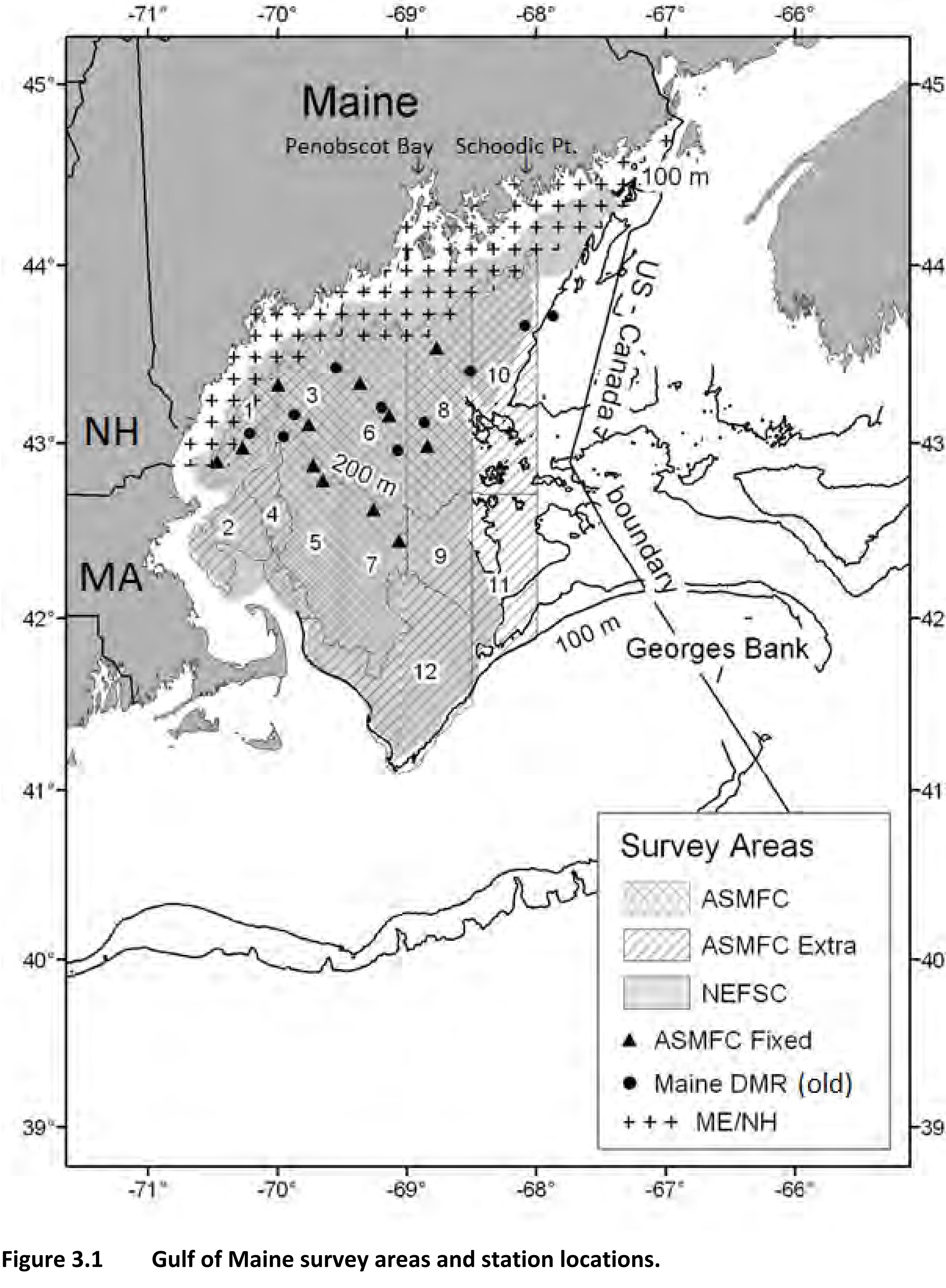


Figure 3.1 Gulf of Maine survey areas and station locations.

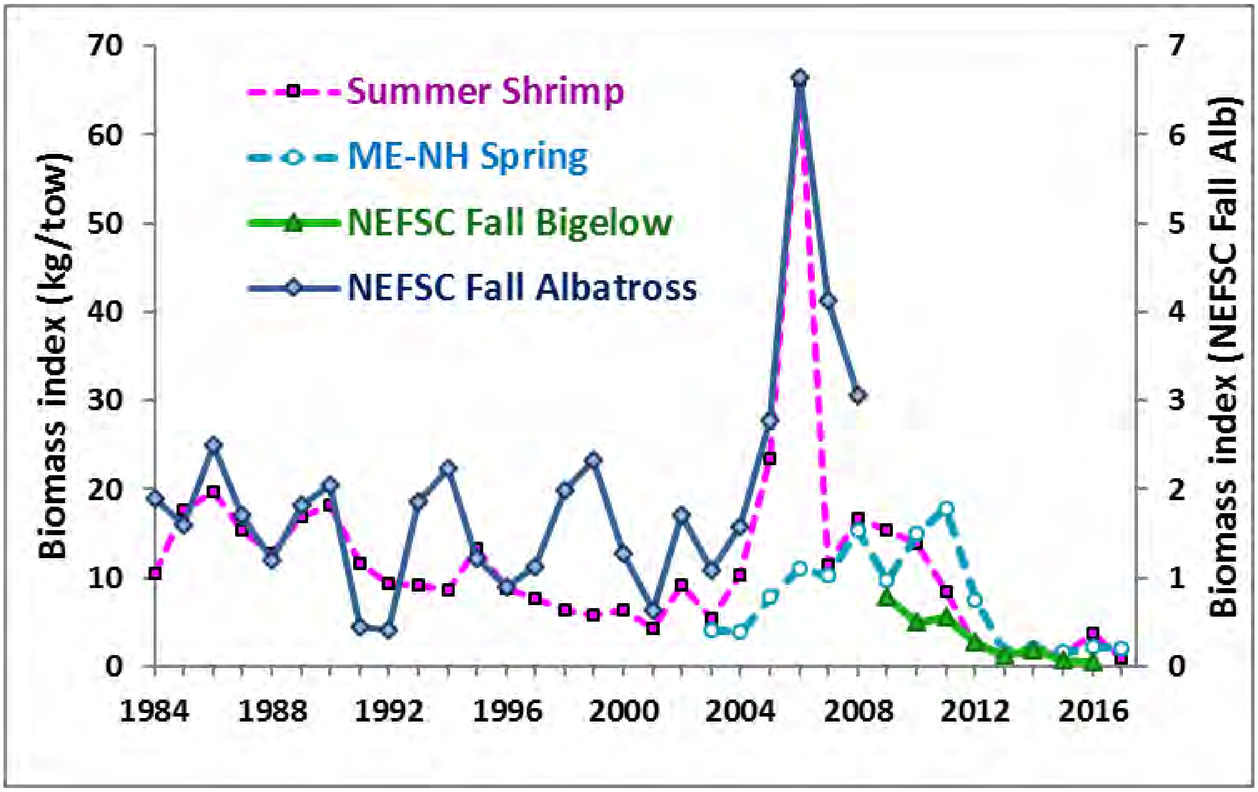


Figure 3.2 **Biomass indices (kg/tow) from fishery-independent surveys in the Gulf of Maine.**

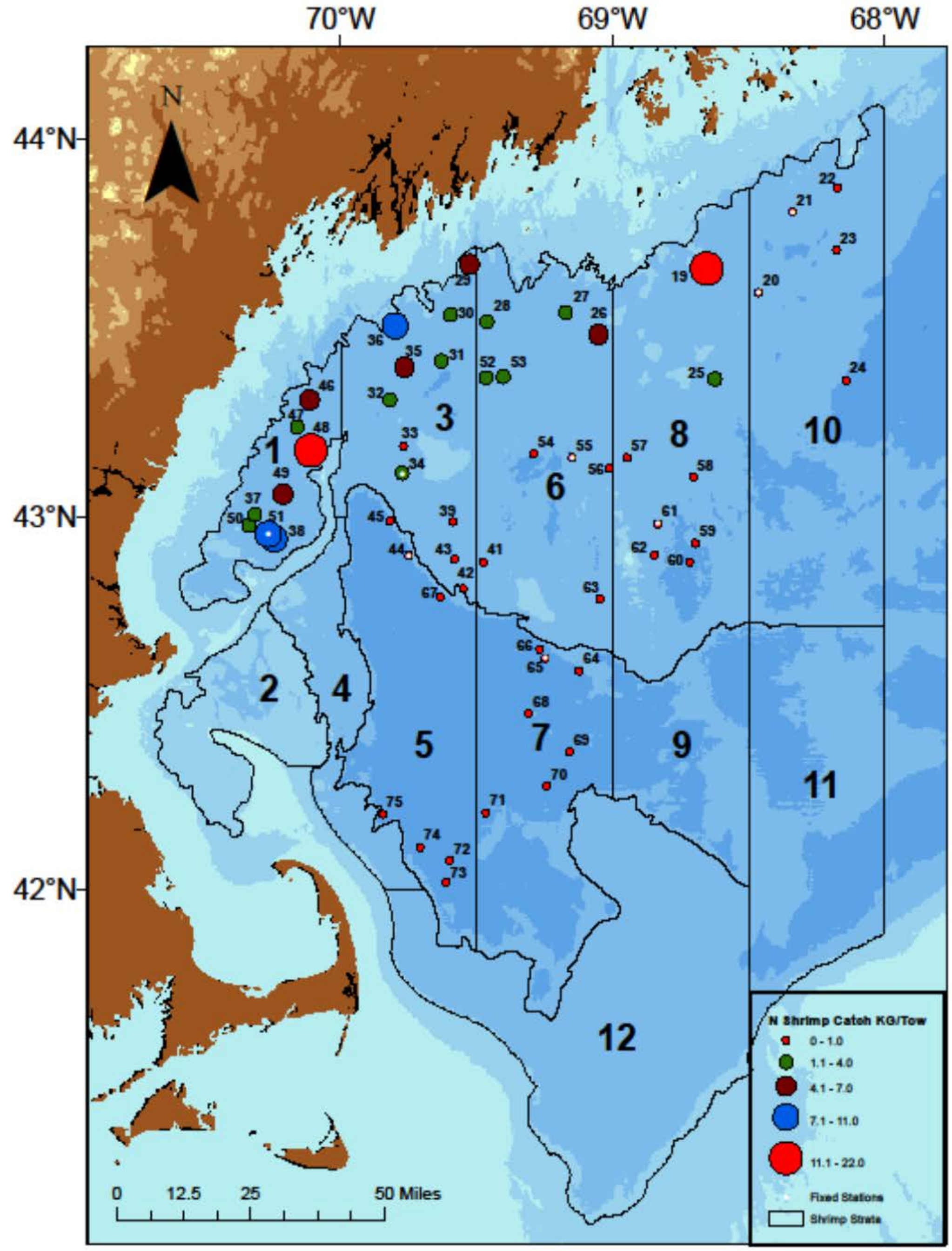


Figure 3.3 Shrimp catches (kg/tow) at stations surveyed during the 2017 ASMFC northern shrimp summer survey aboard the R/V *Gloria Michelle,* fixed and random survey sites. Black lines and large numbers indicate survey strata. 2-digit numbers are station IDs.

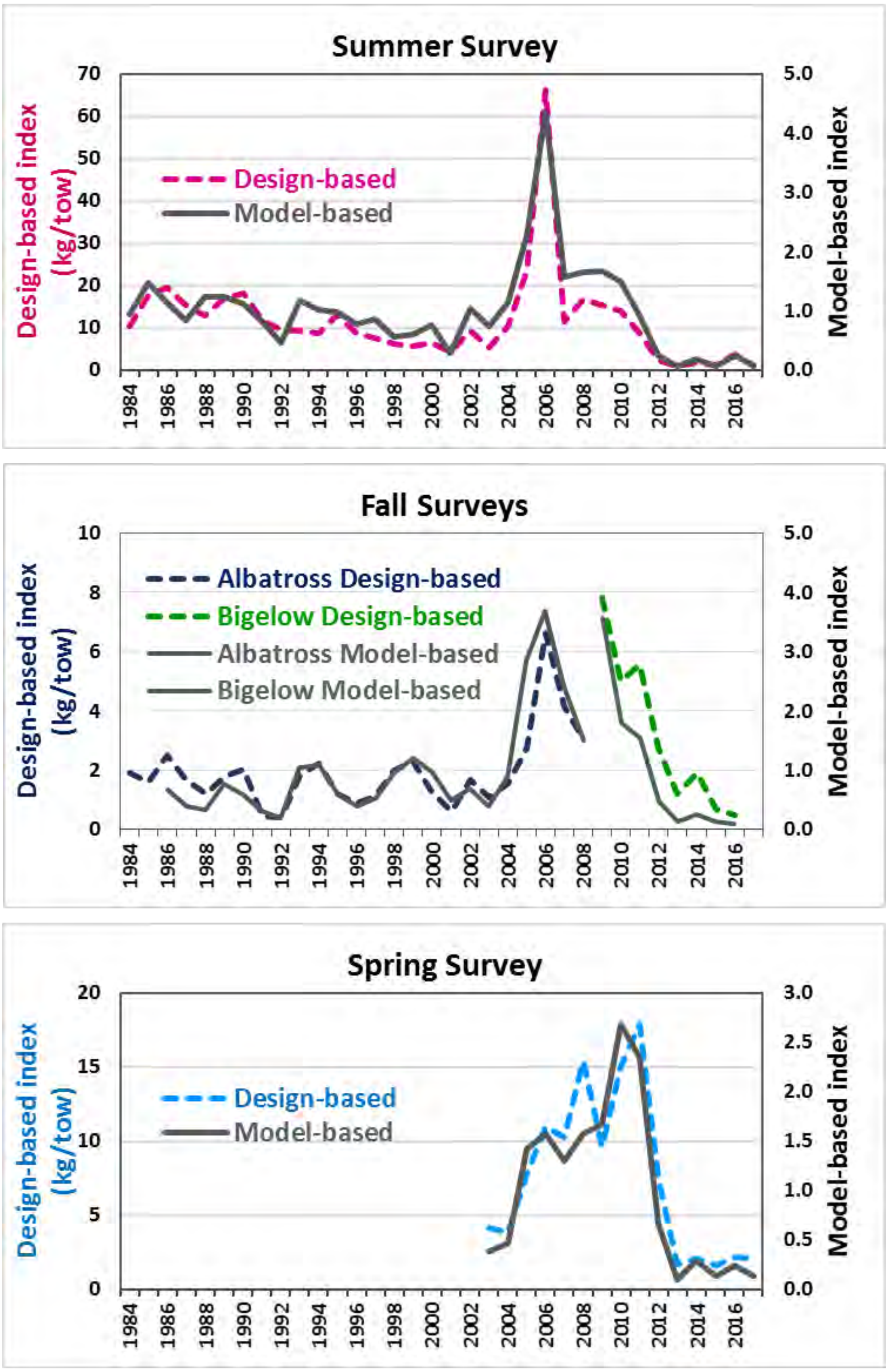


Figure 3.4 Design-based survey indices (geometric mean kg per tow for spring and summer, arithmetic mean kg per tow for fall) compared with spatio-temporal model-based standardized indices.

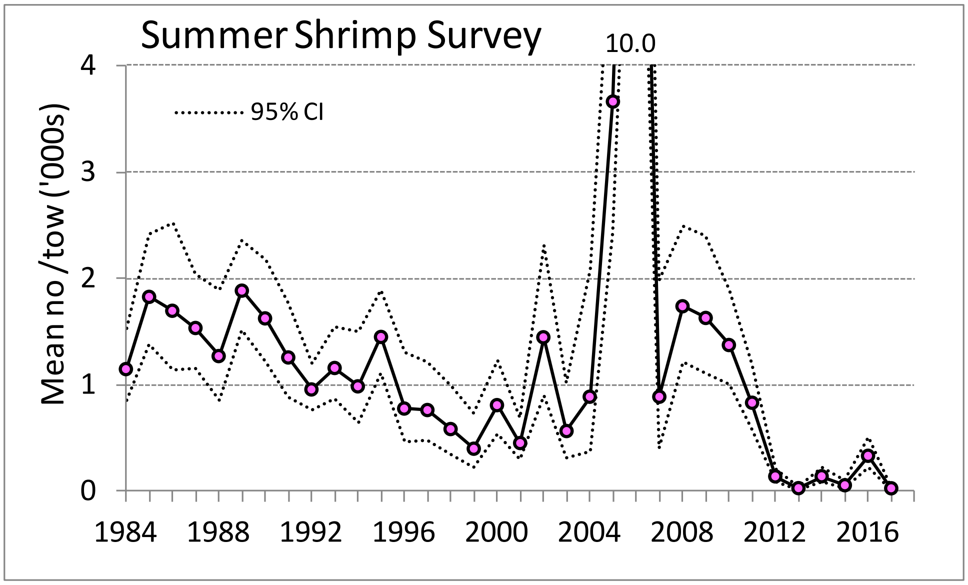


Figure 3.5 **Abundance indices (stratified geometric mean number per tow in thousands) of northern shrimp from ASMFC summer surveys in the Gulf of Maine.**

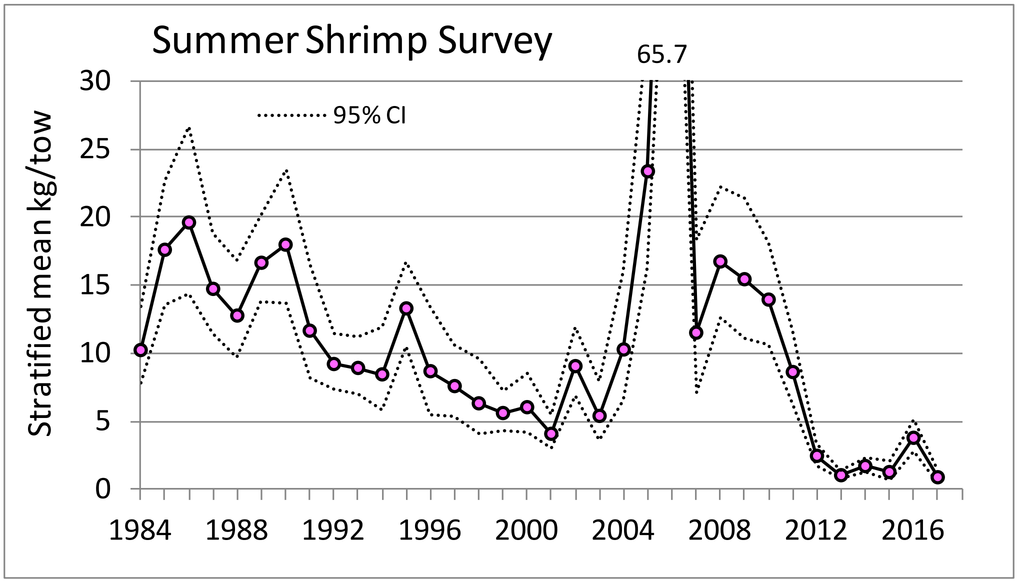


Figure 3.6 **Biomass indices (stratified geometric mean kg per tow) of northern shrimp from ASMFC summer surveys in the Gulf of Maine.**

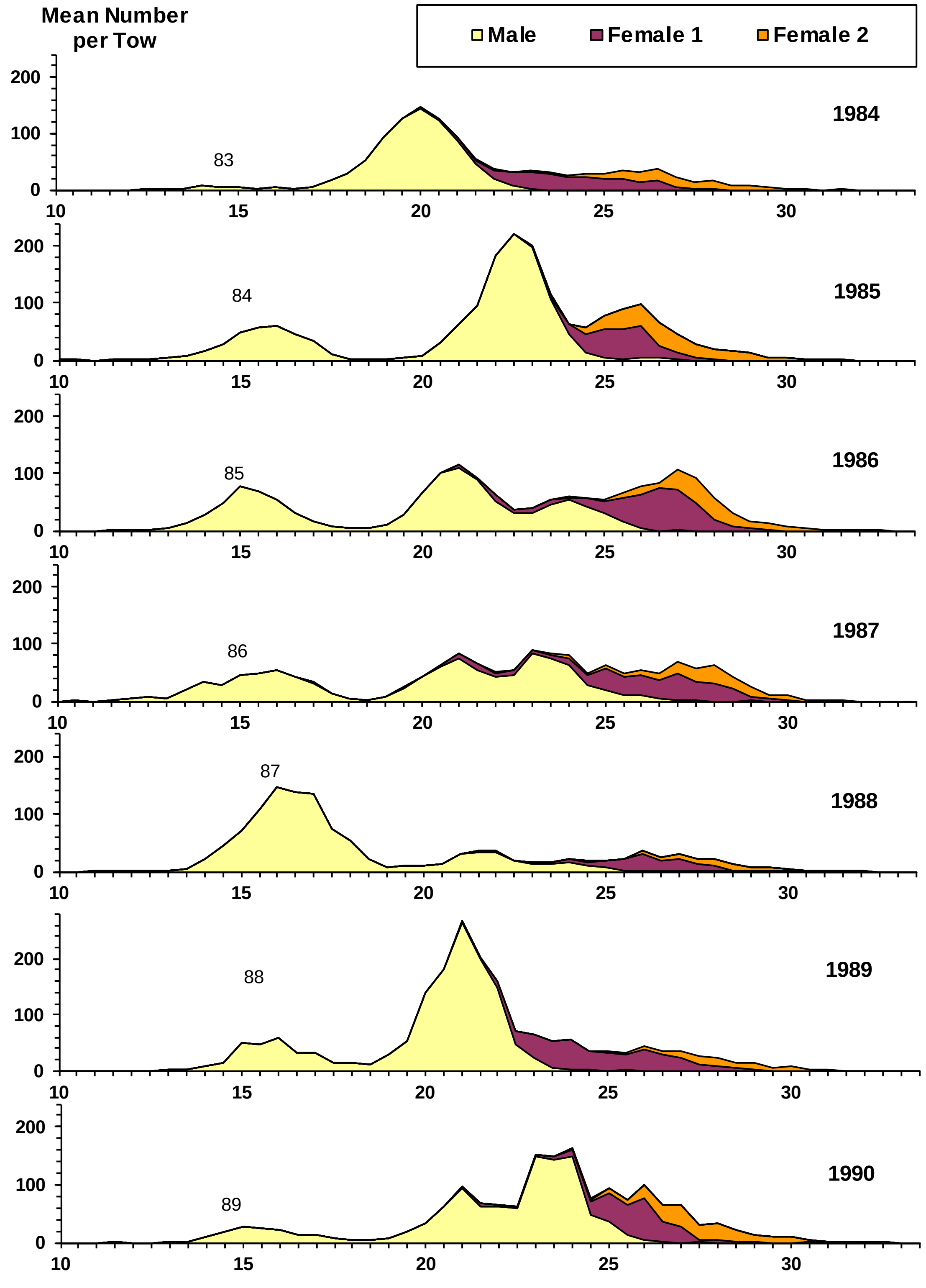


Figure 3.7 Gulf of Maine northern shrimp summer survey mean catch per tow by year, length, and life history stage. Two-digit years are year class at assumed age 1.5.

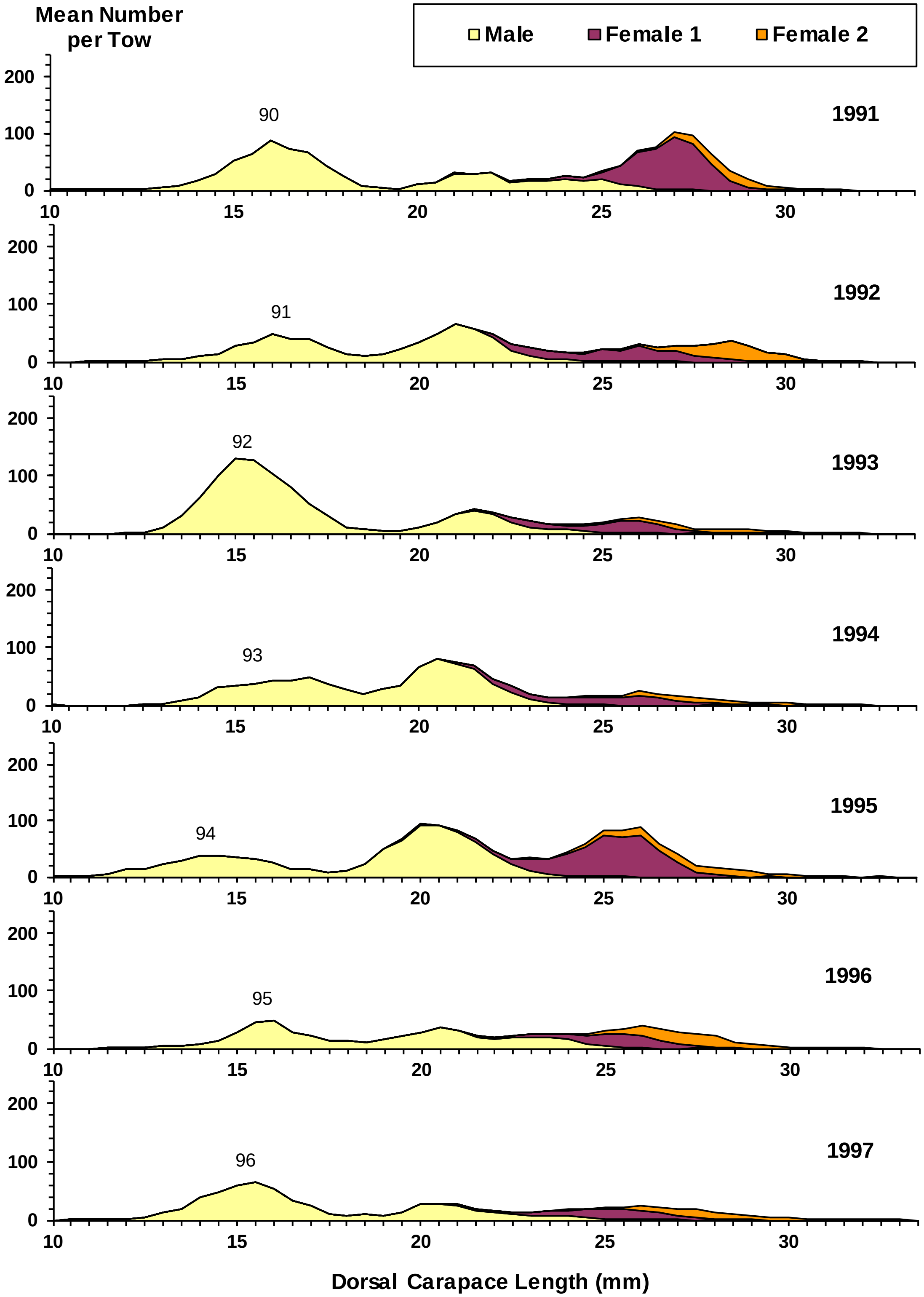


Figure 3.7 continued: Summer survey.

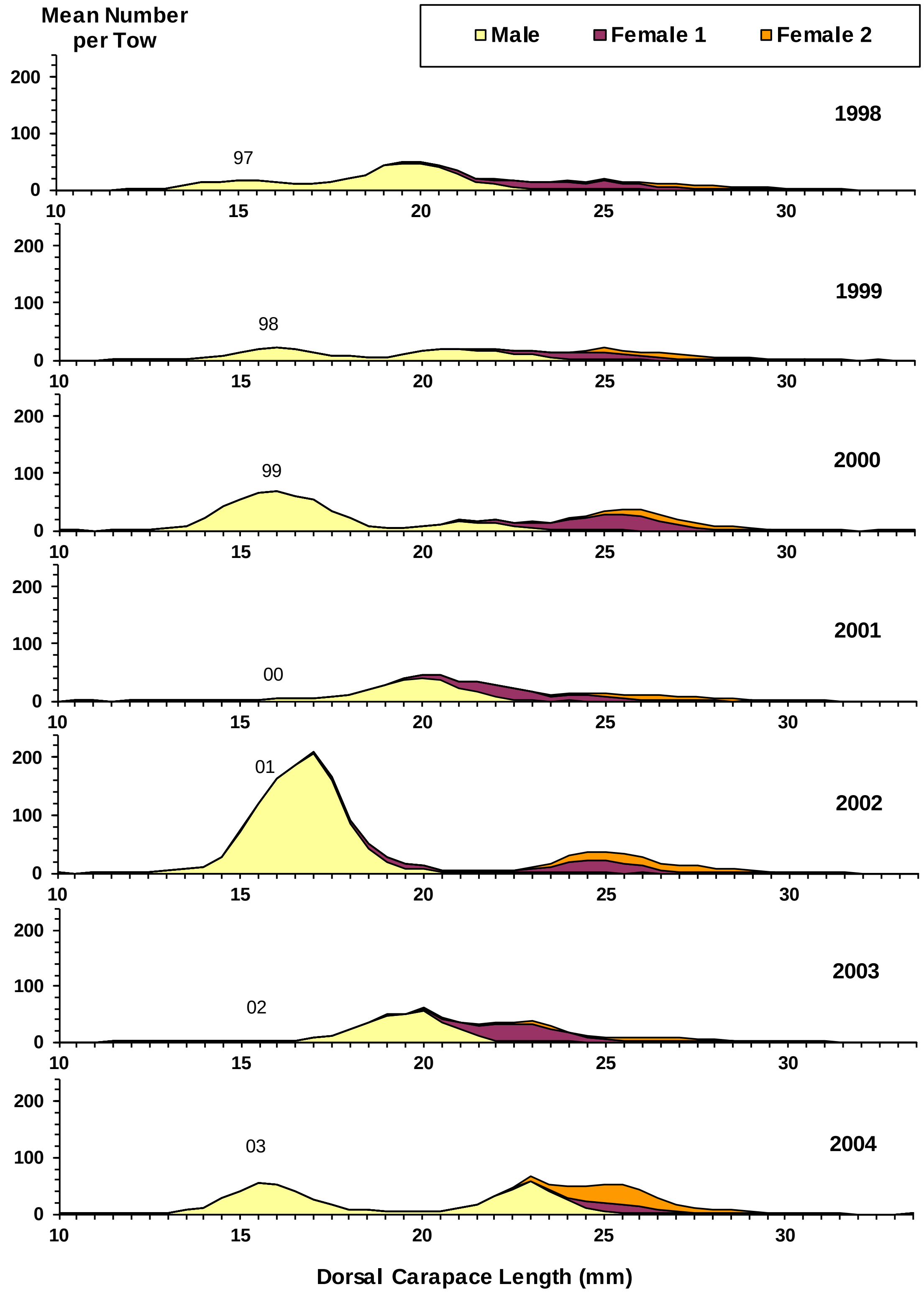


Figure 3.7 continued: Summer survey.

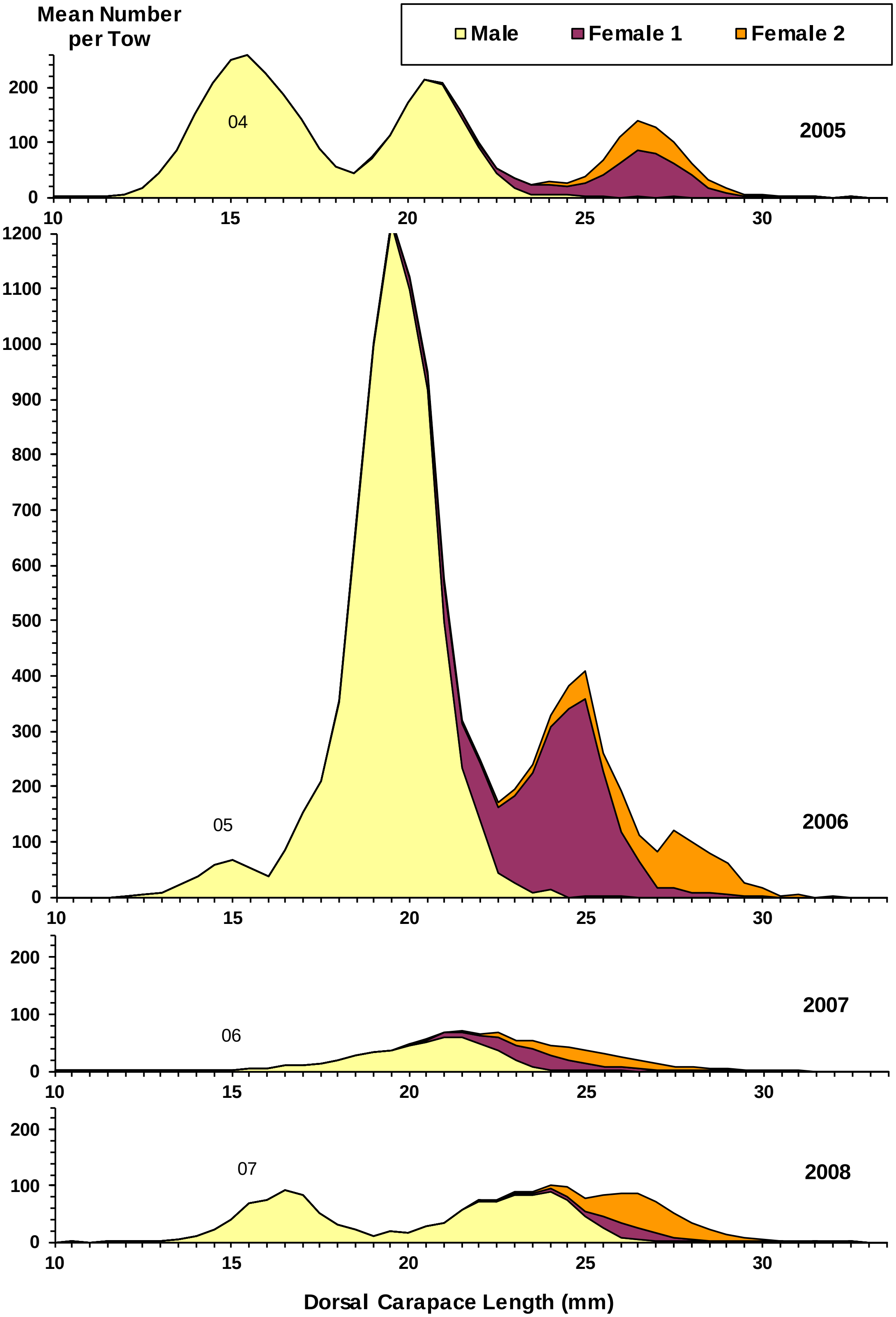


Figure 3.7 continued: Summer survey.

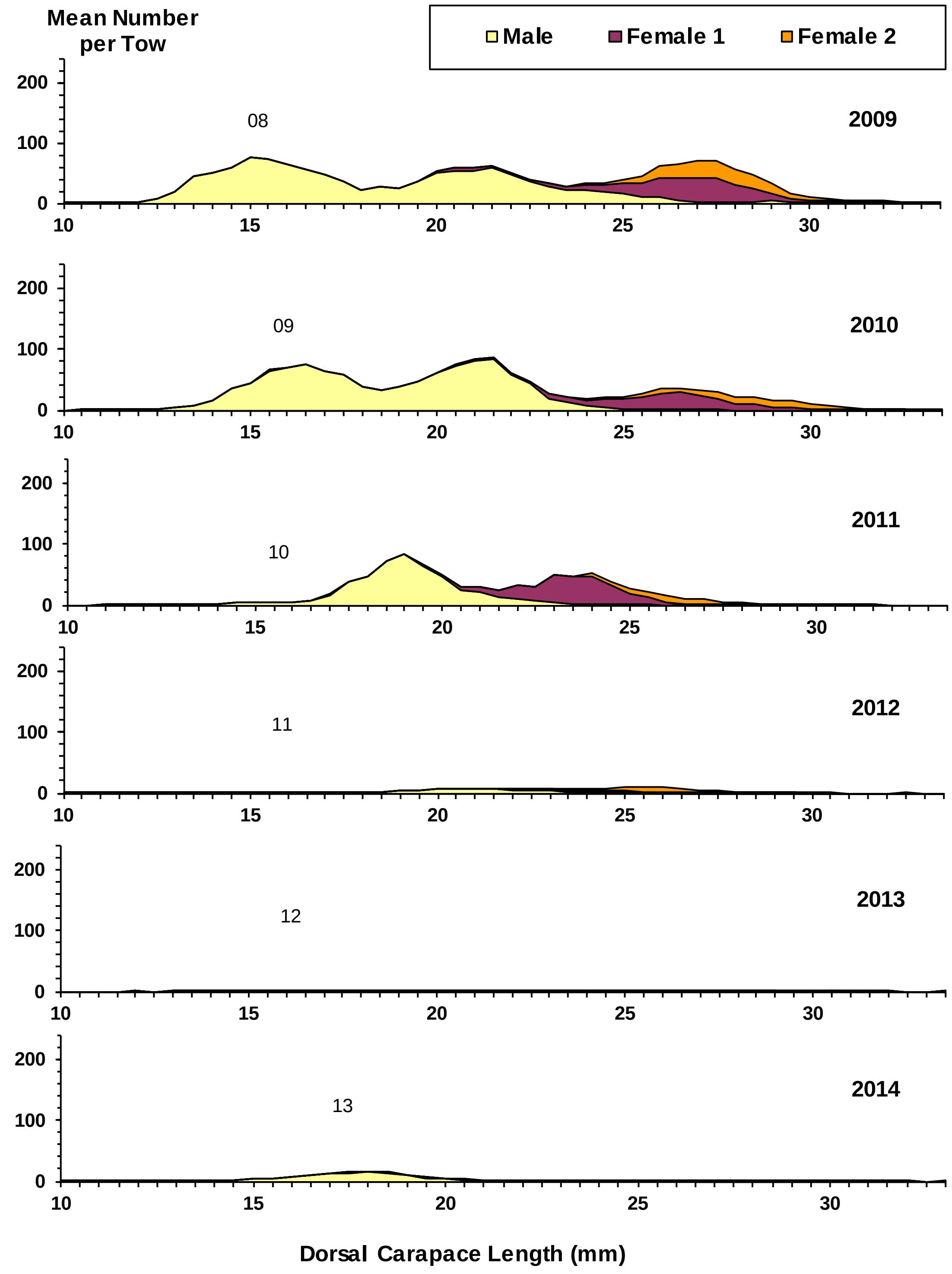


Figure 3.7 continued: Summer survey.

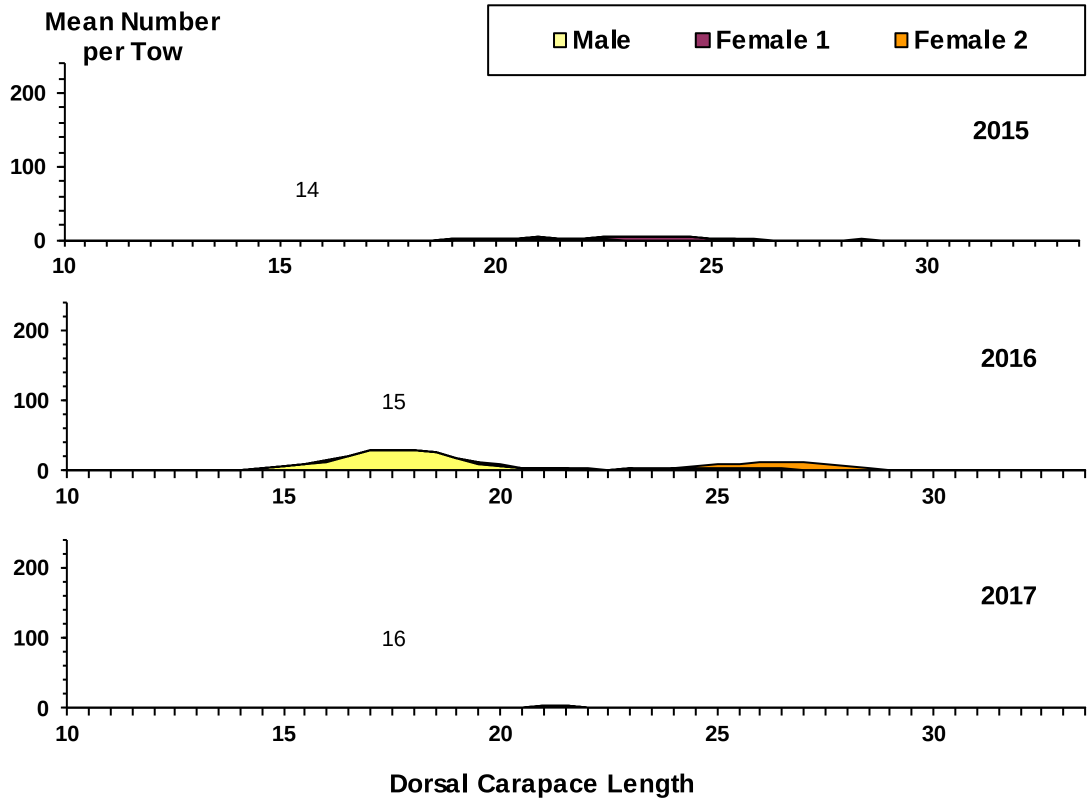


Figure 3.7 continued: Summer survey.

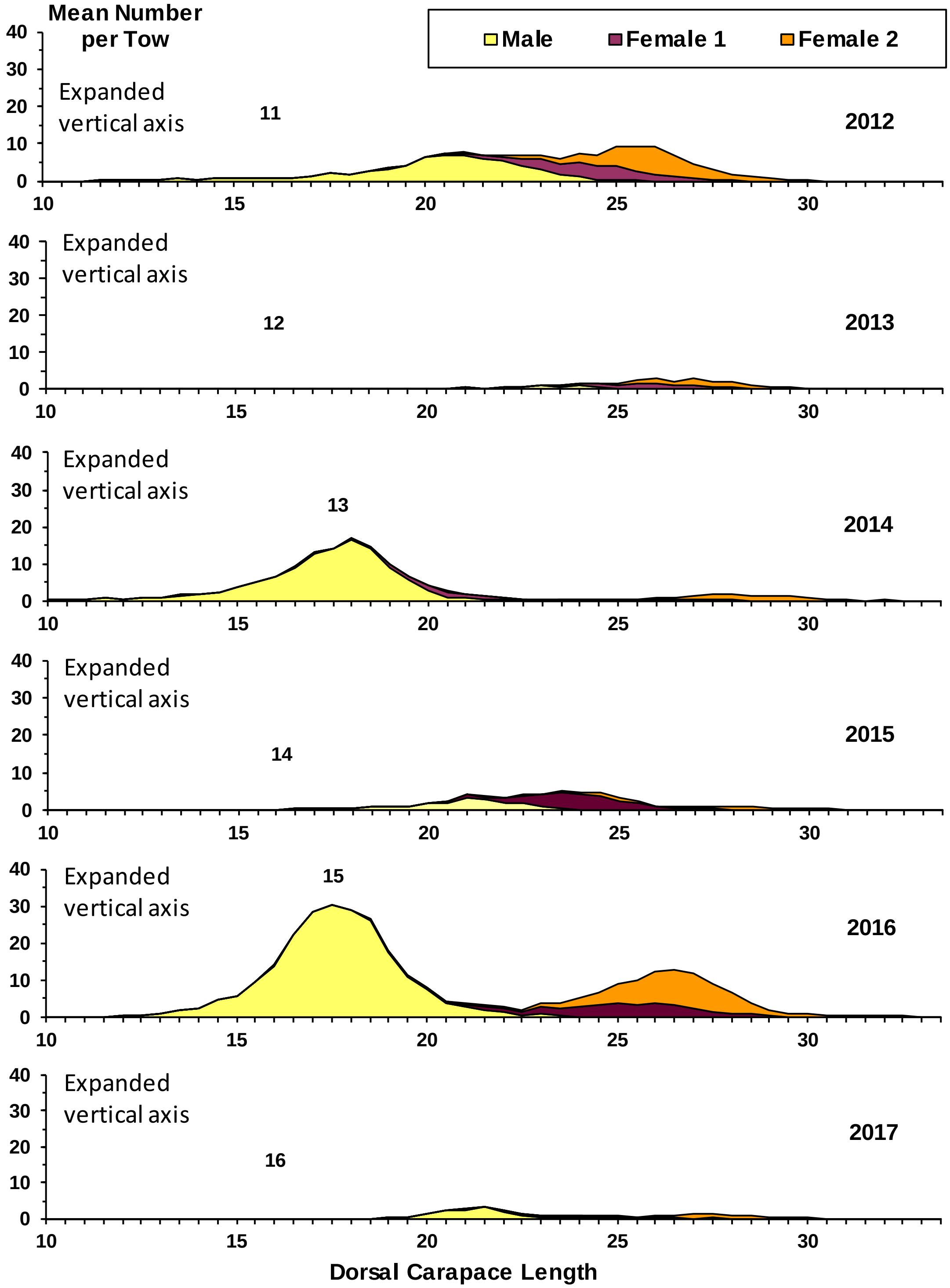


Figure 3.8 Gulf of Maine northern shrimp summer survey mean catch per tow by year (2012–2017 only), length, and life history stage, with expanded vertical axes. Two-digit years indicate the year class mode at assumed age 1.5.

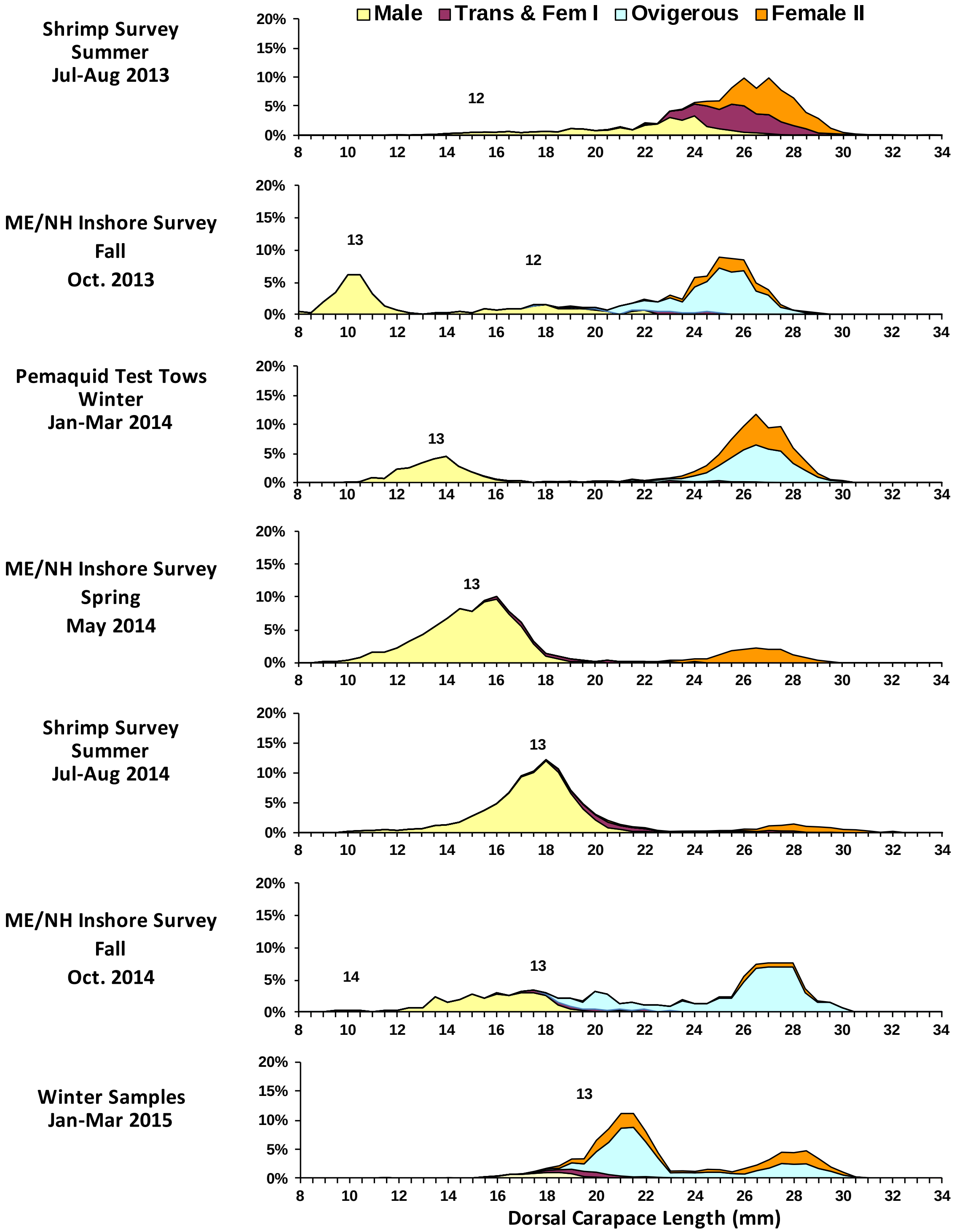


Figure 3.9 **Northern shrimp relative size-sex-stage frequencies from 2013–2017 Gulf of Maine surveys and winter sampling programs (which used commercial gear). Two-digit years denote the mode of assumed 2012–2016 year classes.**

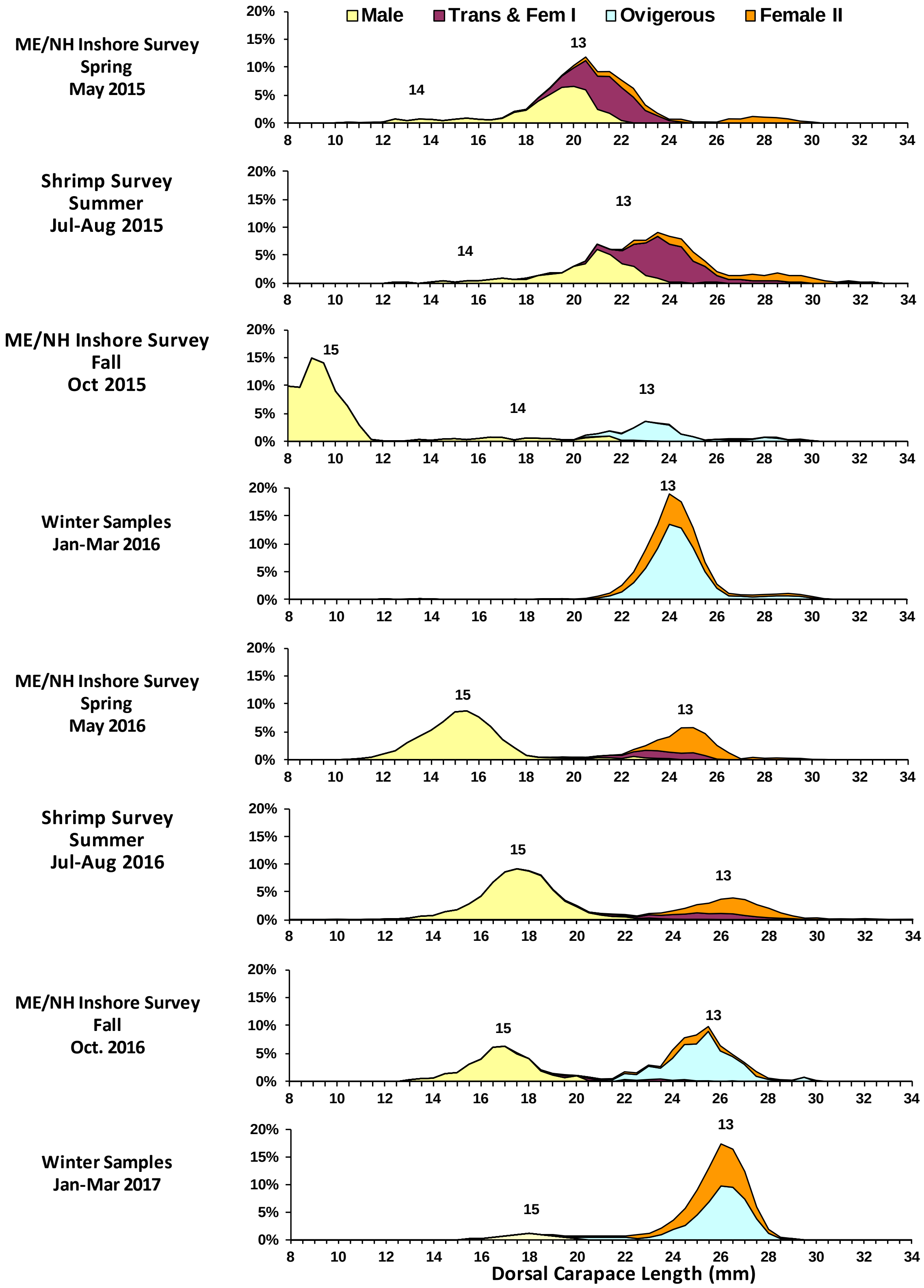
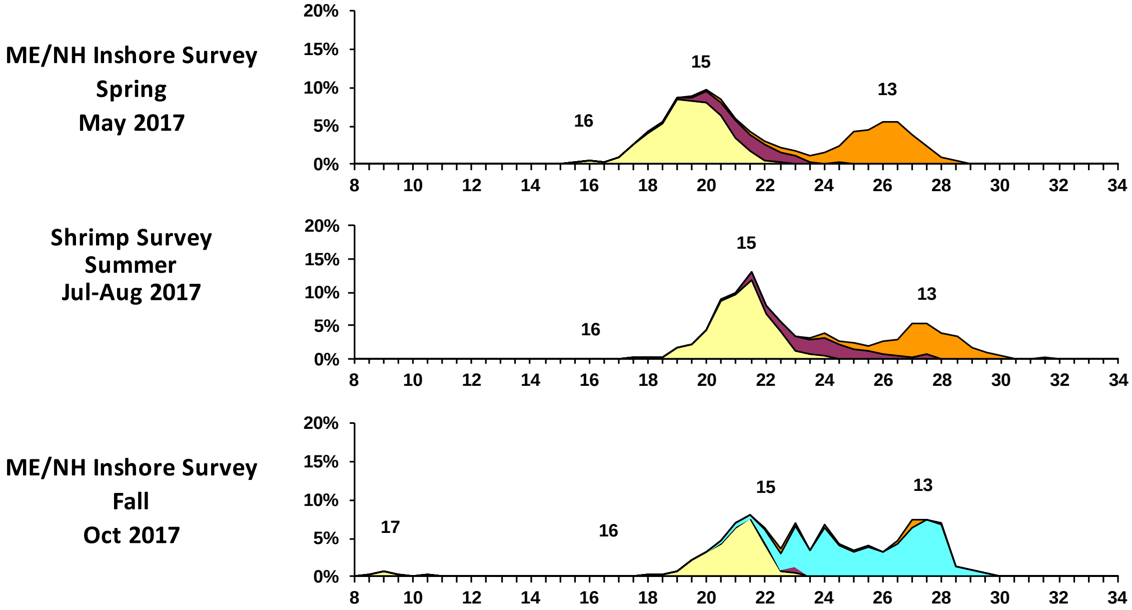


Figure 3.9 Continued from previous page



ME/NH Inshore Survey
Spring
May 2017

Shrimp Survey
Summer
Jul-Aug 2017

ME/NH Inshore Survey
Fall
Oct 2017

Figure 3.9 **Continued from previous page**

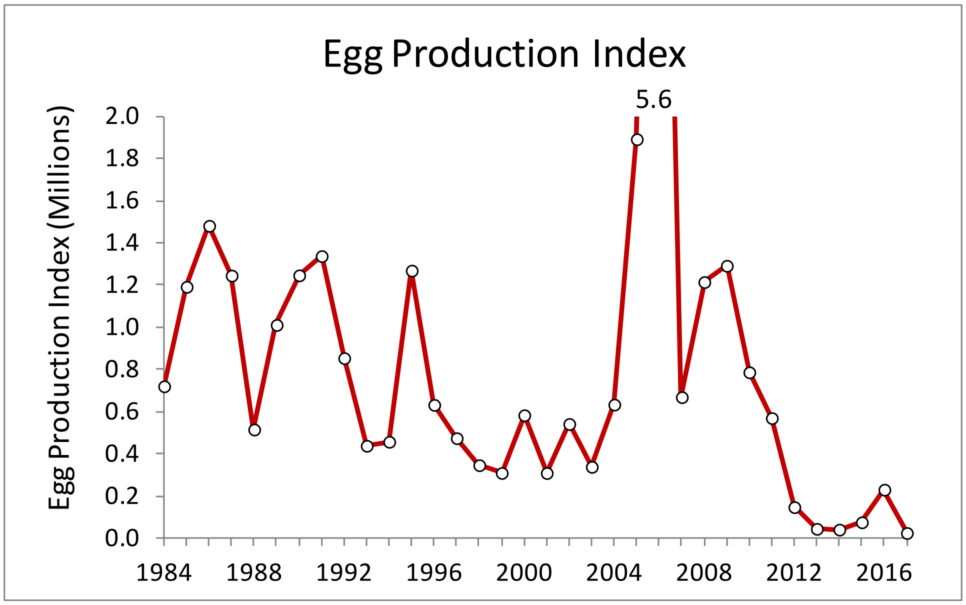


Figure 3.10 Egg production index for Gulf of Maine northern shrimp based on stratified mean number of females at length from the summer shrimp survey and estimated fecundity at length (Haynes and Wigley 1969).

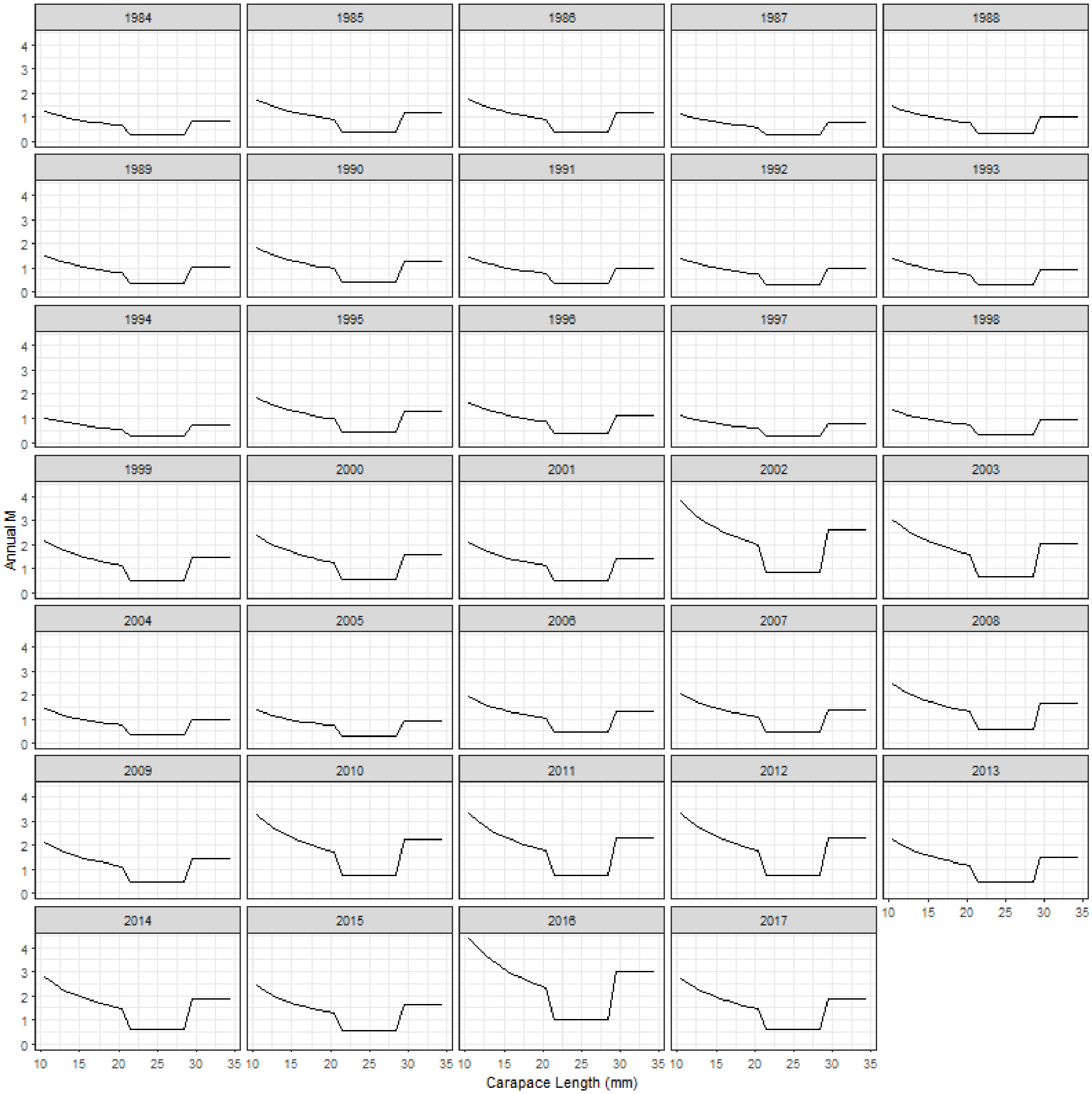
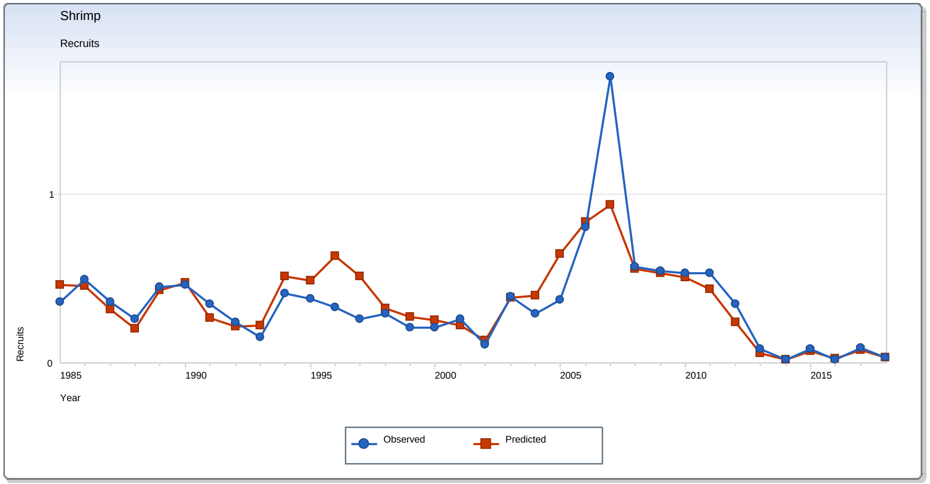
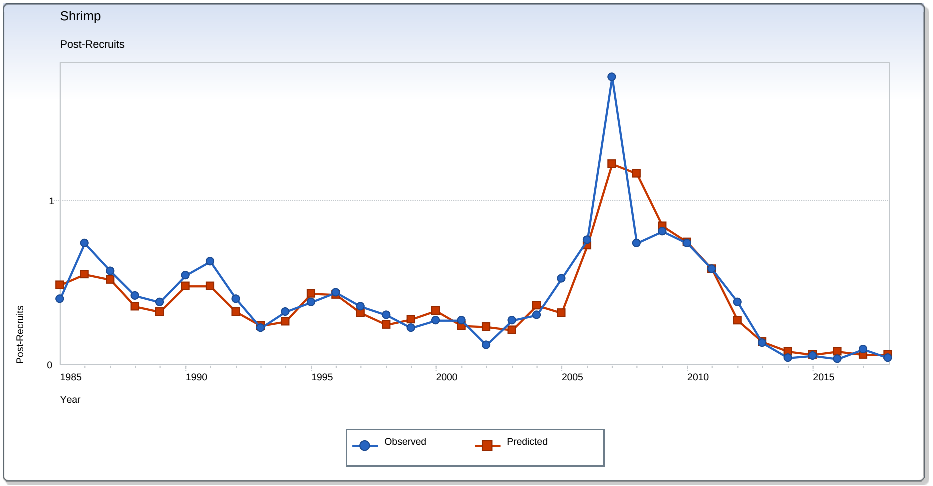


Figure 4.1. Length- and time-varying estimates of natural mortality used in the base case of the UME model.

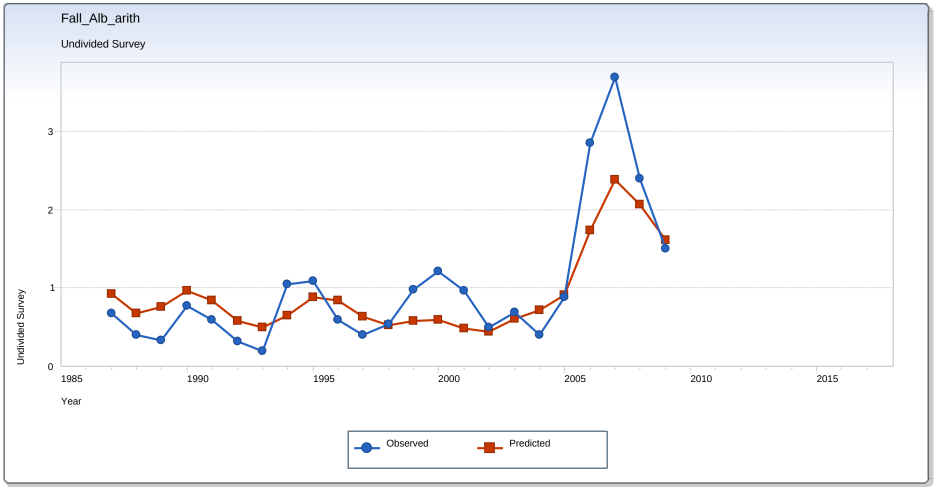
(a)


Shrimp
Recruits
Recruits
0
1
1985
1990
1995
2000
2005
2010
2015
Year
Observed
Predicted

(b)


Shrimp
Post-Recruits
Post-Recruits
0
1
1985
1990
1995
2000
2005
2010
2015
Year
Observed
Predicted

(c)


Fall_Alb_arith
Undivided Survey
Undivided Survey
0
1
2
3
1985
1990
1995
2000
2005
2010
2015
Year
Observed
Predicted

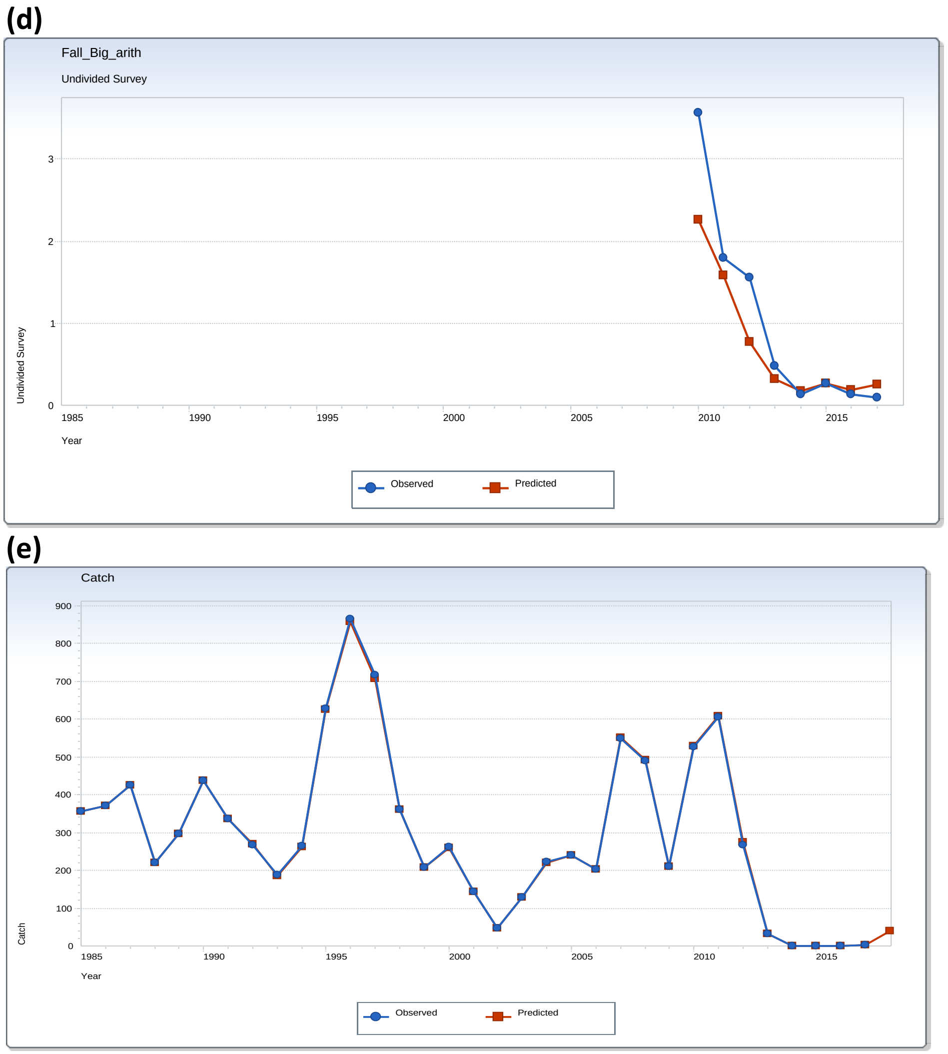
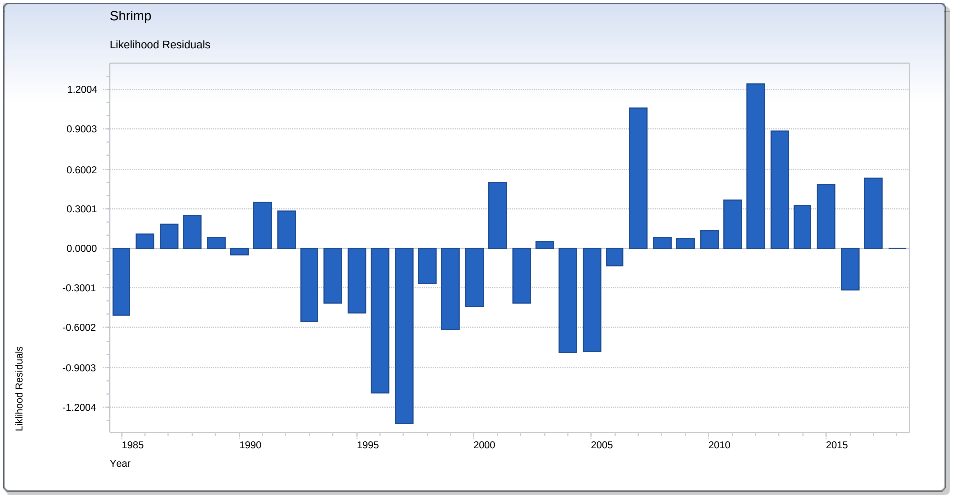
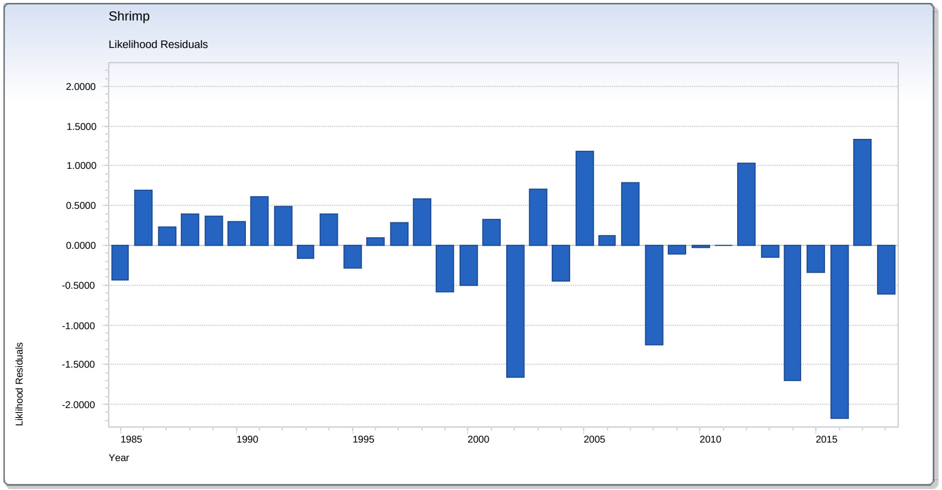


Figure 5.1 (a-e) CSA model fits to survey indices and catch using model-based indices and PPI-scaled M (based on M=0.5). (a) pre-recruits, (b) post-recruits, (c) fall albatross survey data, (d) fall Bigelow survey data (e) catch.

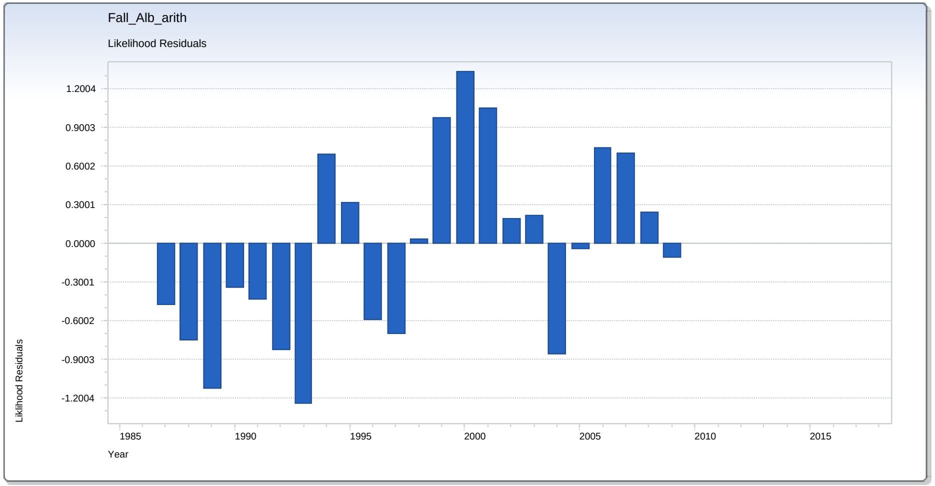
(a)


Shrimp
Likelihood Residuals
1.2004
0.9003
0.6002
0.3001
0.0000
-0.3001
-0.6002
-0.9003
-1.2004
Likilhood Residuals
1985
1990
1995
2000
2005
2010
2015
Year

(b)


Shrimp
Likelihood Residuals
2.0000
1.5000
1.0000
0.5000
0.0000
-0.5000
-1.0000
-1.5000
-2.0000
Likilhood Residuals
1985
1990
1995
2000
2005
2010
2015
Year

(c)


Fall_Alb_arith
Likelihood Residuals
1.2004
0.9003
0.6002
0.3001
0.0000
-0.3001
-0.6002
-0.9003
-1.2004
Likilhood Residuals
1985
1990
1995
2000
2005
2010
2015
Year

(d)

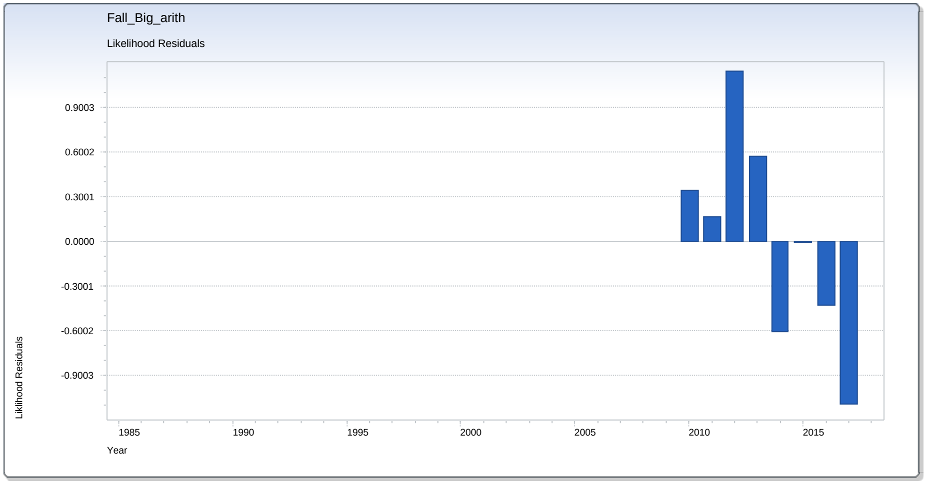
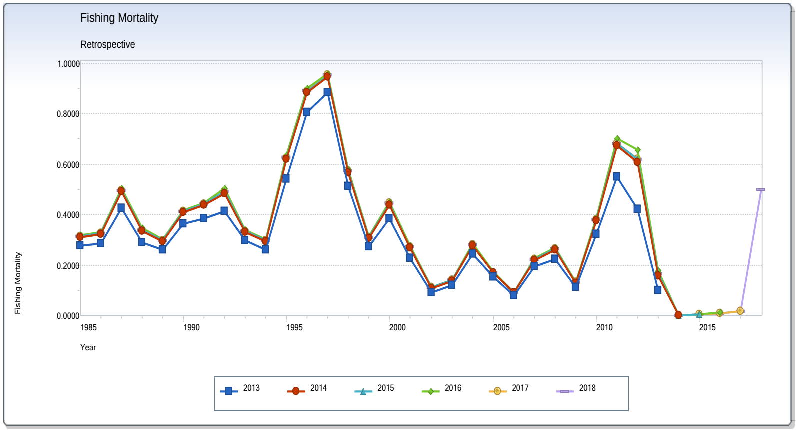
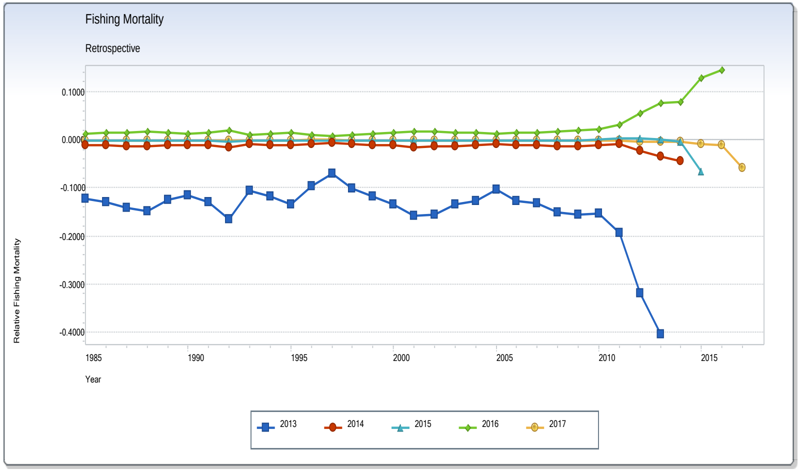


Figure 5.2 (a-d) Standardized residuals for final the CSA model using model-based indices and PPI-scaled M (based on M=0.5). (a) summer survey recruits, (b) summer survey post-recruits, (c) fall Albatross survey combined stages, (d) fall Bigelow survey combined stages.

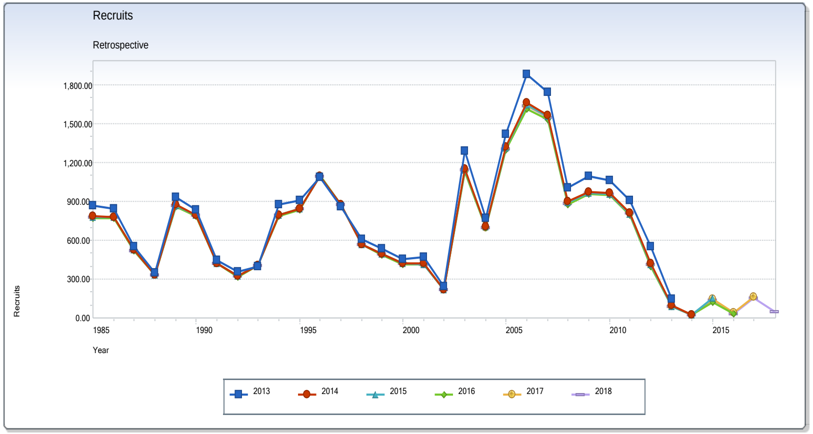
(a)


Fishing Mortality
Retrospective
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
Fishing Mortality
1985
1990
1995
2000
2005
2010
2015
Year
2013
2014
2015
2016
2017
2018

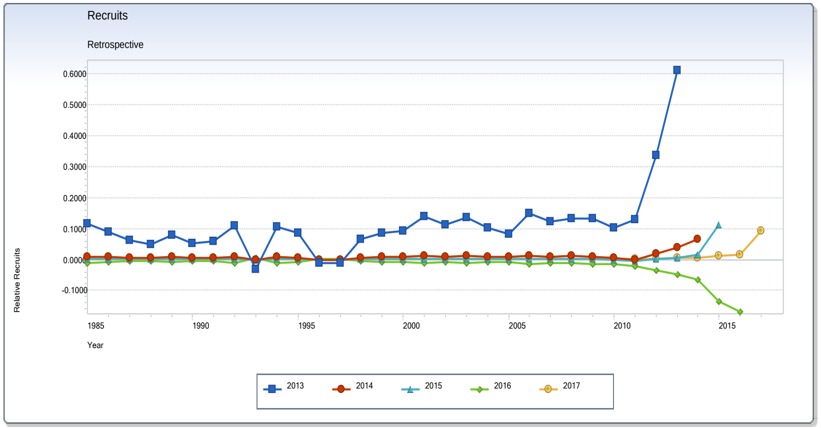
(b)


Fishing Mortality
Retrospective
0.1000
0.0000
-0.1000
-0.2000
-0.3000
-0.4000
Relative Fishing Mortality
1985
1990
1995
2000
2005
2010
2015
Year
2013
2014
2015
2016
2017

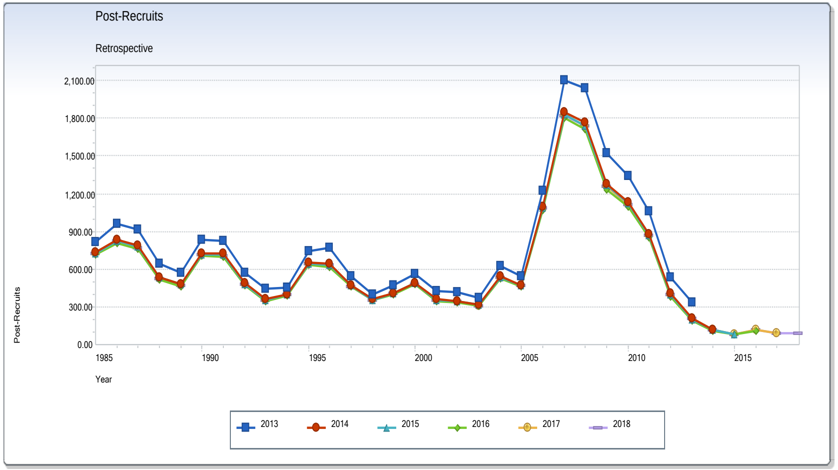
(c)


Recruits
Retrospective
1,800.00
1,500.00
1,200.00
900.00
600.00
300.00
0.00
Recruits
1985
1990
1995
2000
2005
2010
2015
Year
2013
2014
2015
2016
2017
2018

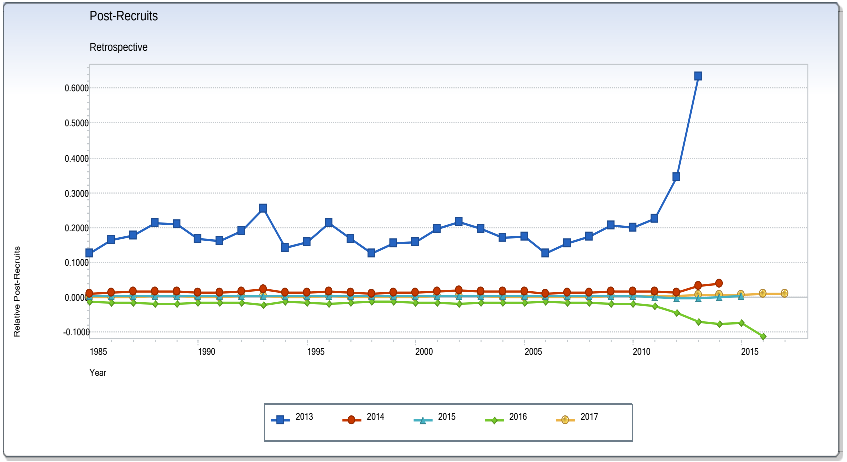
(d)


Recruits
Retrospective
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
-0.1000
Relative Recruits
1985
1990
1995
2000
2005
2010
2015
Year
2013
2014
2015
2016
2017

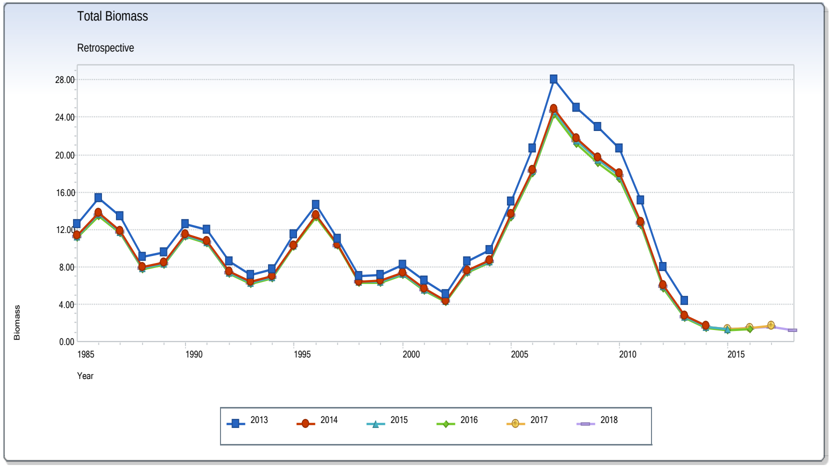
(e)


Post-Recruits
Retrospective
2,100.00
1,800.00
1,500.00
1,200.00
900.00
600.00
300.00
0.00
Post-Recruits
1985
1990
1995
2000
2005
2010
2015
Year
2013
2014
2015
2016
2017
2018

(f)


Post-Recruits
Retrospective
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
-0.1000
Relative Post-Recruits
1985
1990
1995
2000
2005
2010
2015
Year
2013
2014
2015
2016
2017

(g)



(h)

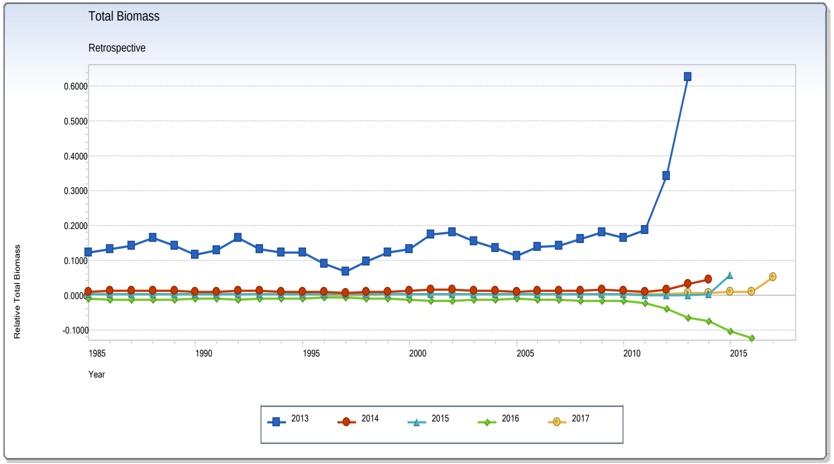
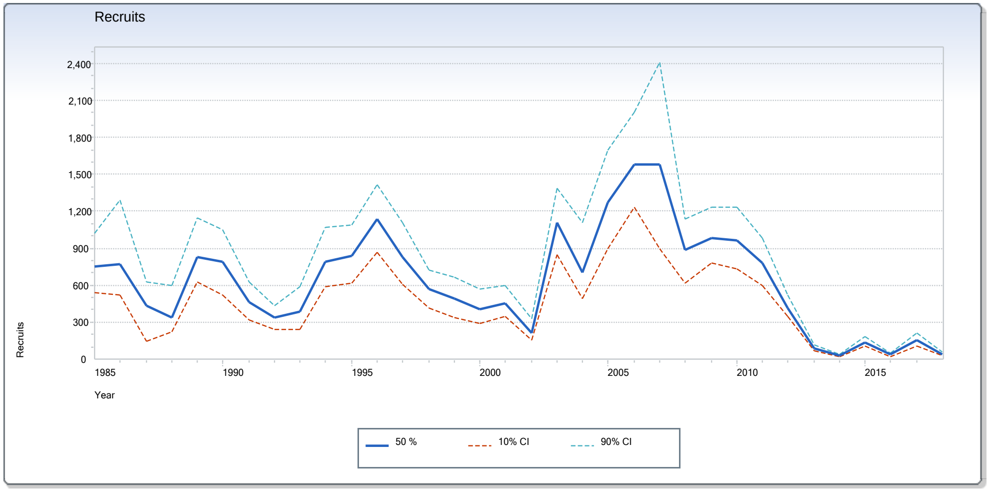


Figure 5.3 (a-h) Retrospective patterns for CSA final run using M=0.5*PPI and model-based indices. (a) F retrospective, (b) F relative retrospective, (c) recruits retrospective, (d) recruits relative retrospective, (e) post recruits retrospective, (f) post recruits relative retrospective, (g) total biomass retrospective, (h) total biomass relative retrospective.

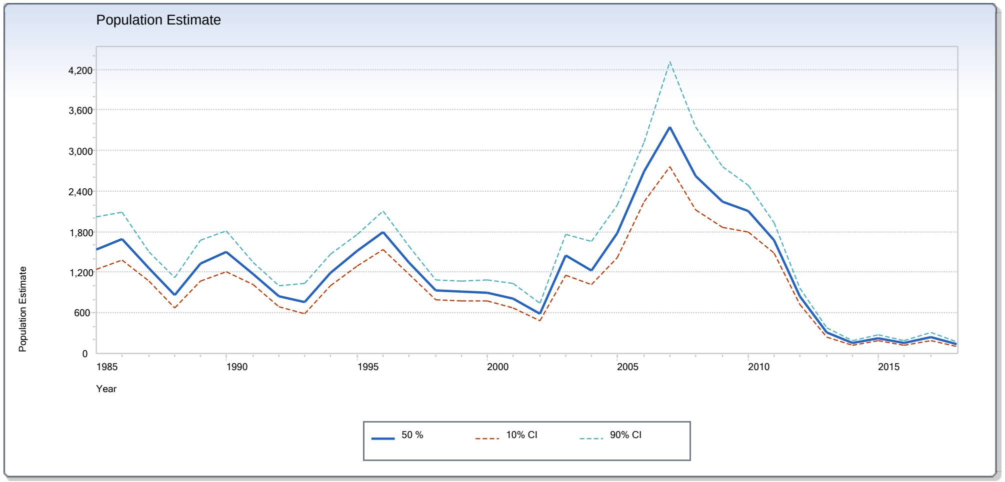
(a)


Recruits
2,400
2,100
1,800
1,500
1,200
900
600
300
0
Recruits
1985
1990
1995
2000
2005
2010
2015
Year
50 %
10% CI
90% CI

(b)


Post-Recruits
2,400
2,100
1,800
1,500
1,200
900
600
300
0
Post-Recruits
1985
1990
1995
2000
2005
2010
2015
Year
50 %
10% CI
90% CI

(c)


Population Estimate
4,200
3,600
3,000
2,400
1,800
1,200
600
0
Population Estimate
1985
1990
1995
2000
2005
2010
2015
Year
50 %
10% CI
90% CI

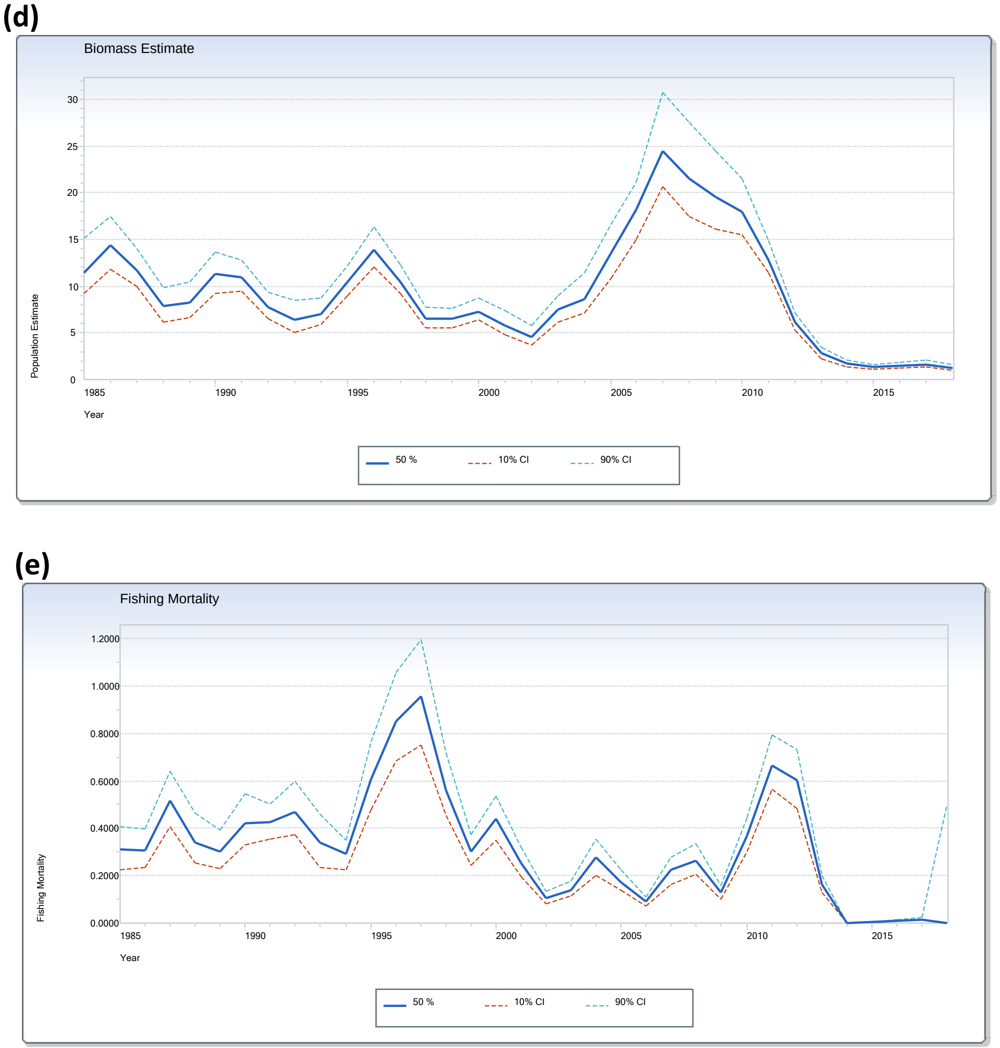


Figure 5.4. (a-e) **MCMC-generated 80% confidence intervals from final CSA model. (a) recruits, (b) post-recruits, (c) total population (recruits plus post-recruits), (d) population biomass, (e) F. Abundance is in millions, biomass in thousands of mt.**

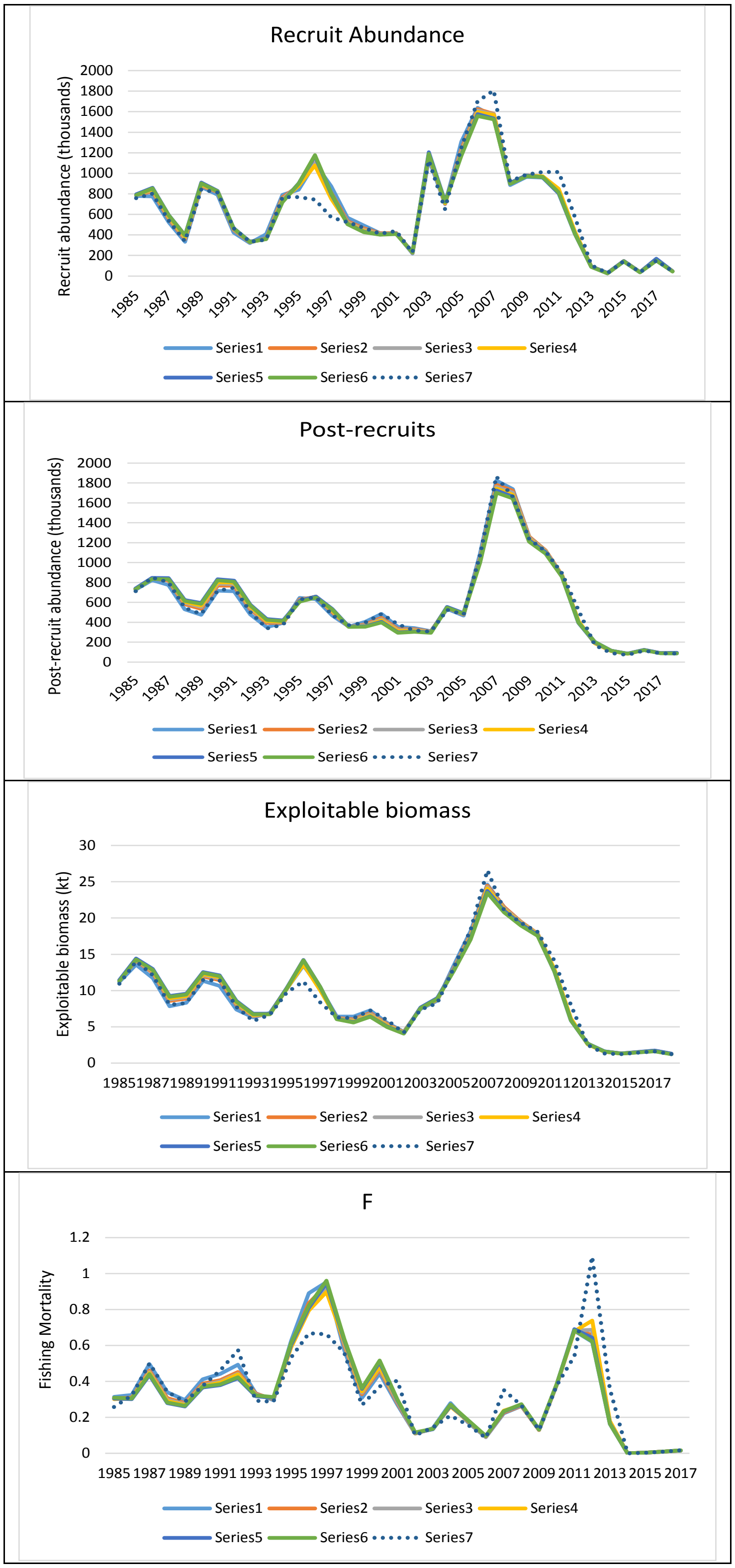


Figure 5.5 CSA estimates using final model with varying likelihood weights. (a) recruits, (b) post-recruits, (c) population biomass, (d) F. Abundance is in millions; biomass in thousands of mt. See Table 5.3 for detail on weighting schemes.

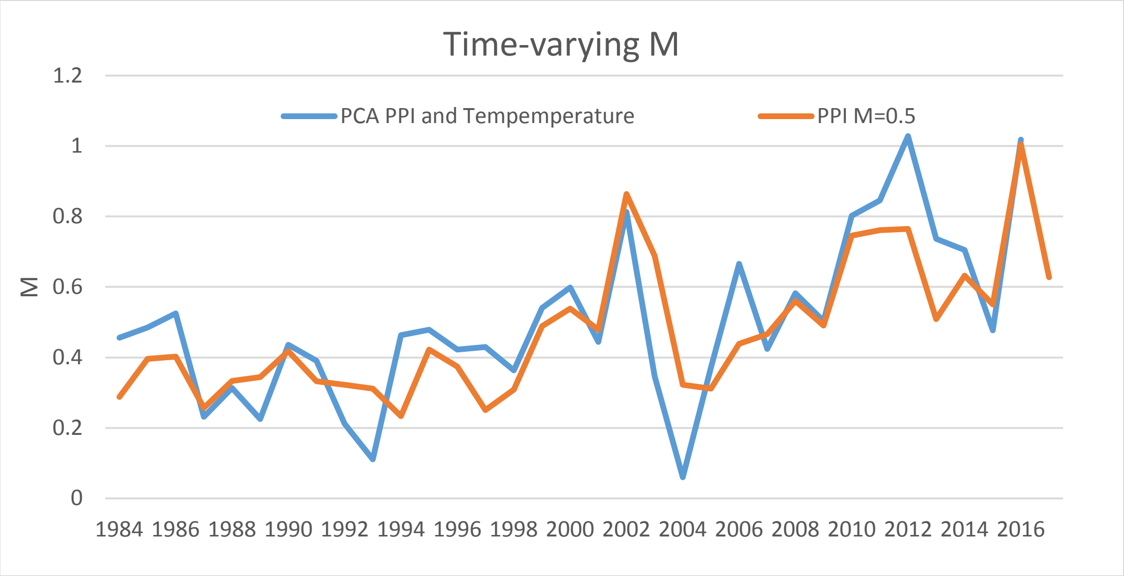
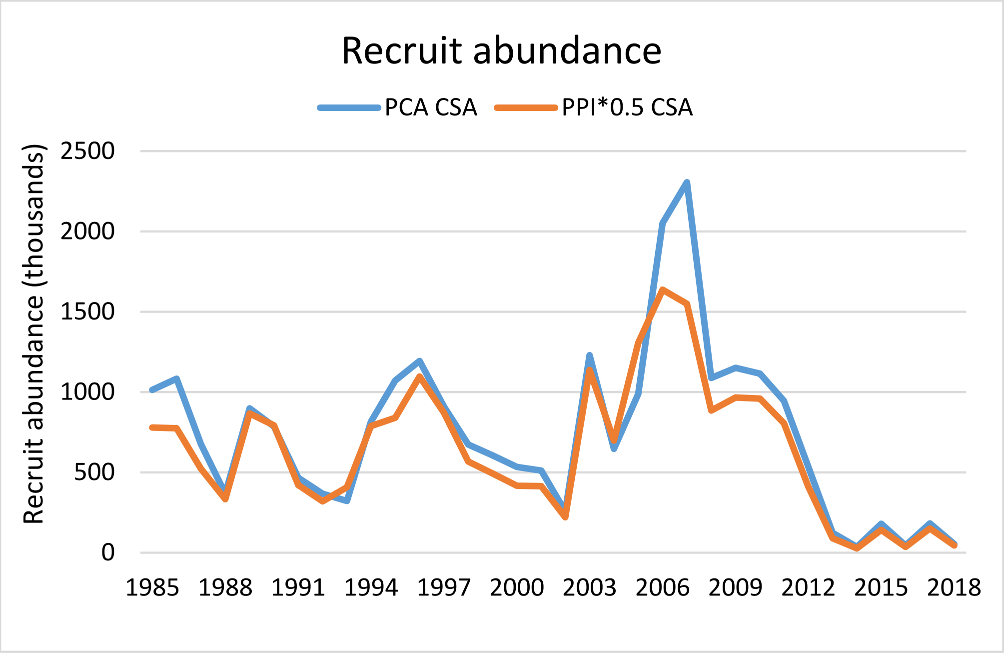
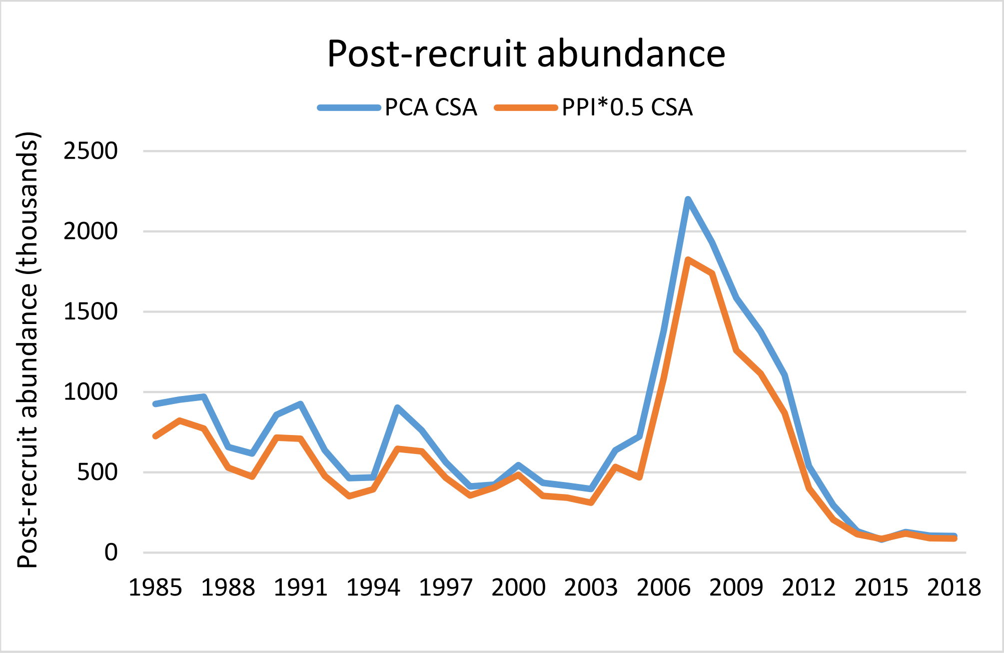


Figure 5.6 Comparison of time-varying M estimated using PPI only or using principal components analysis of temperature data and PPI.

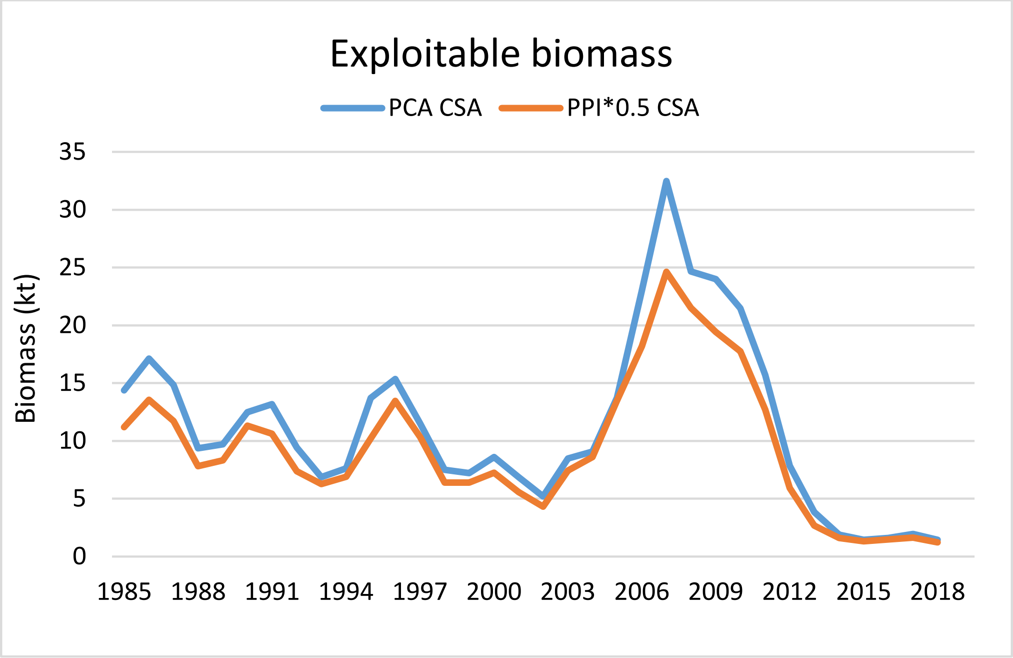
(a)


Recruit abundance
PCA CSA
PPI*0.5 CSA
Recruit abundance (thousands)
2500
2000
1500
1000
500
0
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012
2015
2018

(b)


Post-recruit abundance
PCA CSA
PPI*0.5 CSA
Post-recruit abundance (thousands)
2500
2000
1500
1000
500
0
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012
2015
2018

(c)



(d)

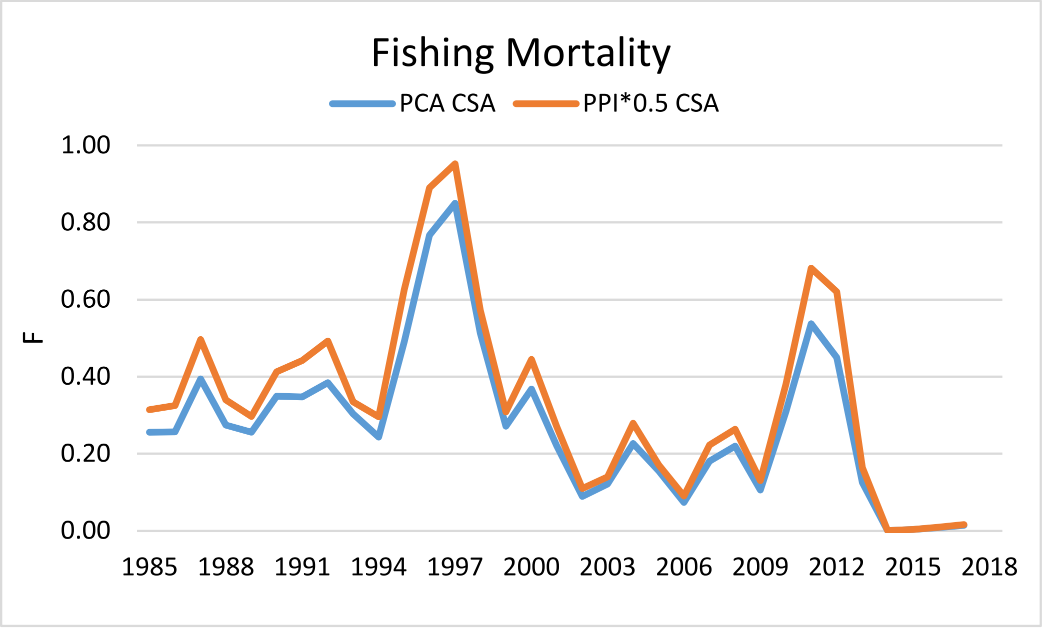


Figure 5.7. (a-d) Comparison of CSA estimates from final model (M=0.5*PPI) and PCA model where M was scaled using a composite environmental variable incorporating both temperature and predation. (a) recruit abundance, (b) post recruit abundance, (c) exploitable biomass, (d) F.

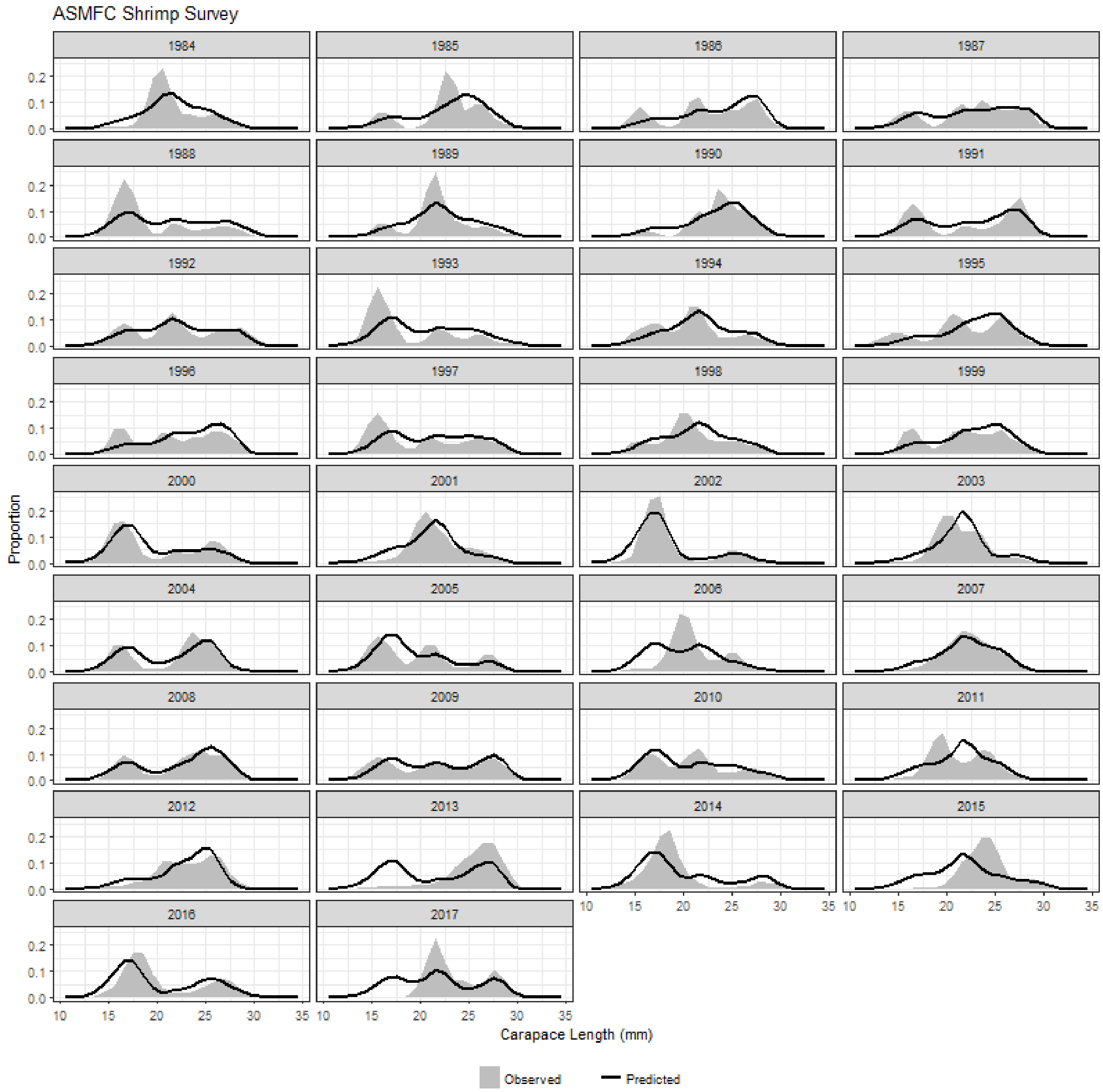


Figure 5.8. **Observed and predicted length composition for the ASMFC Summer Survey by year, from the UME model.**

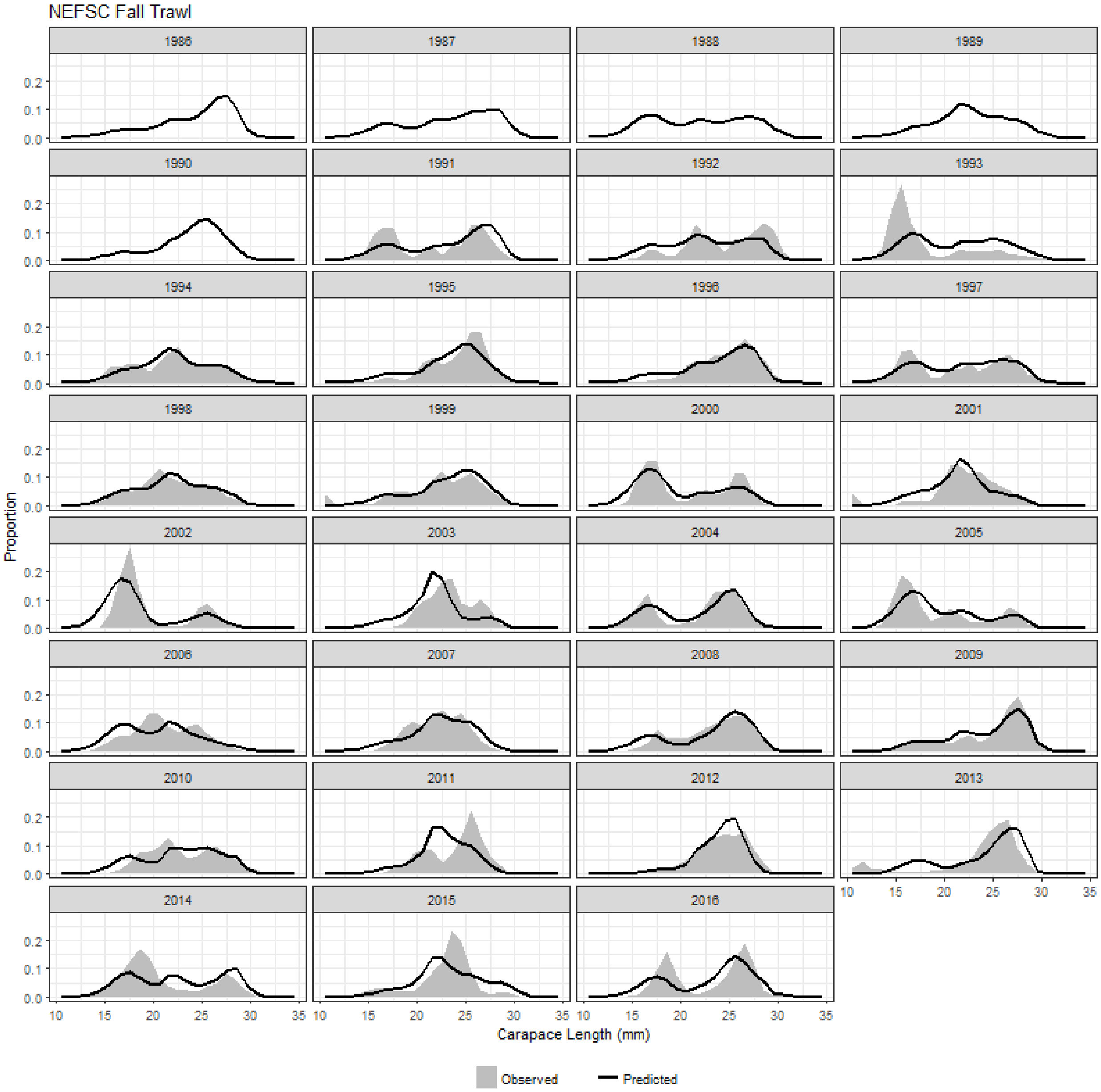


Figure 5.9. **Observed and predicted length composition for the NEFSC Fall Trawl Survey by year, from the UME model.**

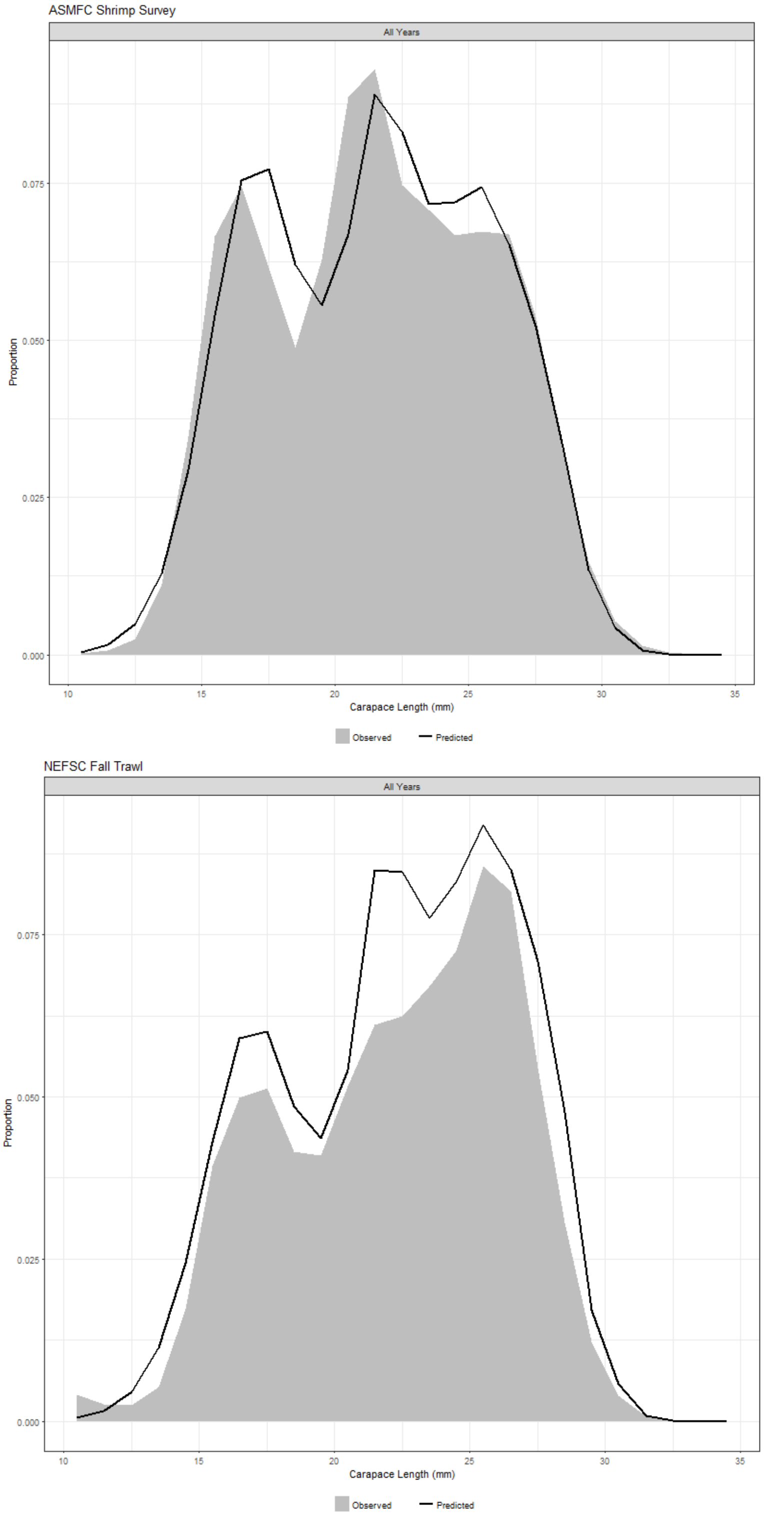


Figure 5.10. Observed and predicted length composition for the ASMFC Summer Survey (top) and NEFSC Fall Survey (bottom) aggregated across years, from the UME model.

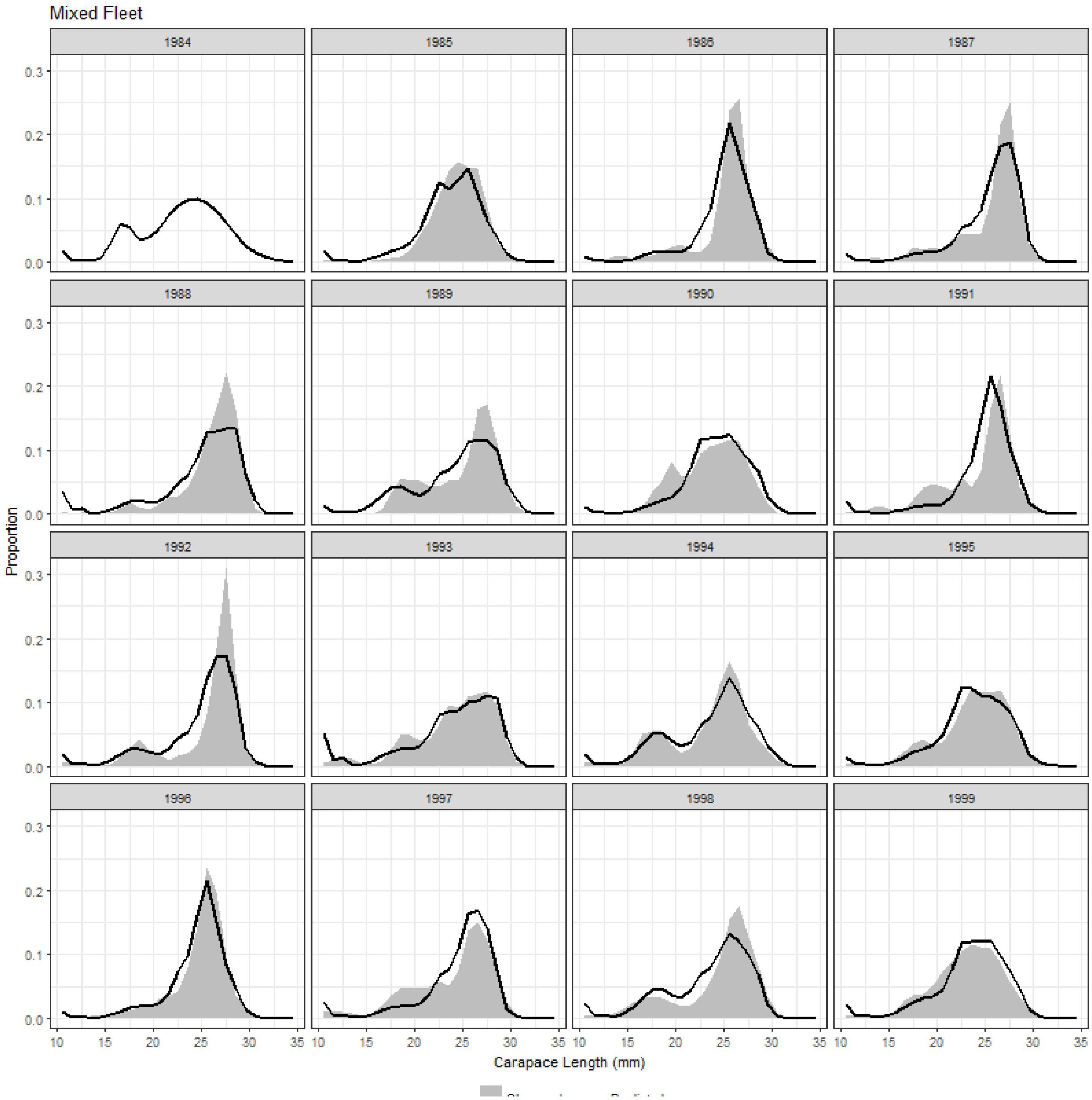


Figure 5.11. Observed and predicted length composition for the mixed trap and trawl fleet by year, from the UME model.

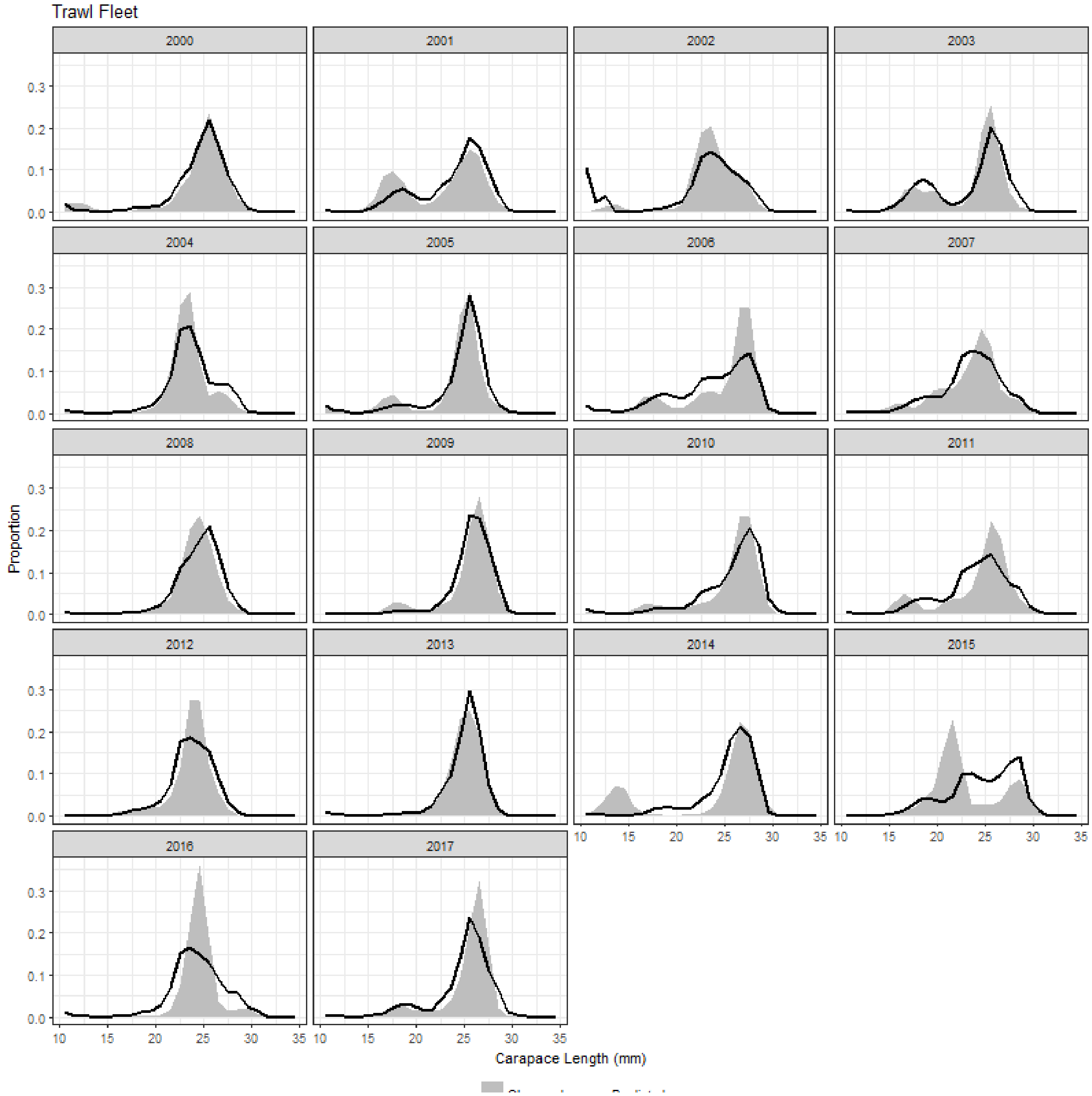


Figure 5.12. **Observed and predicted length composition for the trawl fleet by year, from the UME model.**

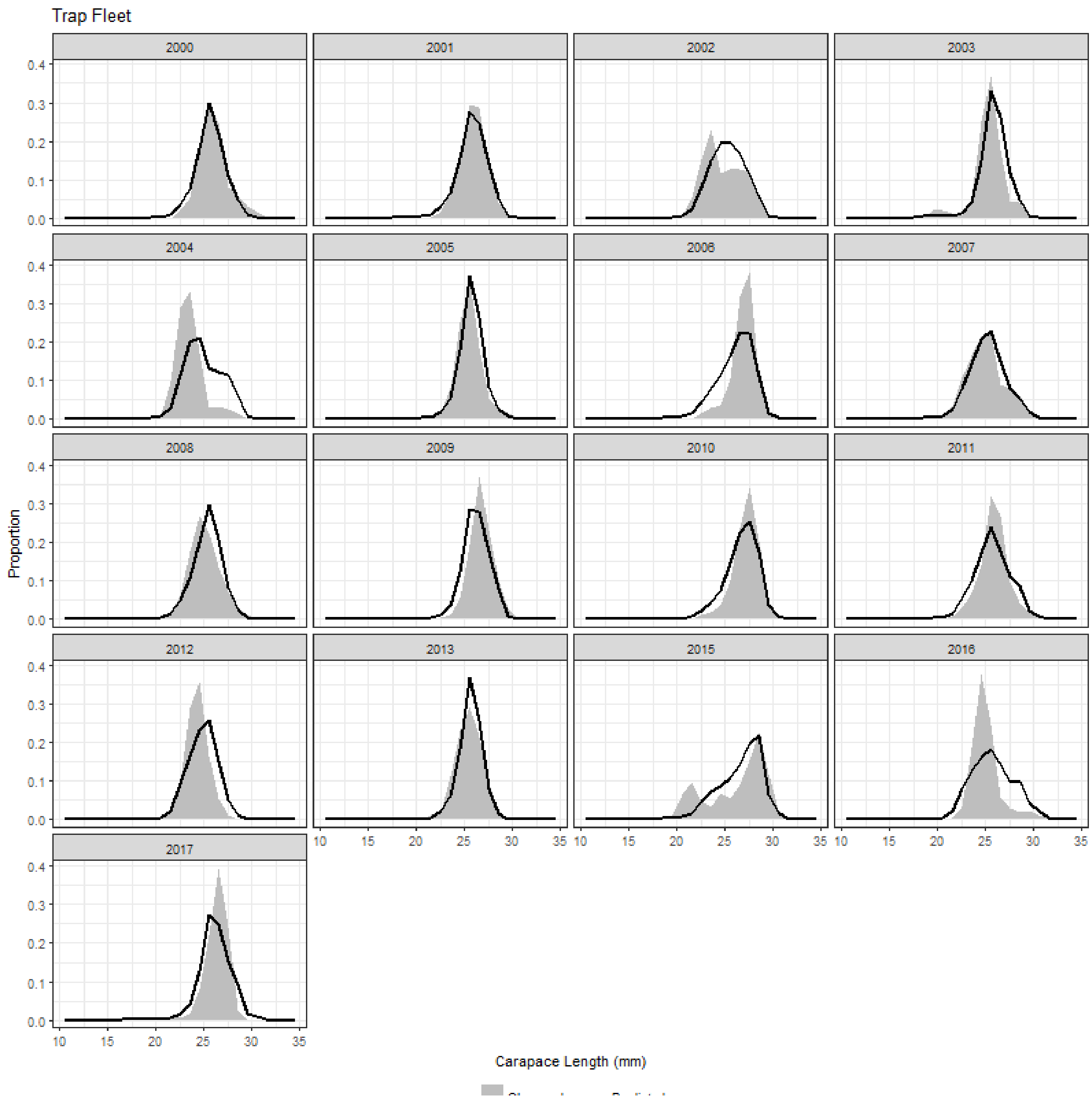


Figure 5.13. Observed and predicted length composition for the trap fleet by year, from the UME model.

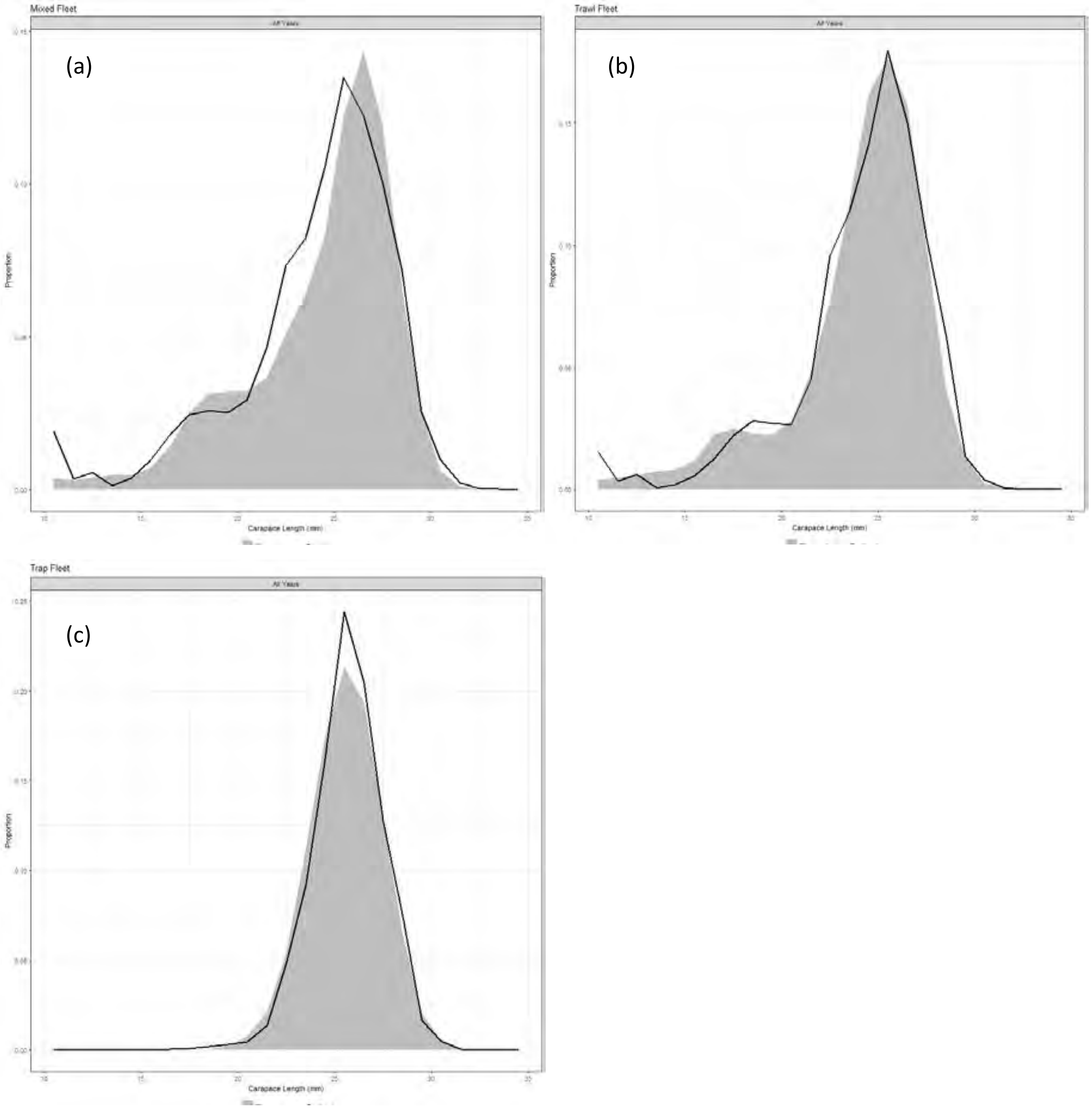


Figure 5.14. **Observed and predicted length composition for the mixed fleet (a), the trawl fleet (b), and the trap fleet (c) aggregated across years, from the UME model.**

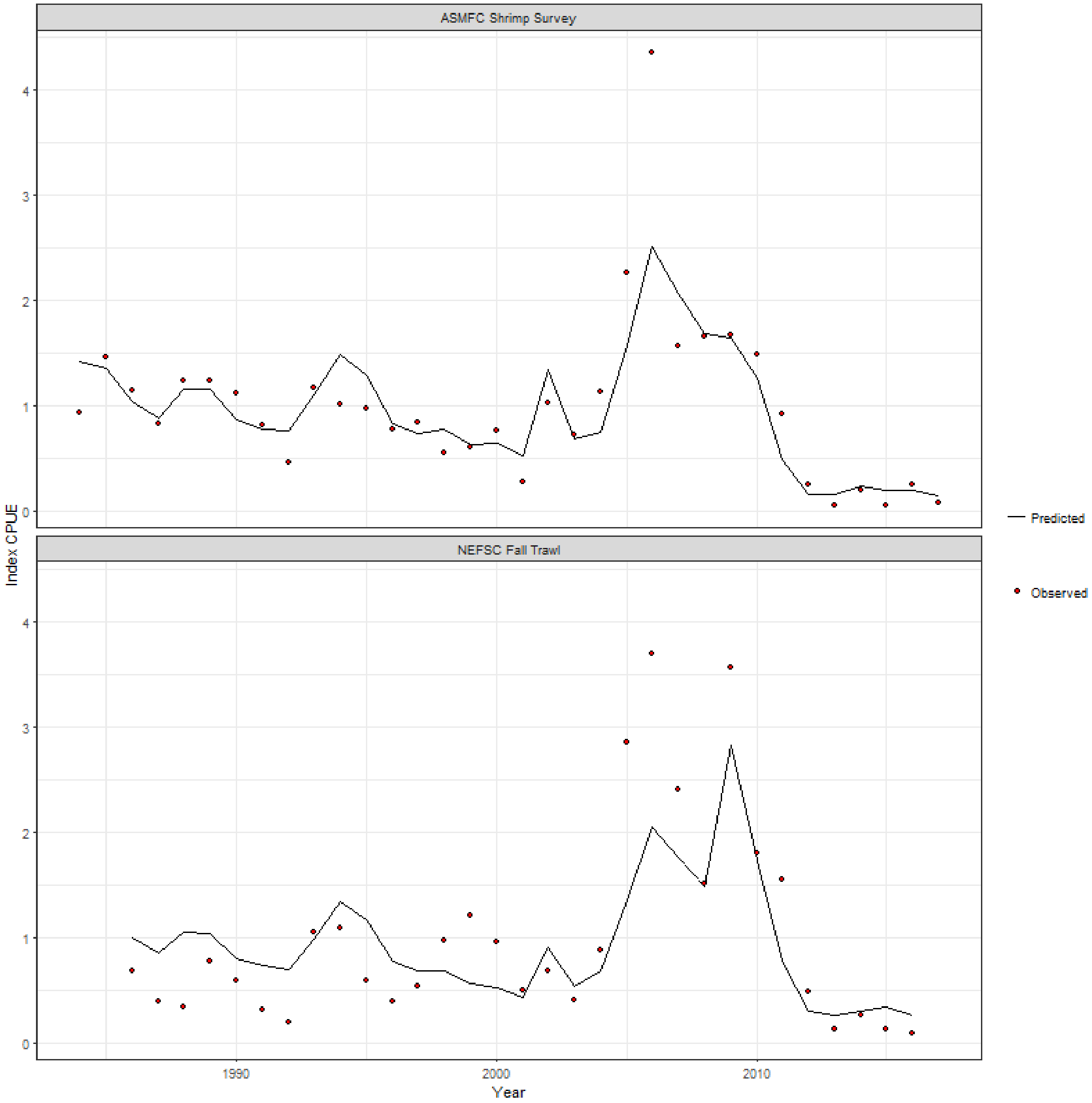


Figure 5.15. Observed and predicted index values from the UME model.

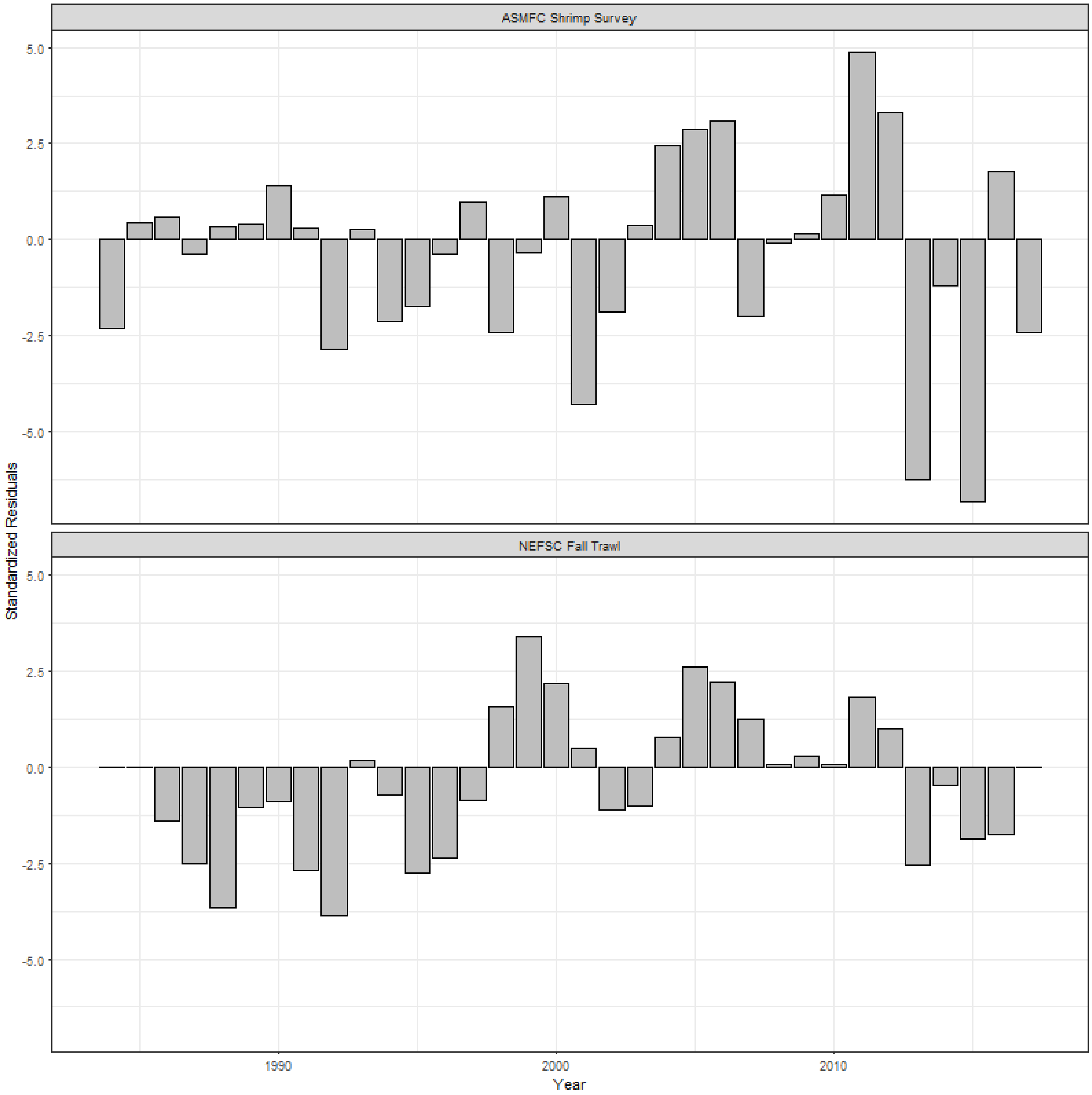


Figure 5.16. Standardized residuals for the survey indices from the UME model.

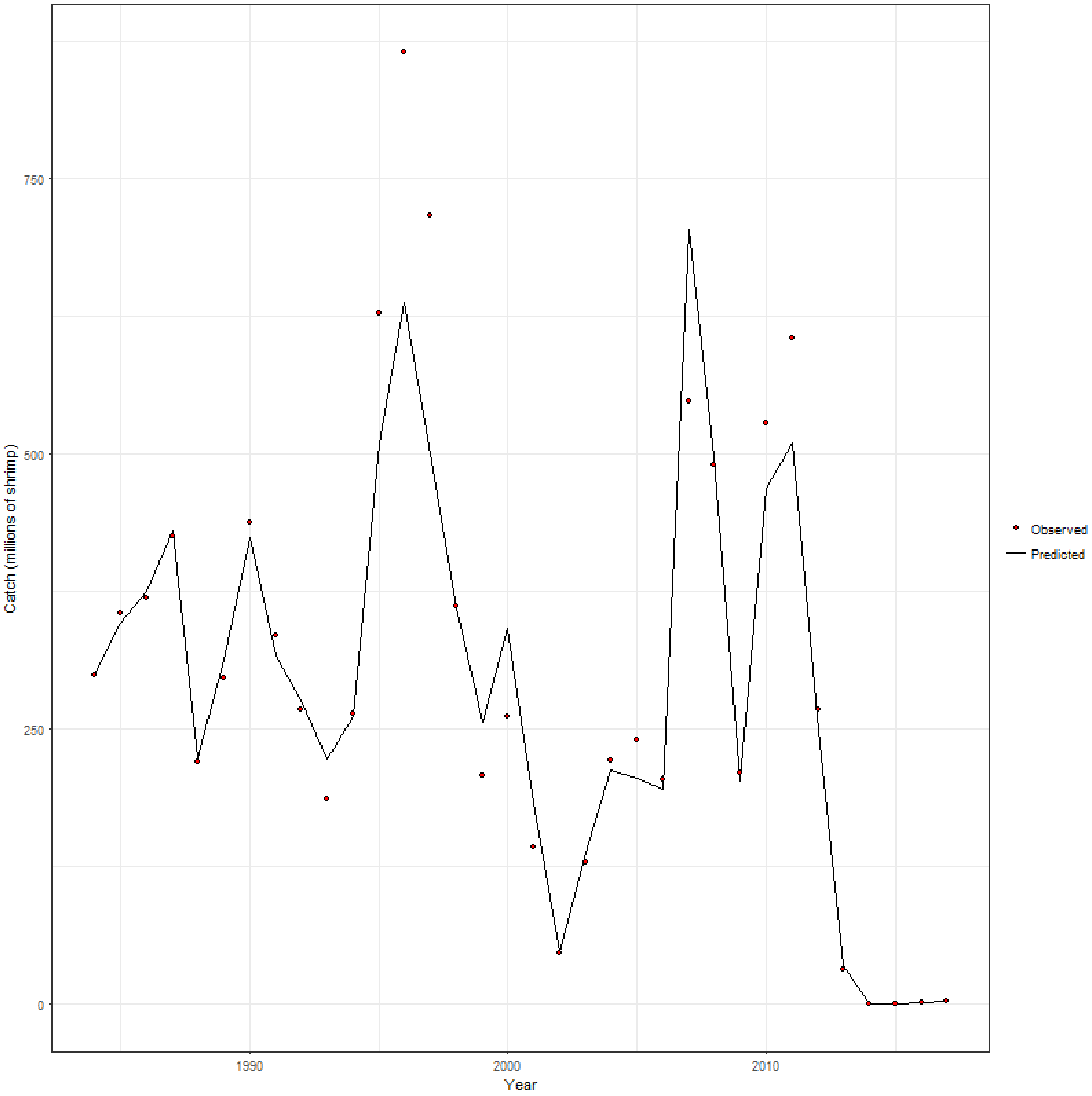


Figure 5.17. Observed and predicted total catch from the UME model.

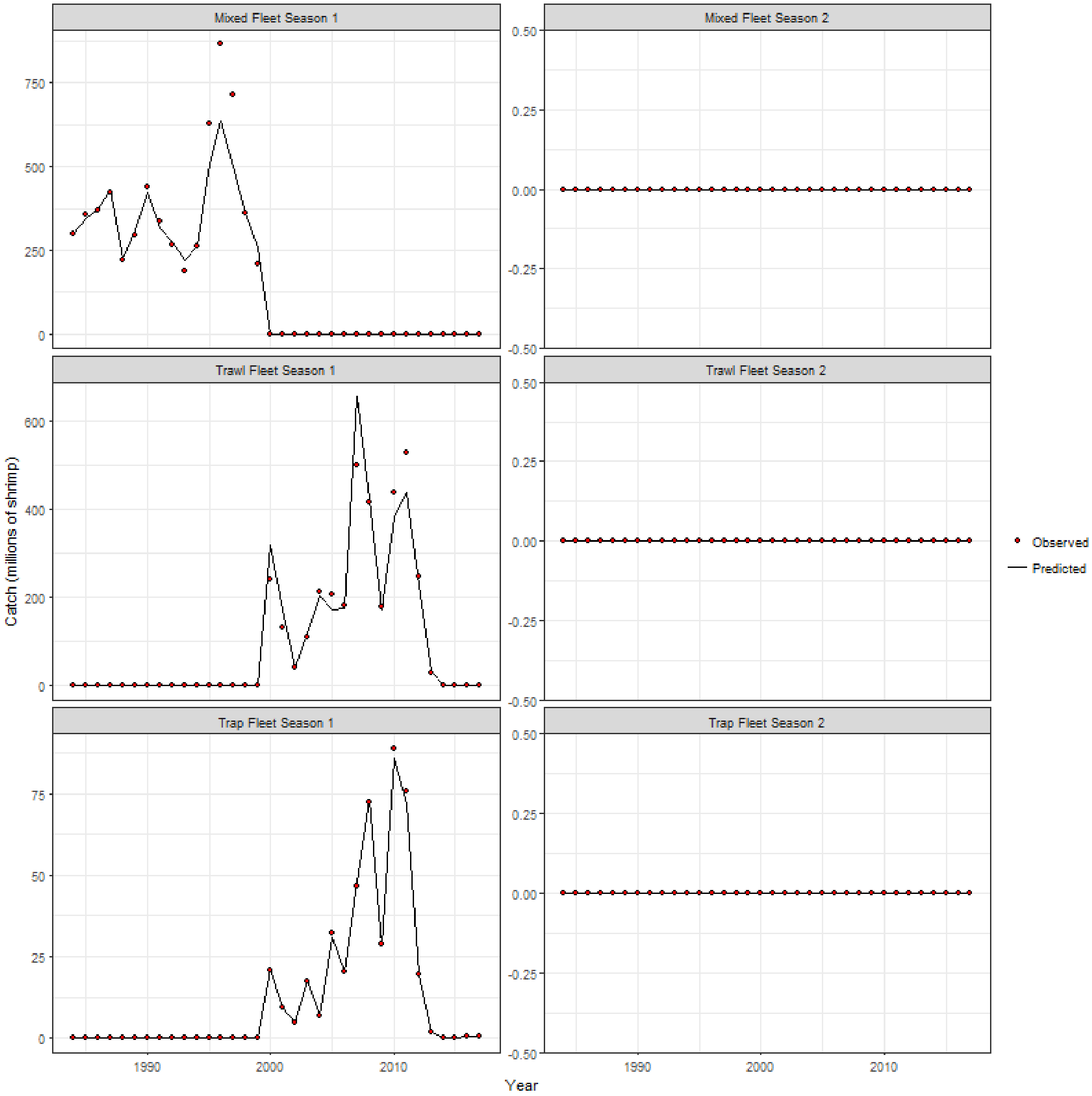


Figure 5.18. Observed and predicted catch by season for each fleet from the UME model.

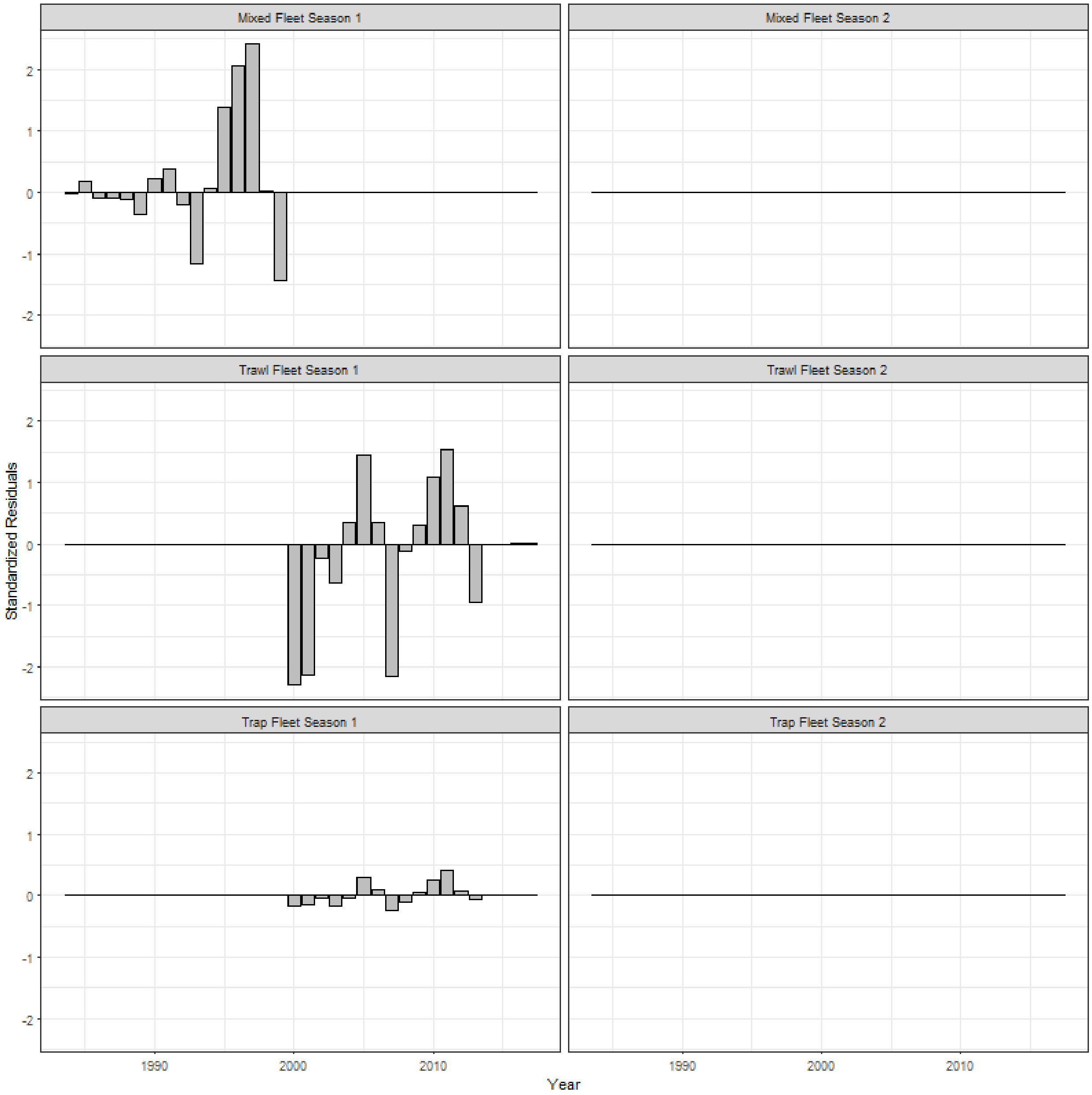


Figure 5.19. **Standardized residuals by season for each fleet from the UME model.**

Figure 5.20. Retrospective analysis results for exploitation rate for the base run of the UME model. Absolute values top, relative to 2017 run bottom.

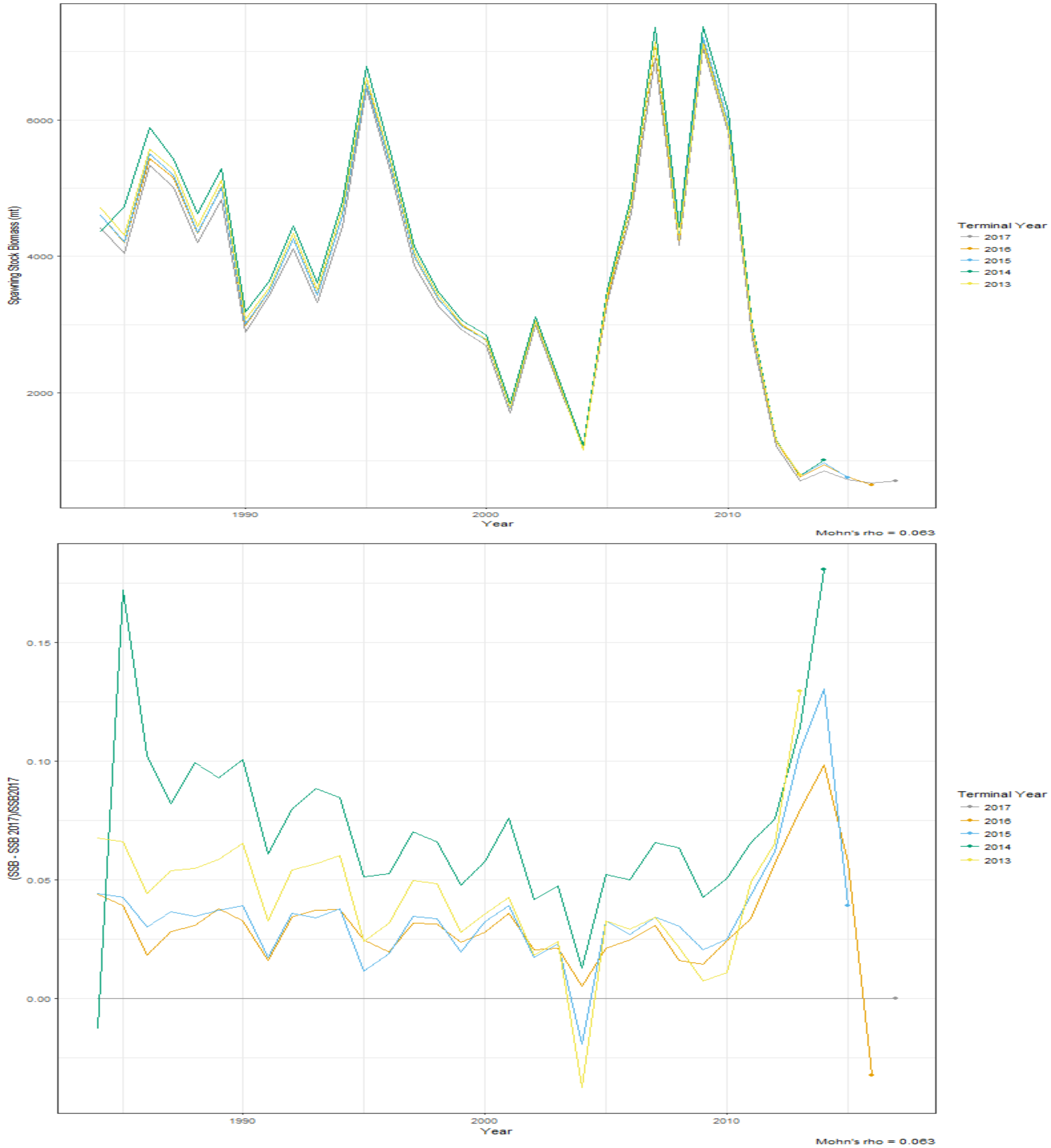


Figure 5.21. **Retrospective analysis results for SSB for the base run of the UME model. Absolute values top, relative to 2017 run bottom.**

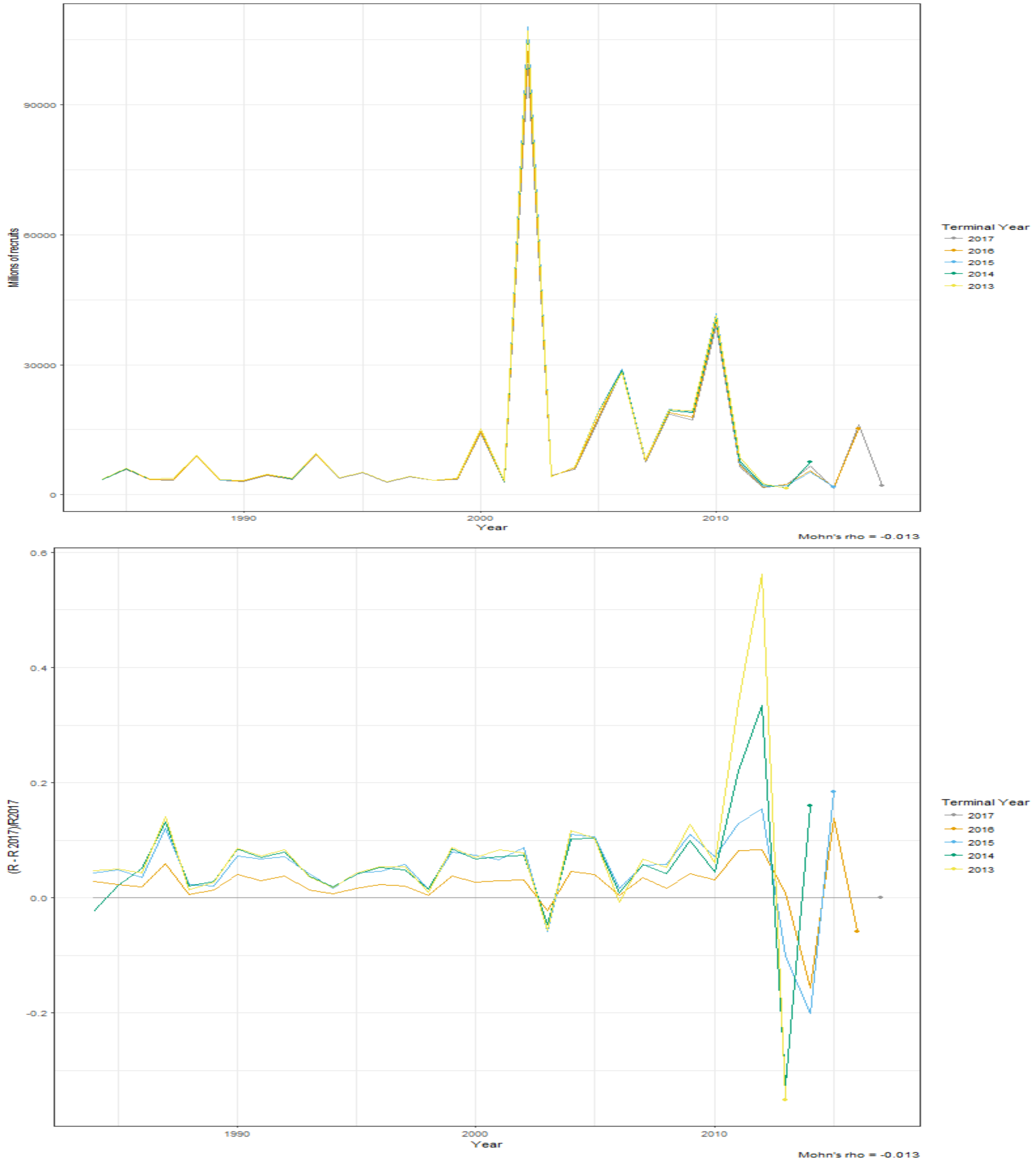


Figure 5.22. Retrospective analysis results for recruitment for the base run of the UME model. Absolute values top, relative to 2017 run bottom.

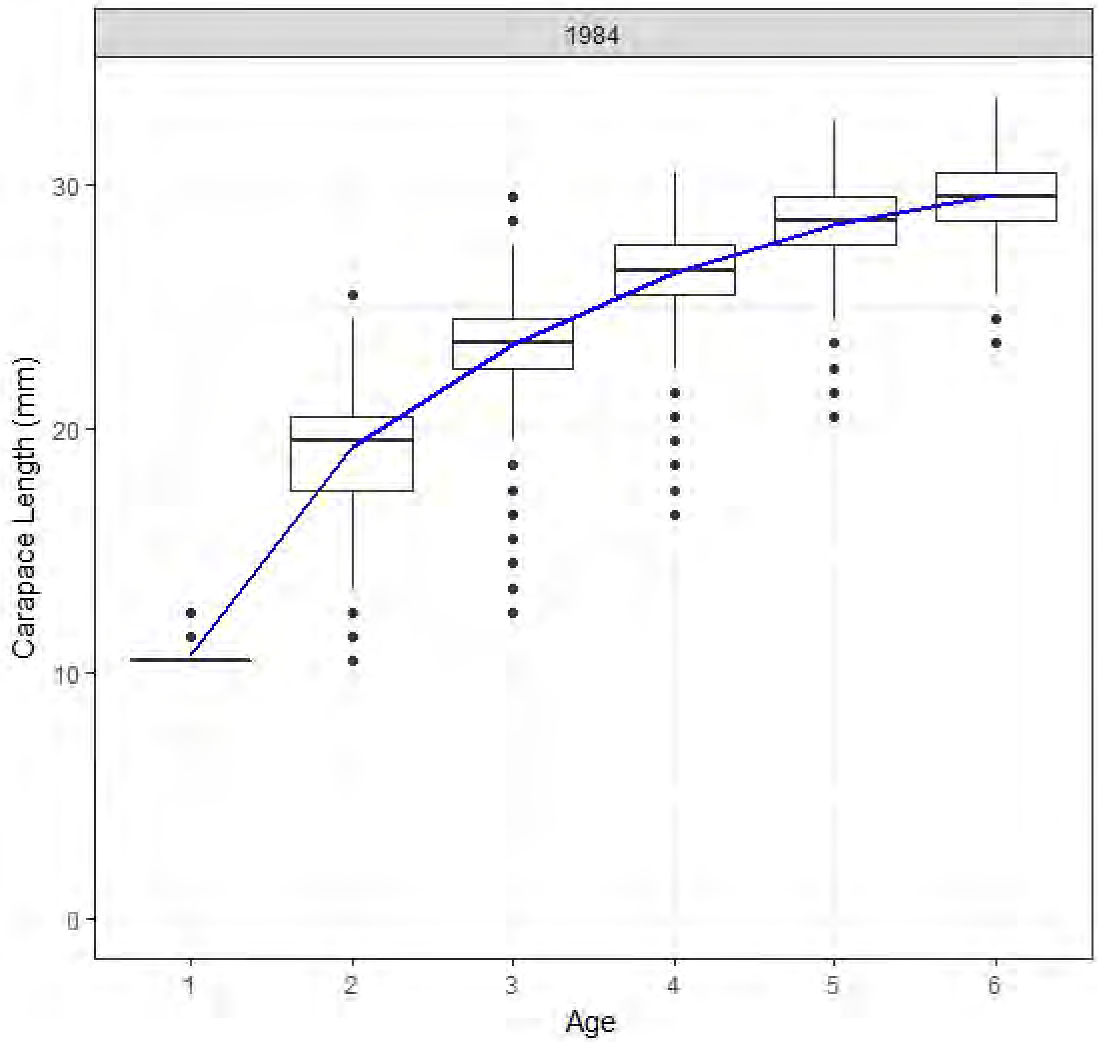


Figure 5.23. Distribution of size at age based on the model-estimated growth parameters from the base run of the UME model. Solid blue line represents the mean size-at-age

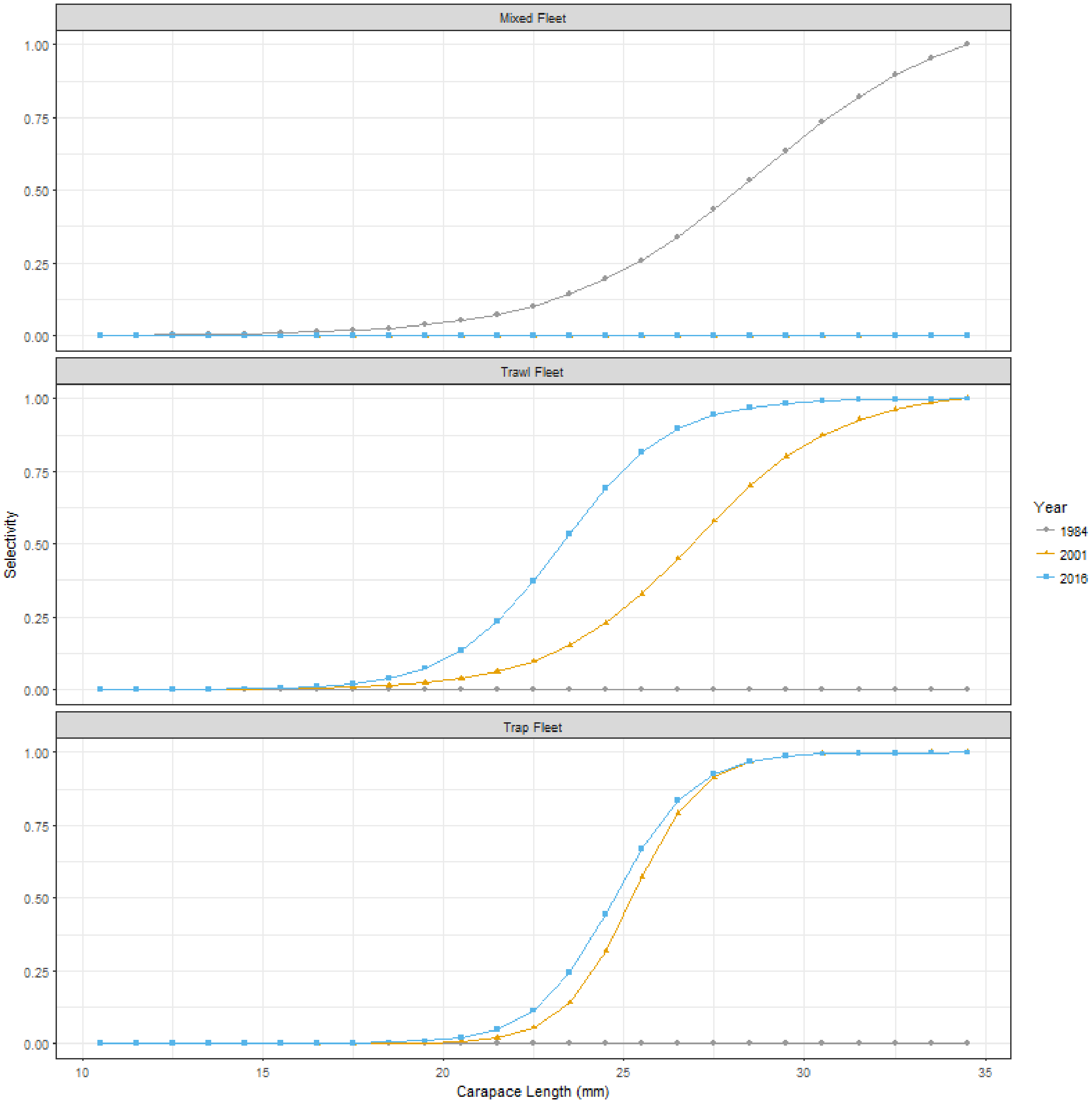


Figure 5.24. Estimated selectivity patterns for the three fleets. Selectivity blocks are 1984-1999, 2000-2013, and 2014-2017.

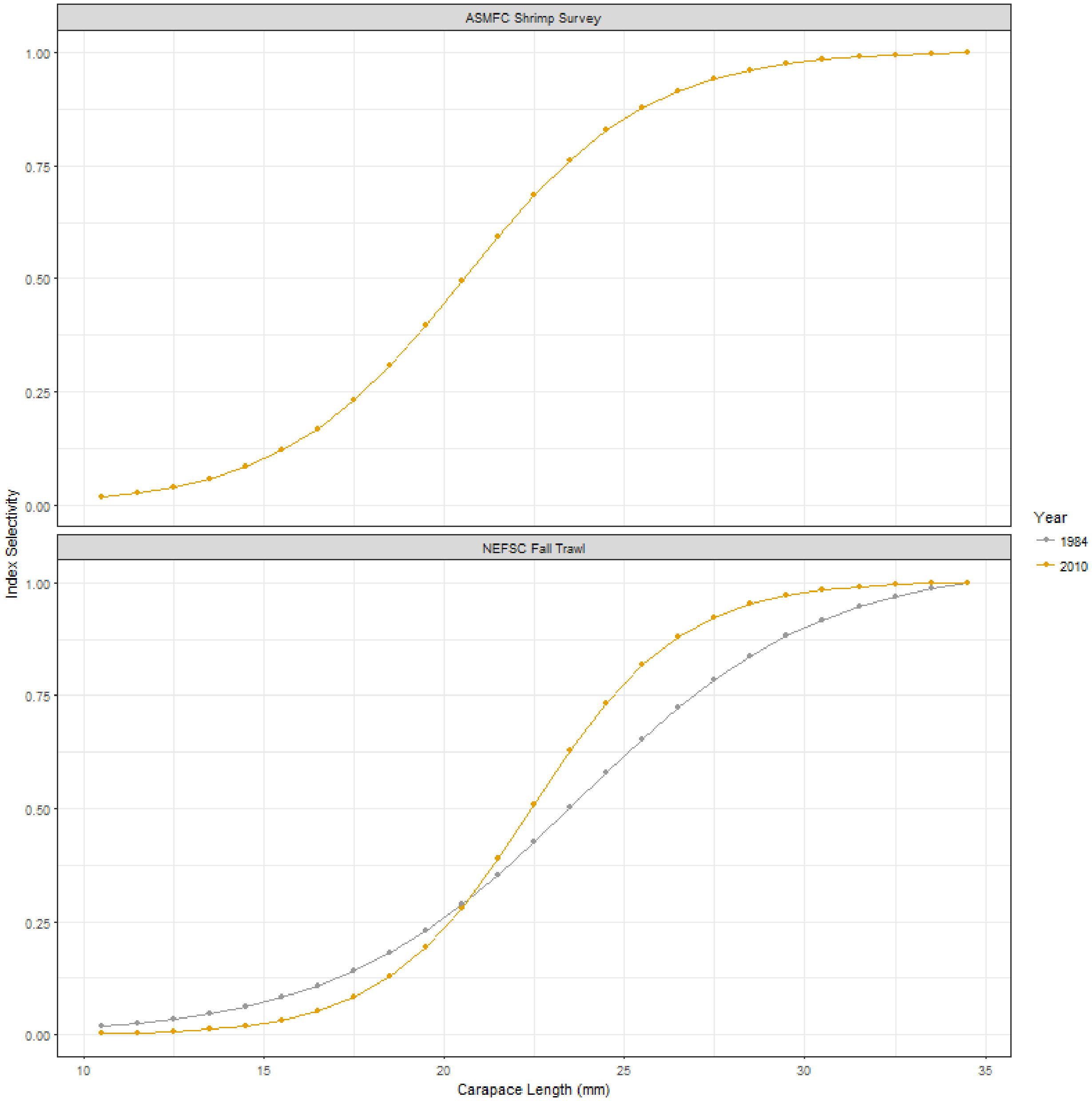


Figure 5.25. Estimated selectivity patterns for the surveys from the base run of the UME model. The NEFSC Fall Trawl has two selectivity blocks due to the vessel change in 2009.

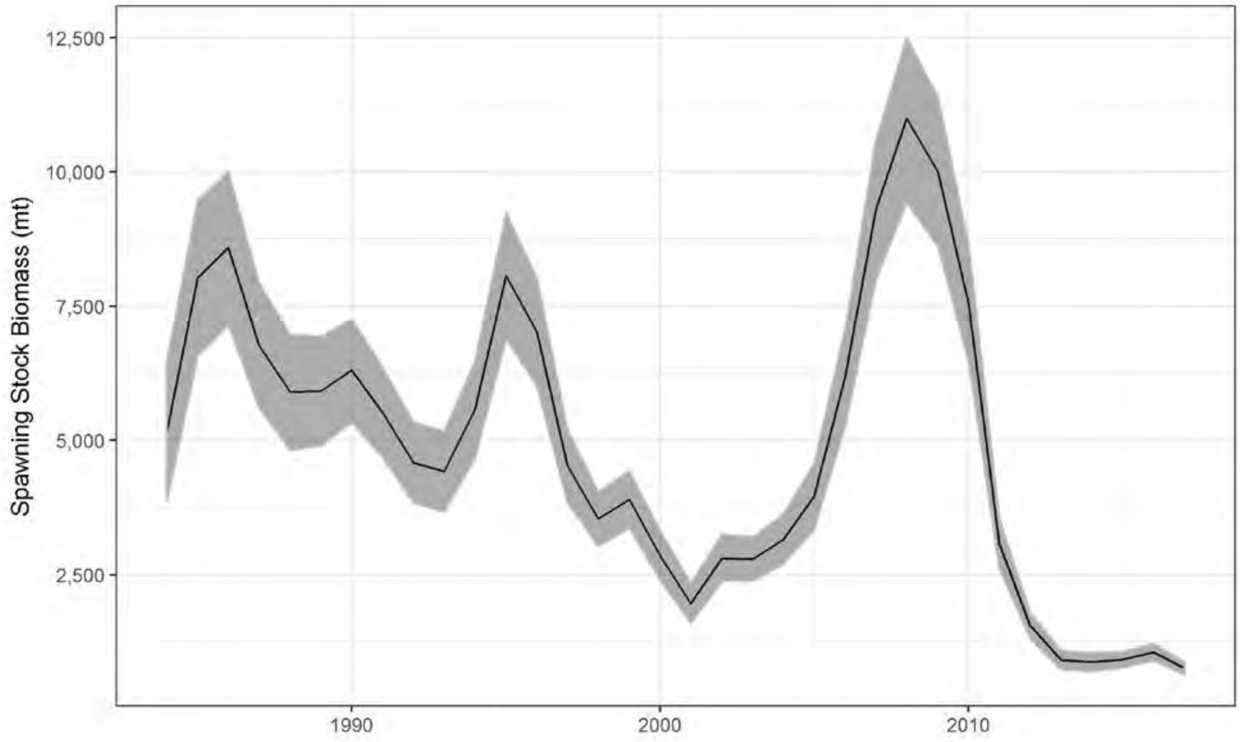


Figure 5.26. SSB estimates from the base run of the UME model. Grey shading indicates 95% confidence intervals of the estimates.

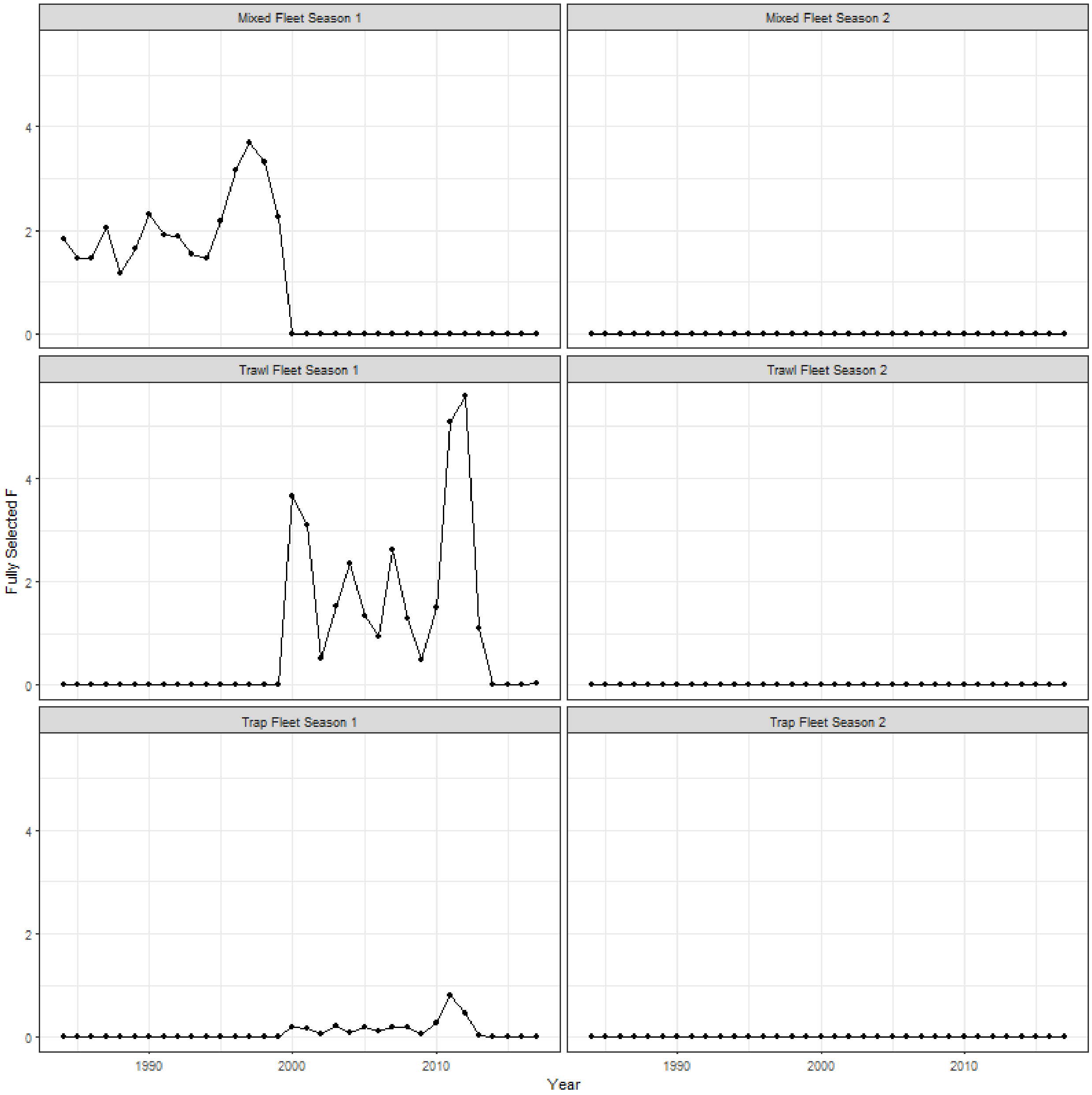


Figure 5.27. Fully recruited F rates by fleet and season for the base run of the UME model.

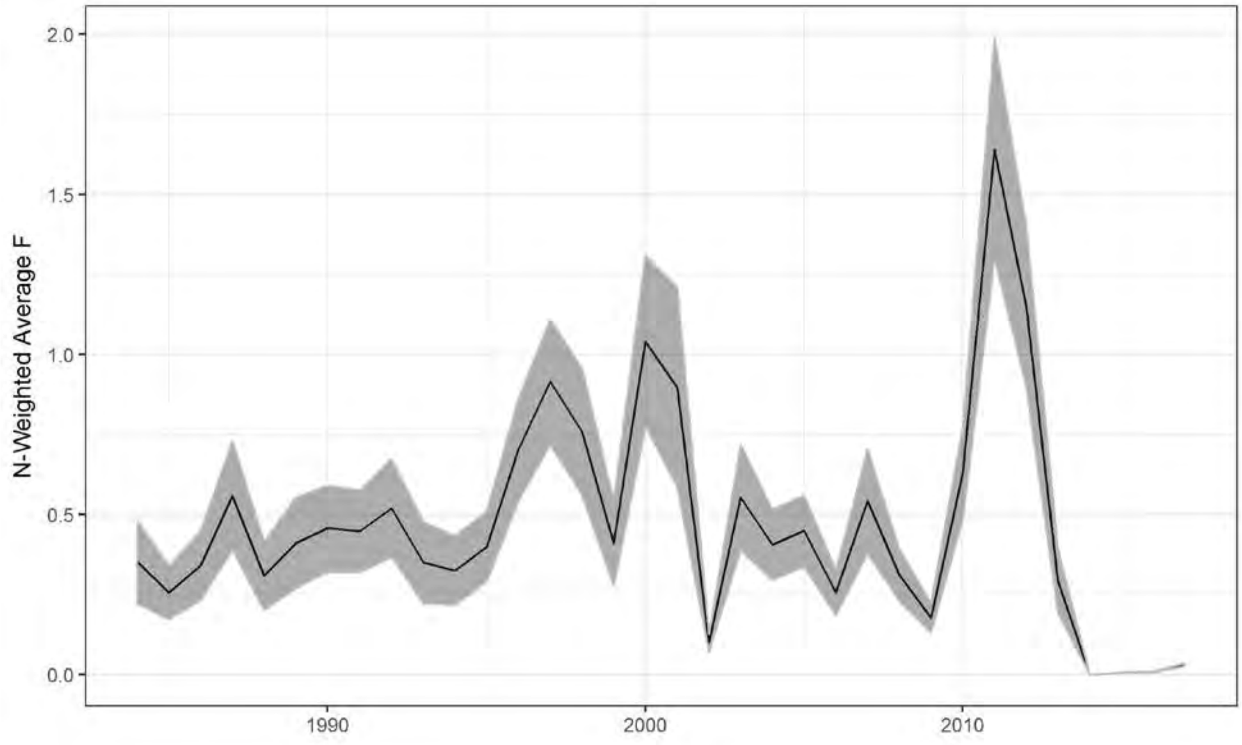


Figure 5.28. Average F for shrimp ≥ 22mm CL, numbers weighted. Grey shading indicates 95% confidence intervals of the estimates.

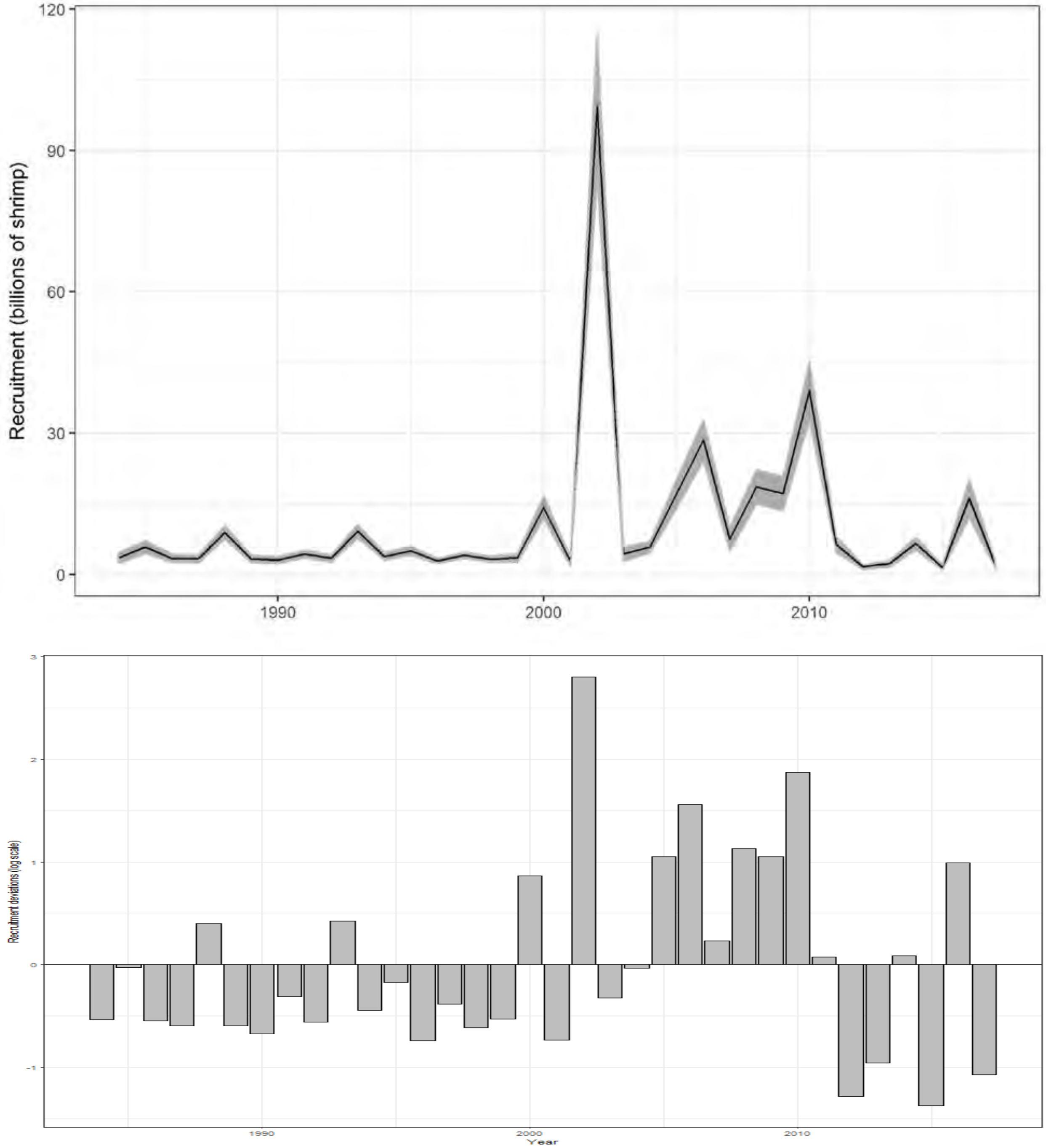


Figure 5.29. Model estimate recruitment in Age-1 shrimp (top) and recruitment deviations (log-scale, bottom) from the base run of the UME model. Grey shading indicates 95% confidence intervals of the estimates.

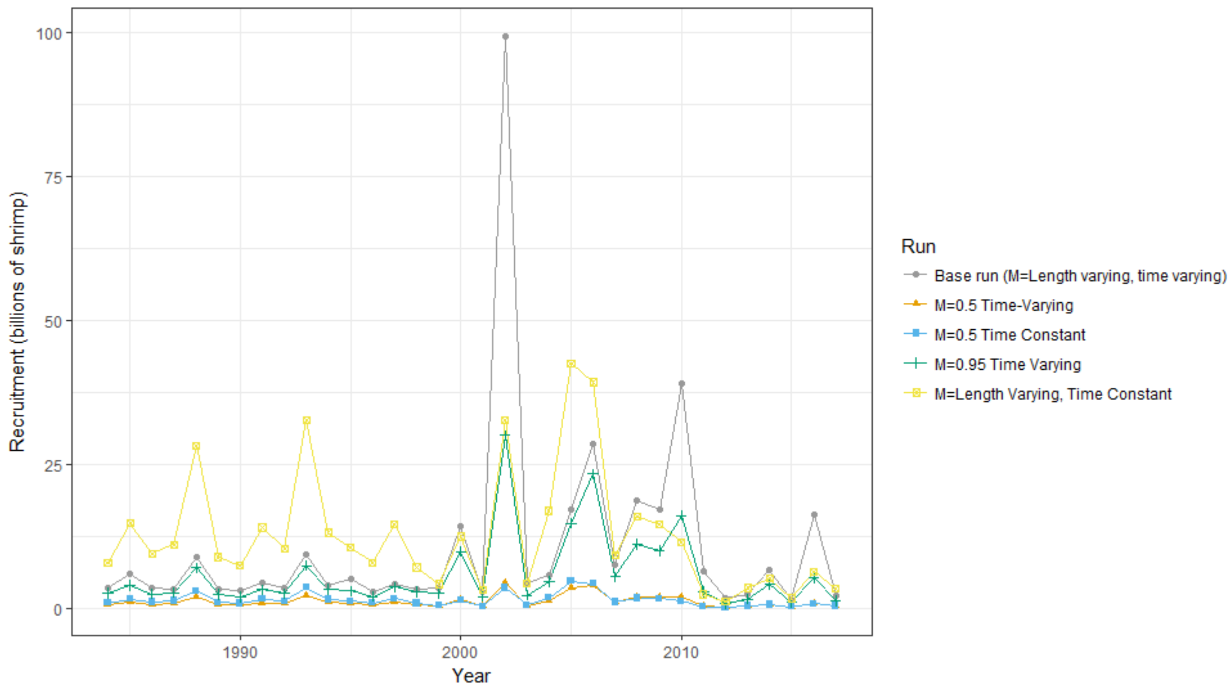


Figure 5.30. **Recruitment estimates from the UME model under different M scenarios.**

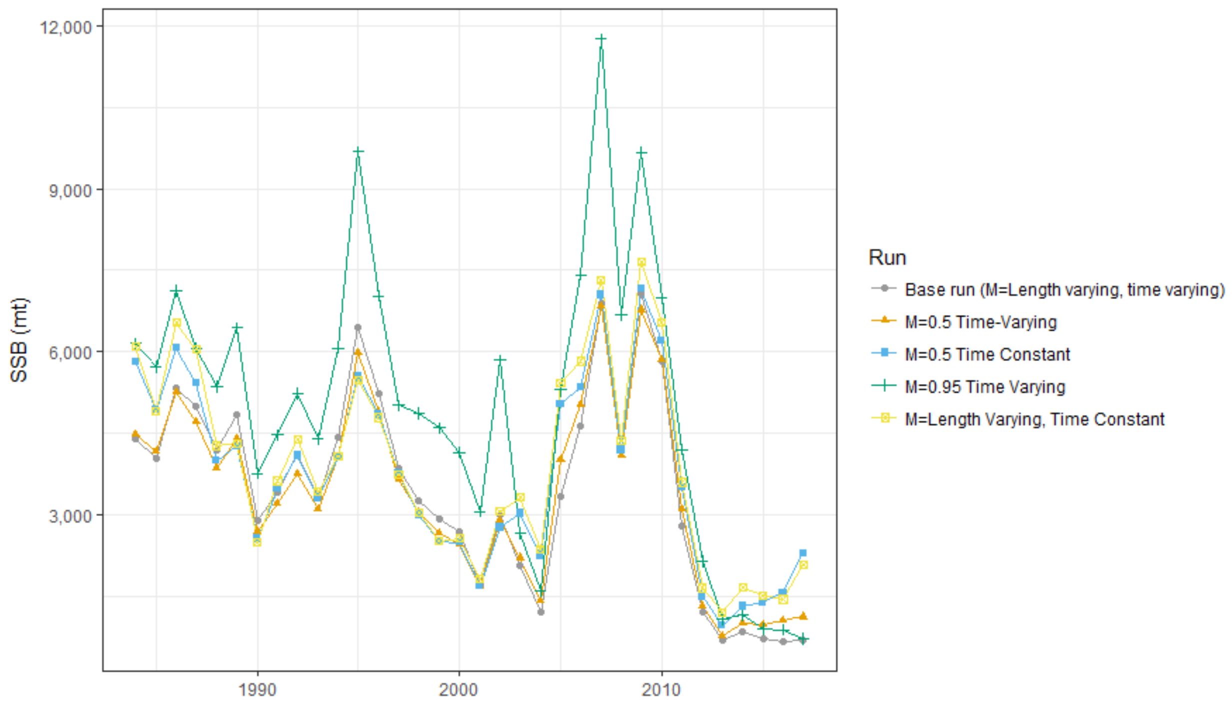


Figure 5.31. SSB estimates from the UME model under different M scenarios.

Figure 5.32. **Average F estimates from the UME model under different M scenarios.**

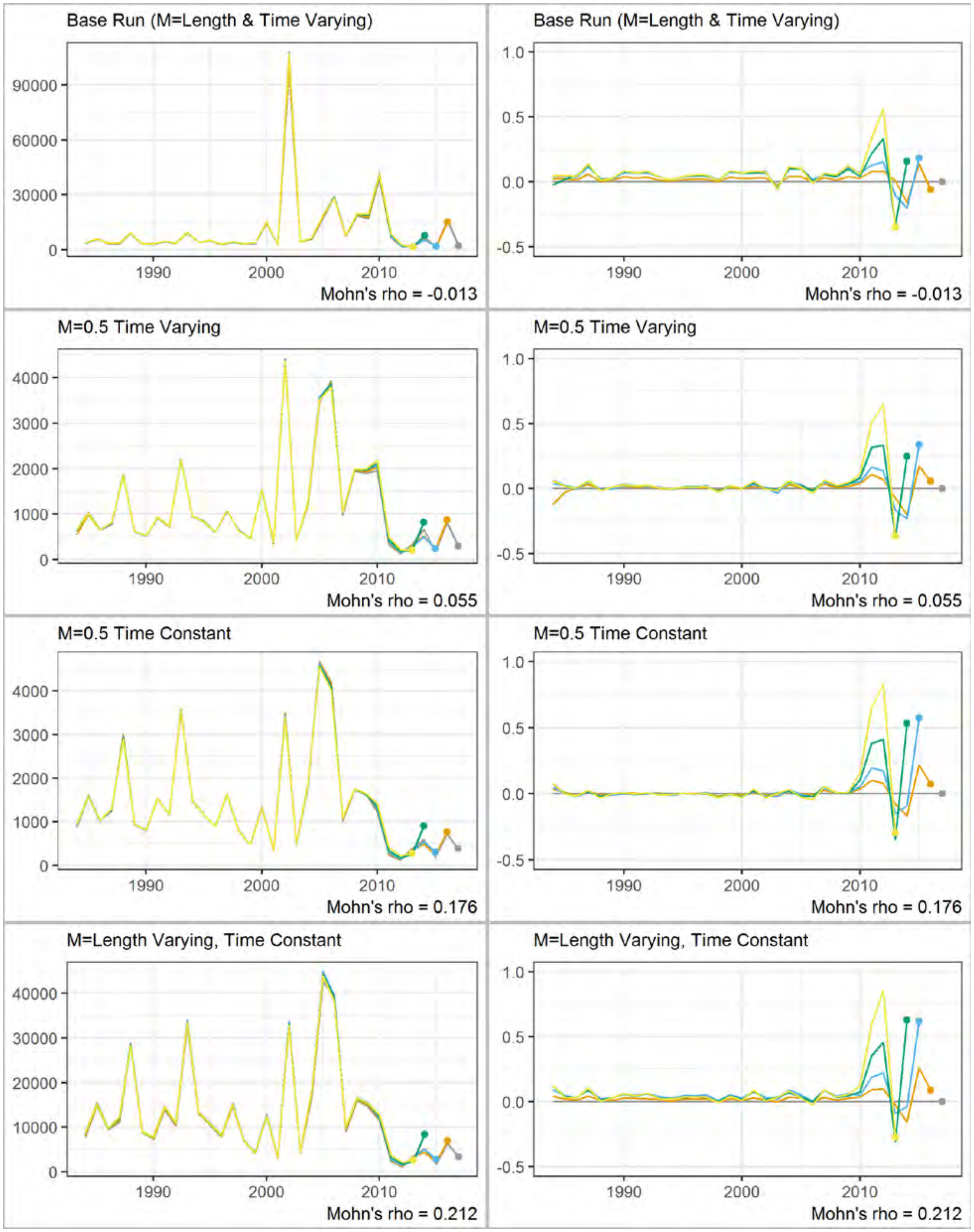


Figure 5.33. **Retrospective patterns in recruitment from the UME model under different M scenarios.**

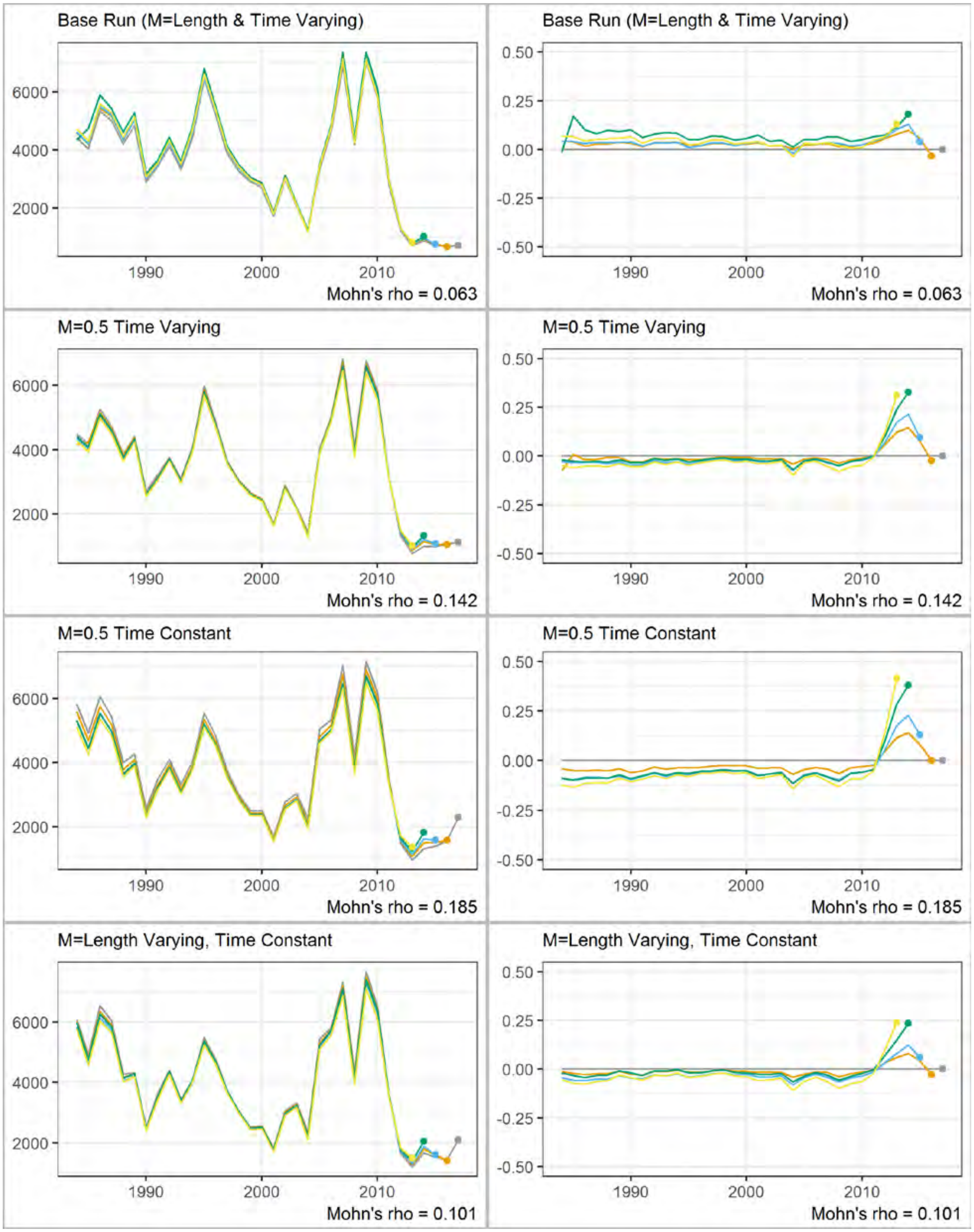


Figure 5.34. Retrospective patterns in SSB from the UME model under different M scenarios.

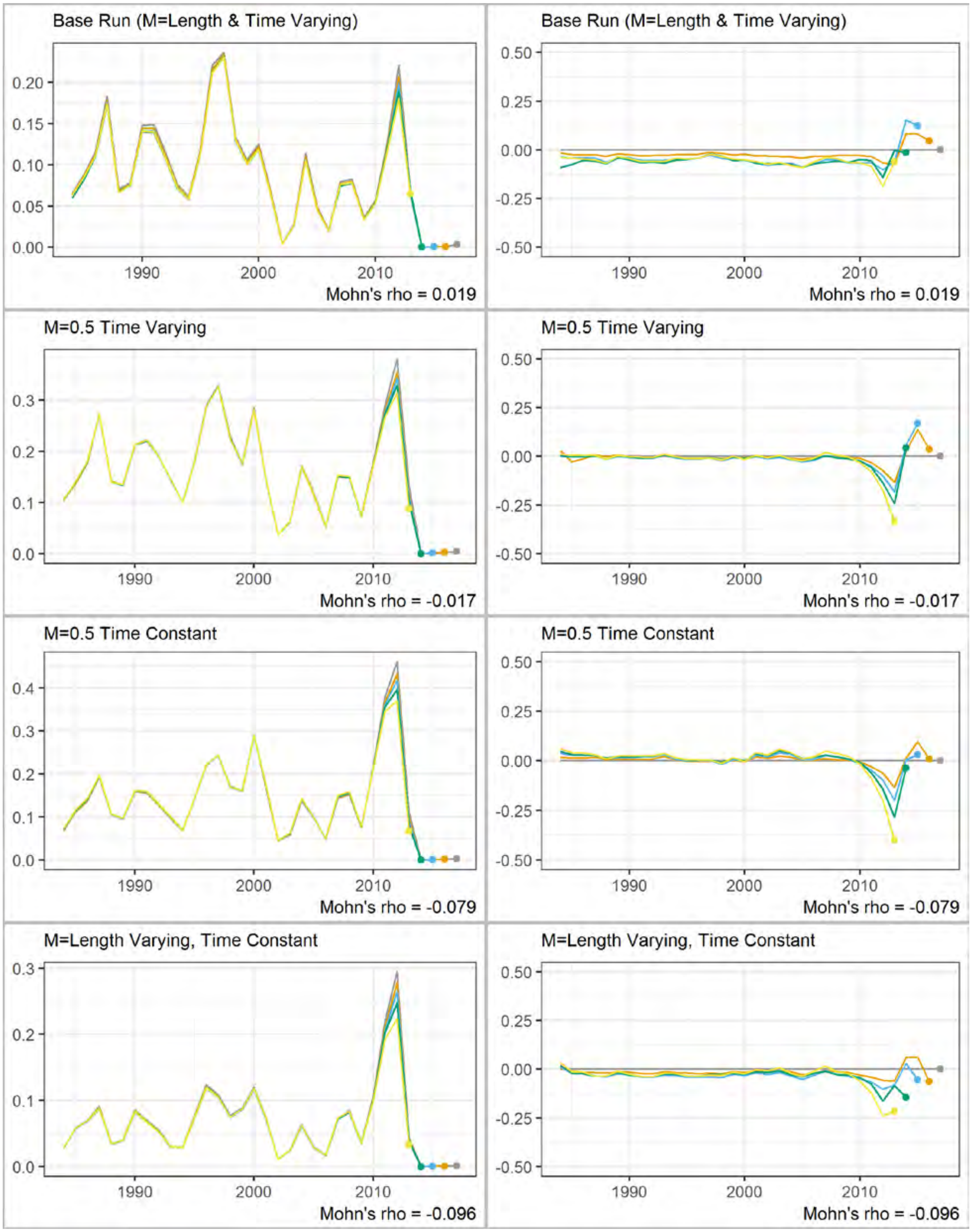


Figure 5.35. Retrospective patterns in exploitation rate from the UME model under different M scenarios.

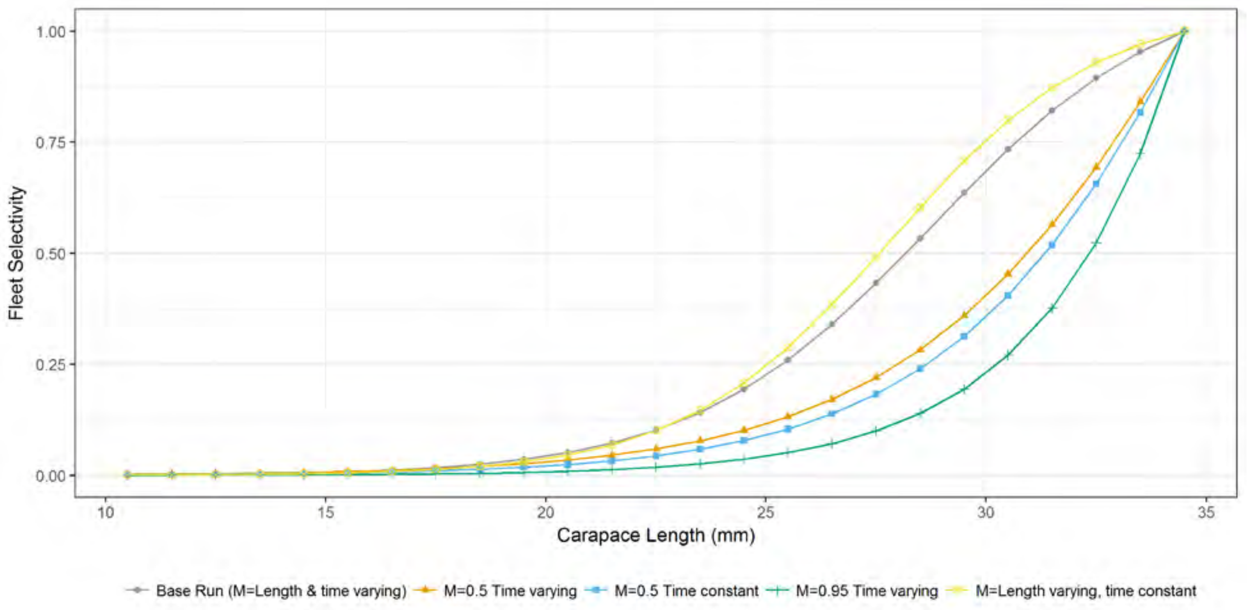


Figure 5.36. Differences in selectivity patterns for the mixed fleet from the UME model under different M scenarios.

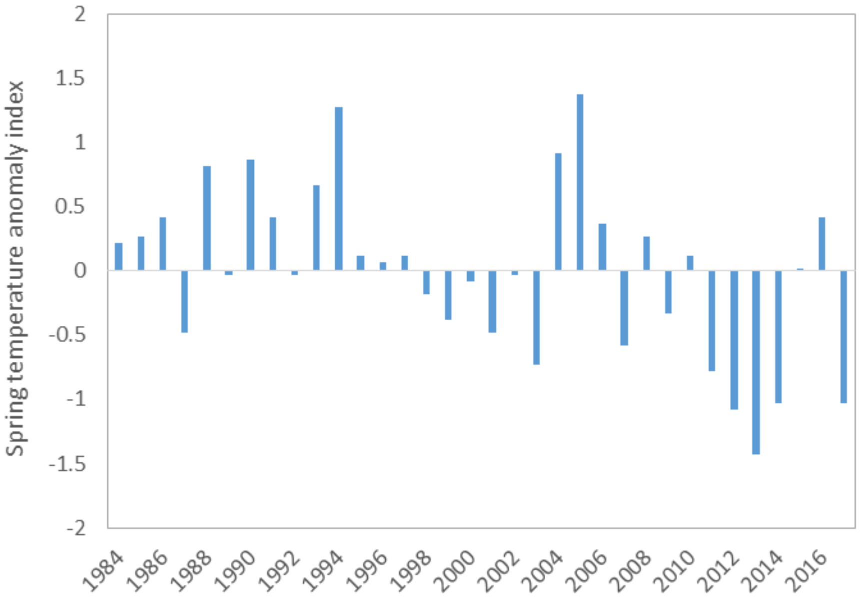


Figure 5.37. Environmental index of recruitment deviations used in UME model sensitivity runs.

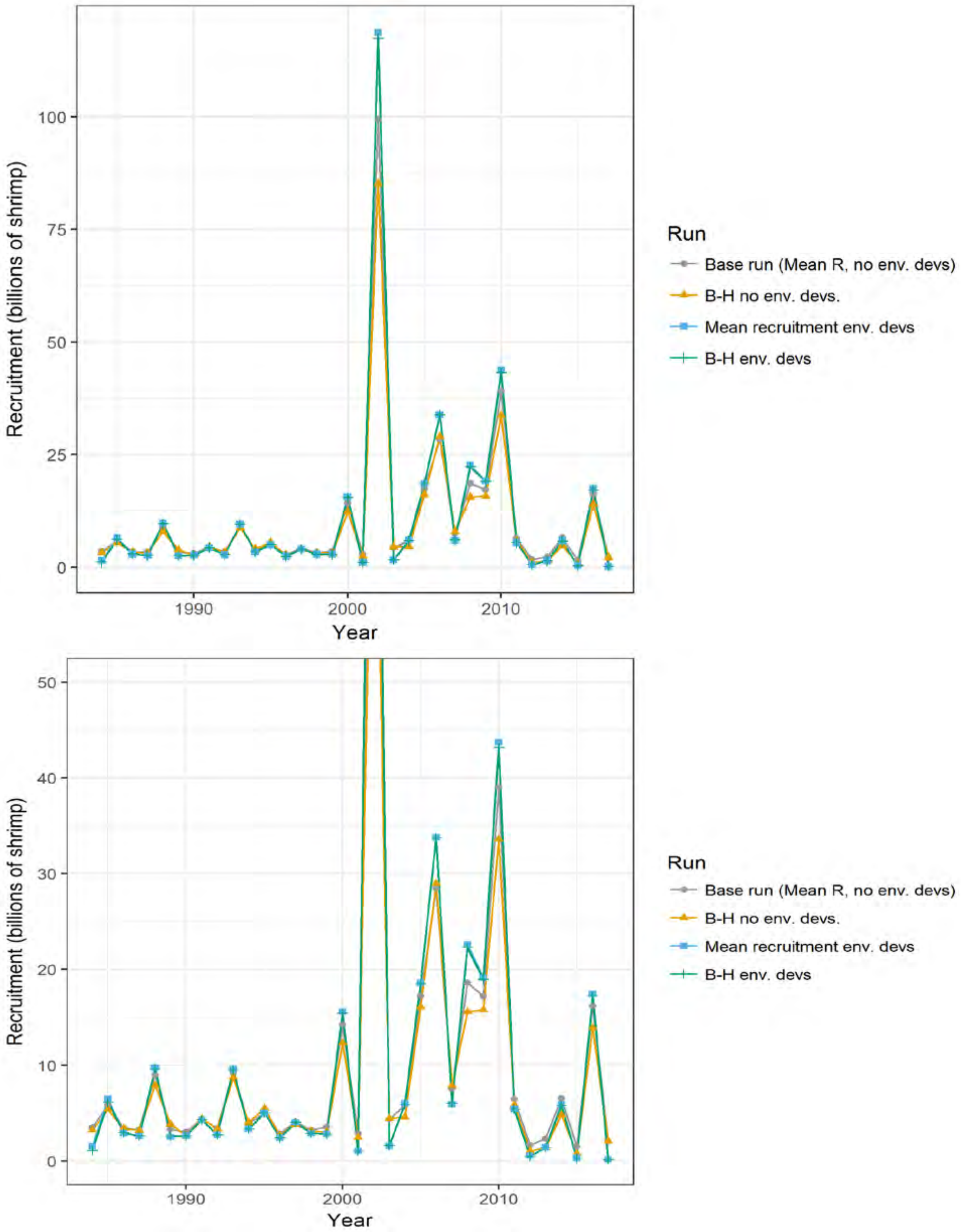


Figure 5.38. Estimates of recruitment from the UME model fit with and without an environmental index of recruitment deviations. The y-axis on the lower graph has been truncated to show detail.

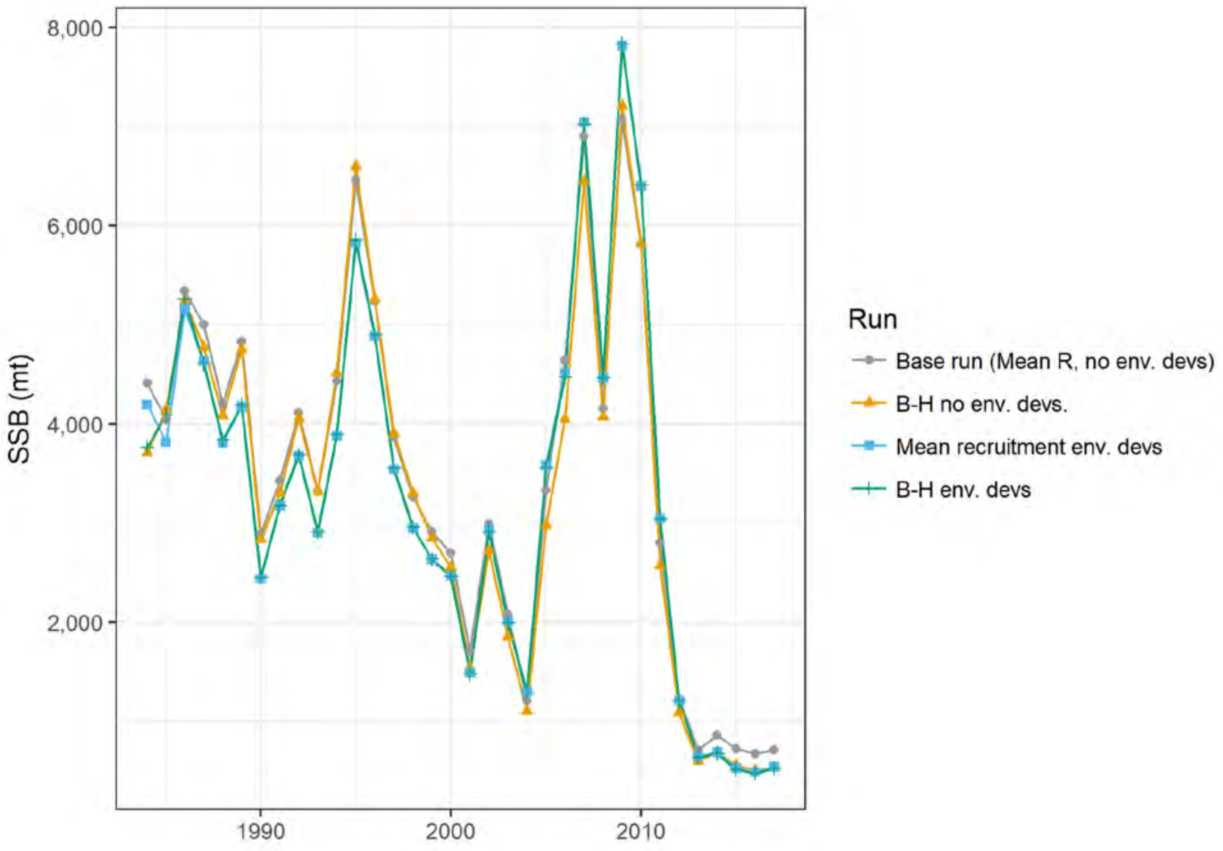


Figure 5.39. SSB estimates from the UME model fit with and without an environmental index of recruitment deviations.

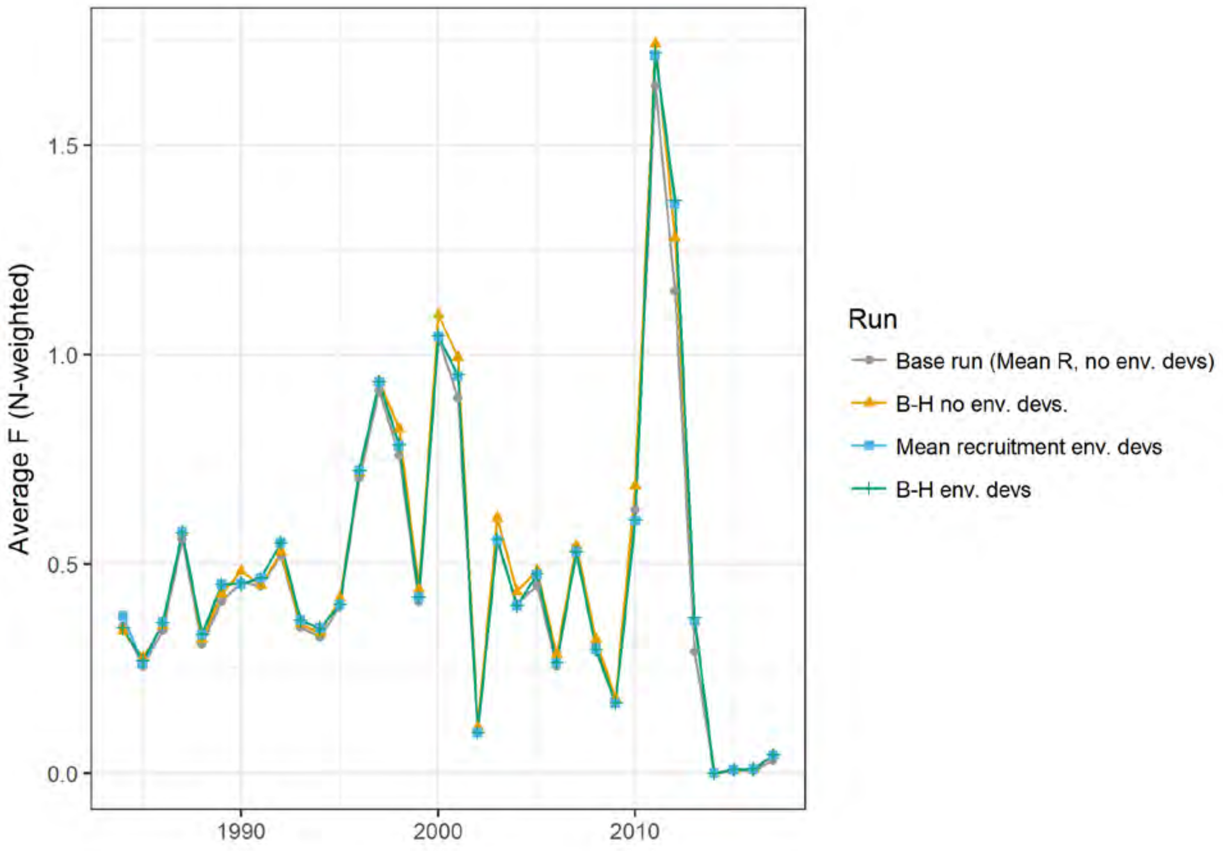


Figure 5.40. **Estimates of average F from the UME model fit with and without an environmental index of recruitment deviations.**

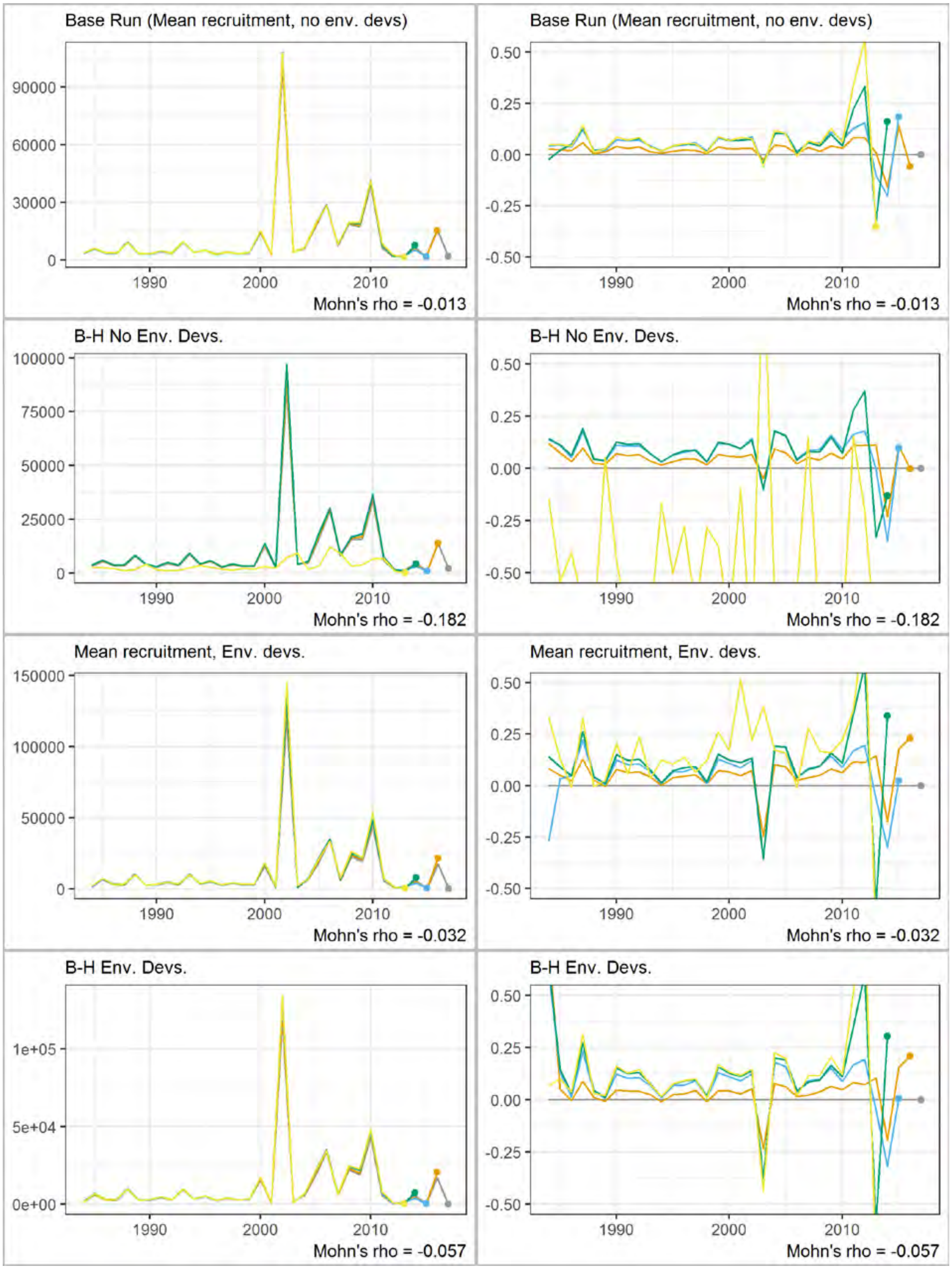


Figure 5.41. Recruitment retrospective patterns from the UME model fit with and without an environmental index of recruitment deviations.

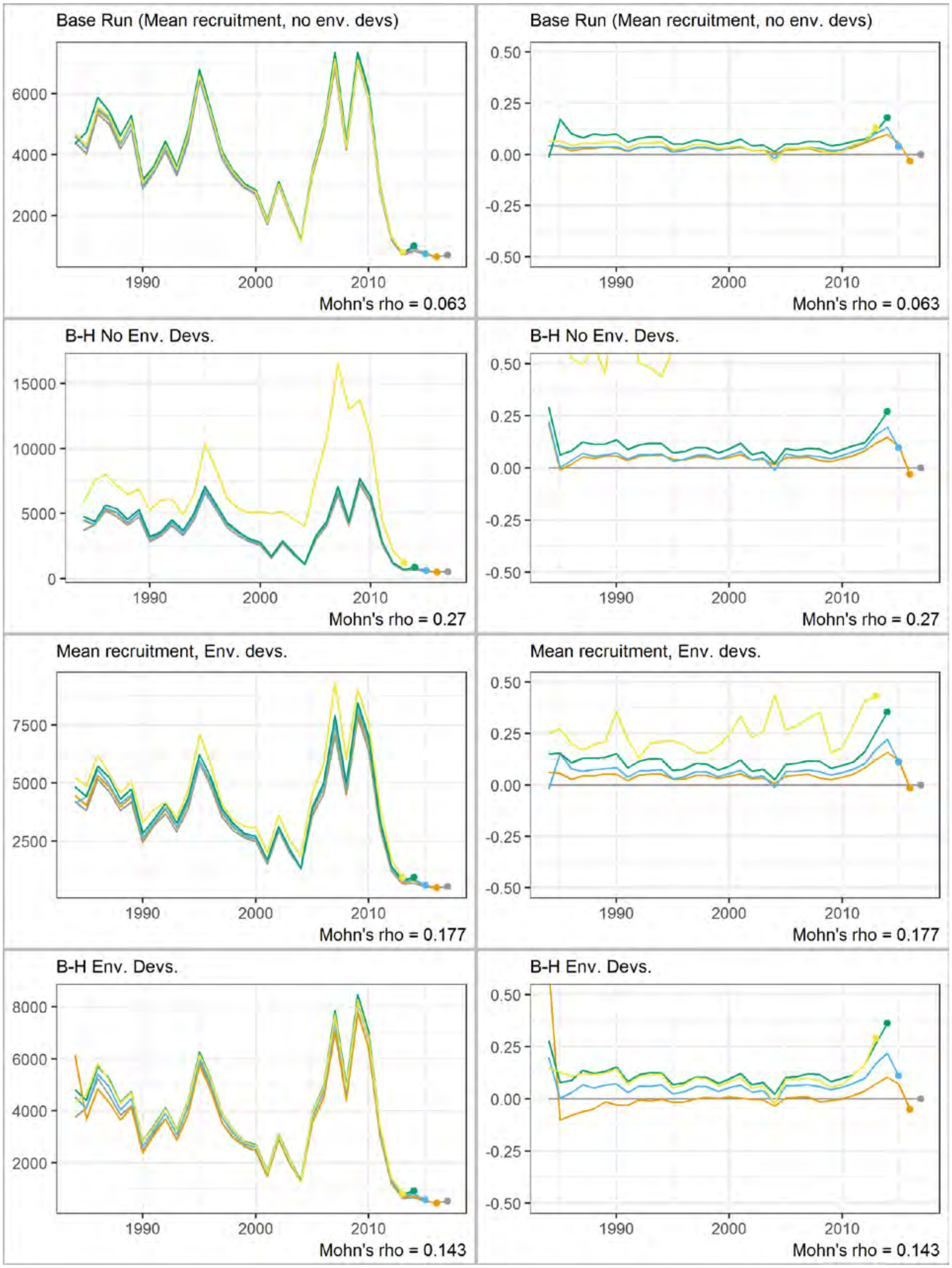


Figure 5.42. **SSB retrospective patterns from the UME model fit with and without an environmental index of recruitment deviations.**

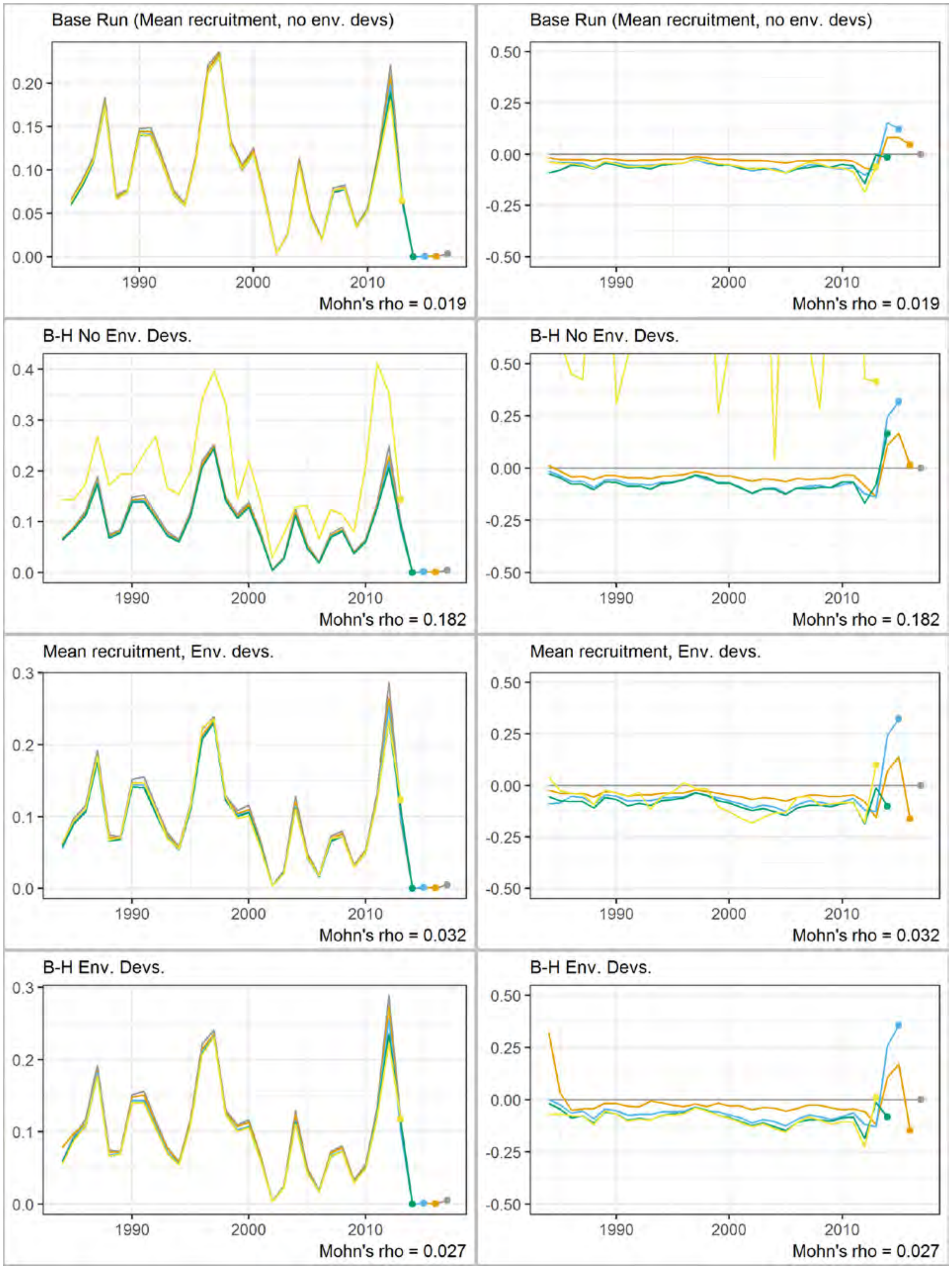


Figure 5.43. Exploitation rate retrospective patterns from the UME model fit with and without an environmental index of recruitment deviations.

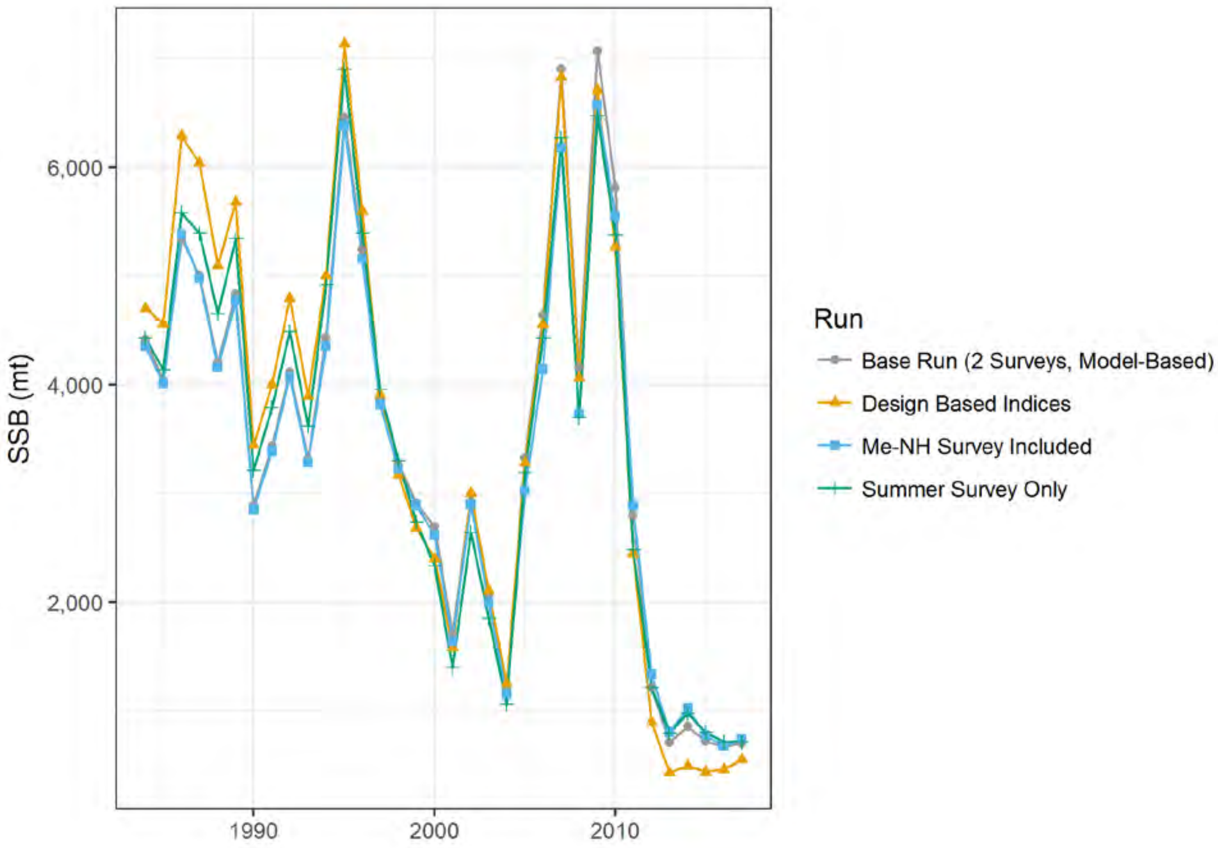


Figure 5.44. Estimates of SSB from the UME model under different index scenarios.

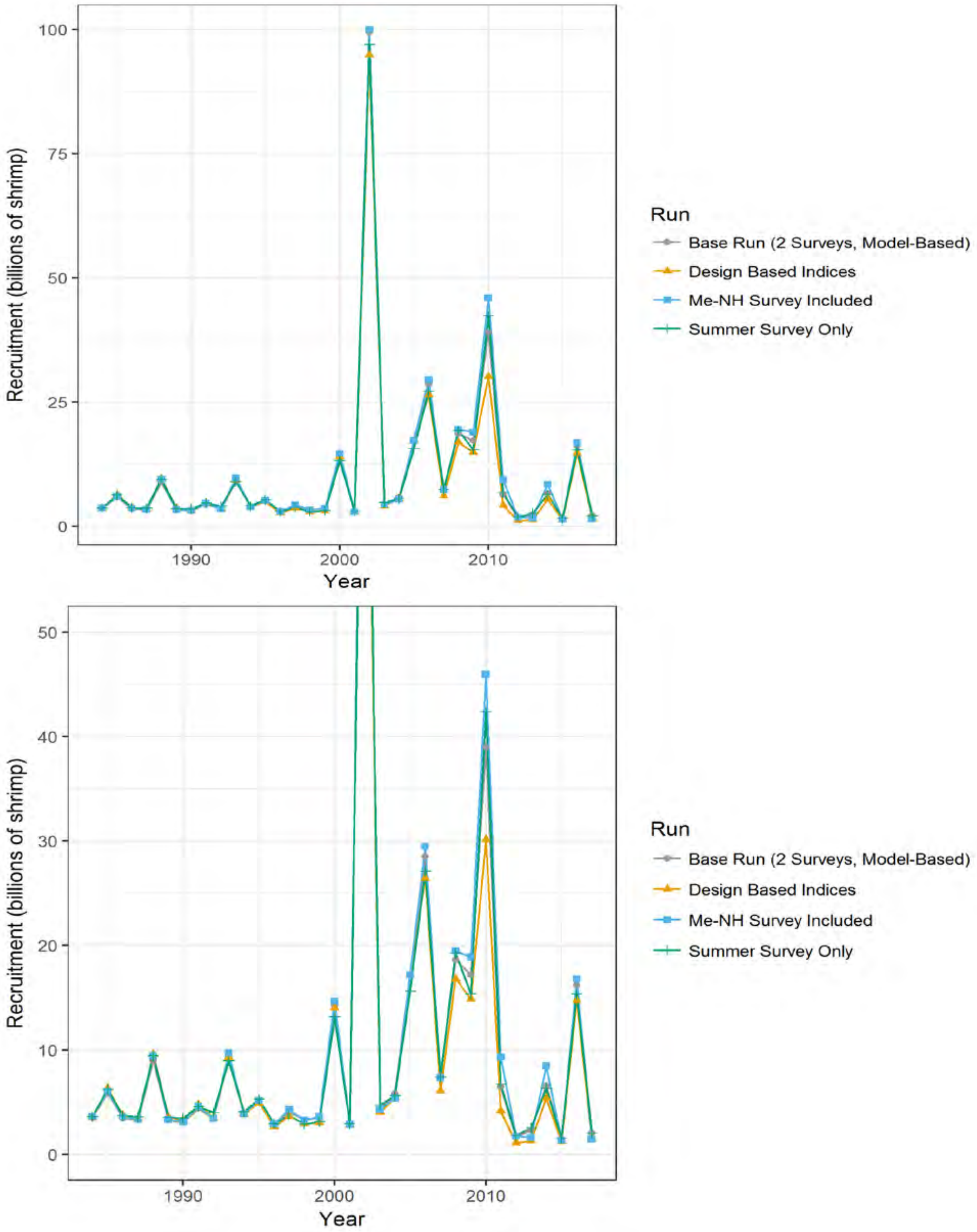


Figure 5.45. Estimates of recruitment from the UME model under different index scenarios. The y-axis on the second graph has been truncated to show detail.

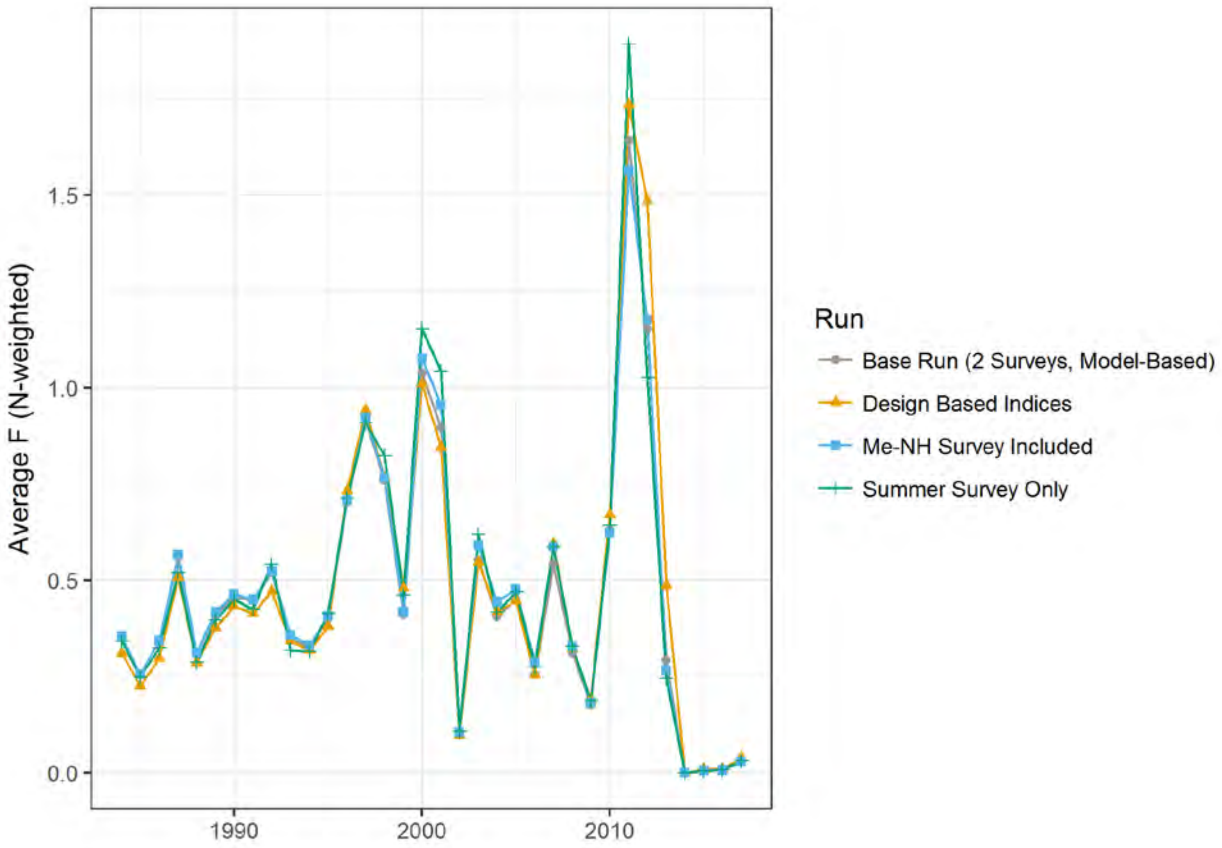


Figure 5.46. **Estimates of average F from the UME model under different index scenarios.**

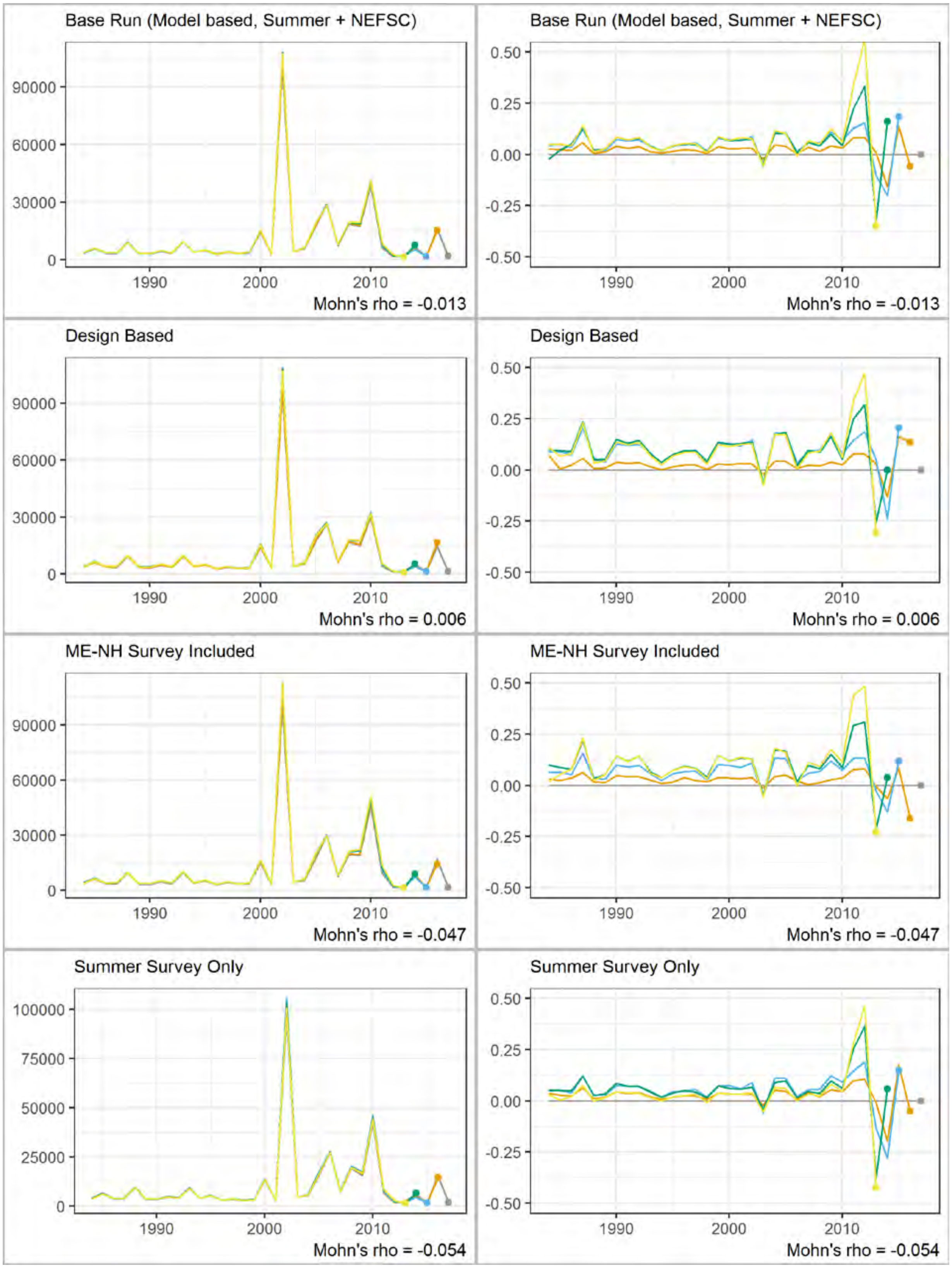


Figure 5.47. Recruitment retrospective patterns. Estimates of recruitment from the UME model under different index scenarios.

Figure 5.48. **SSB retrospective patterns. Estimates of recruitment from the UME model under different index scenarios.**

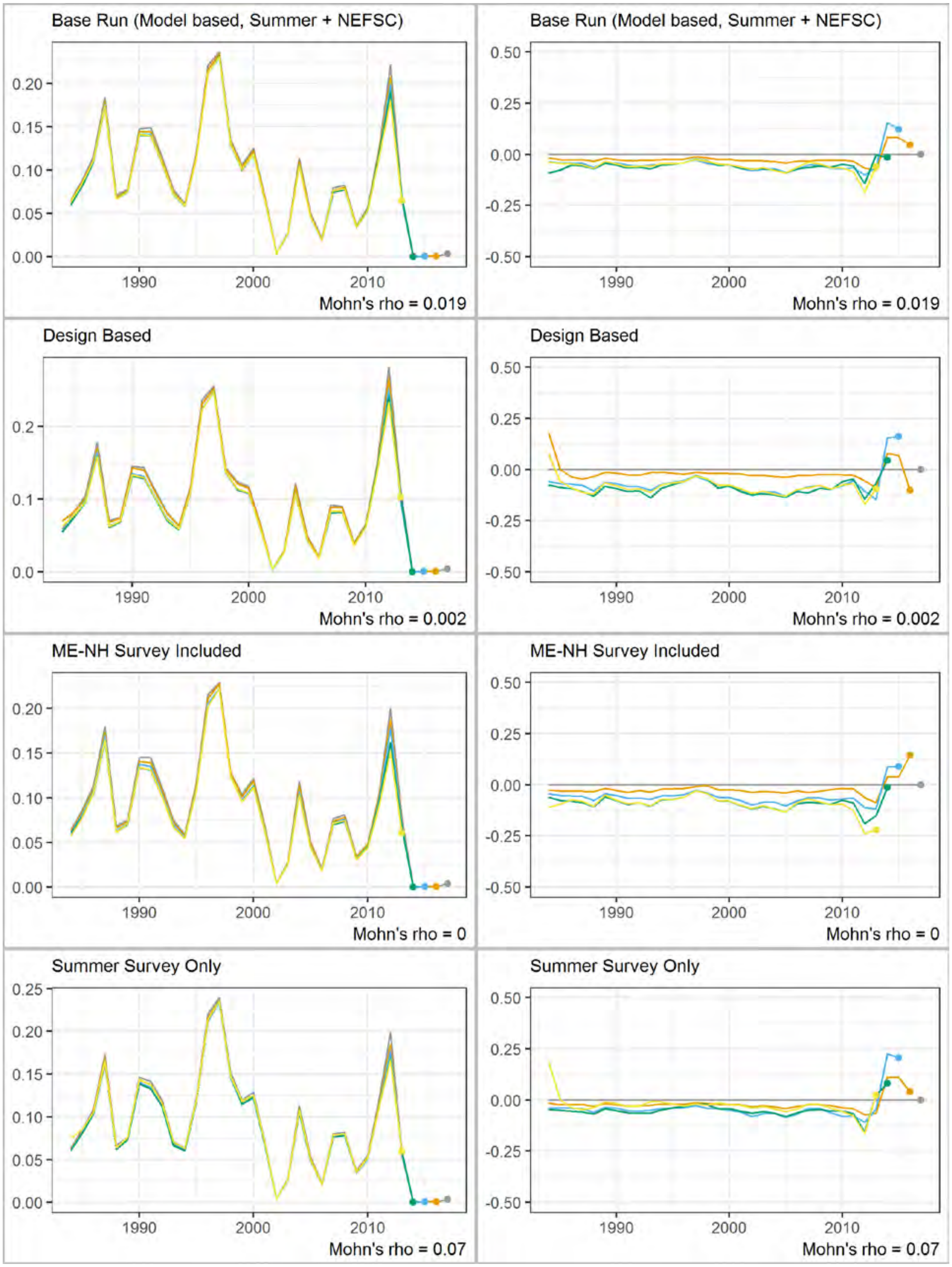


Figure 5.49. Exploitation rate retrospective patterns. Estimates of recruitment from the UME model under different index scenarios.

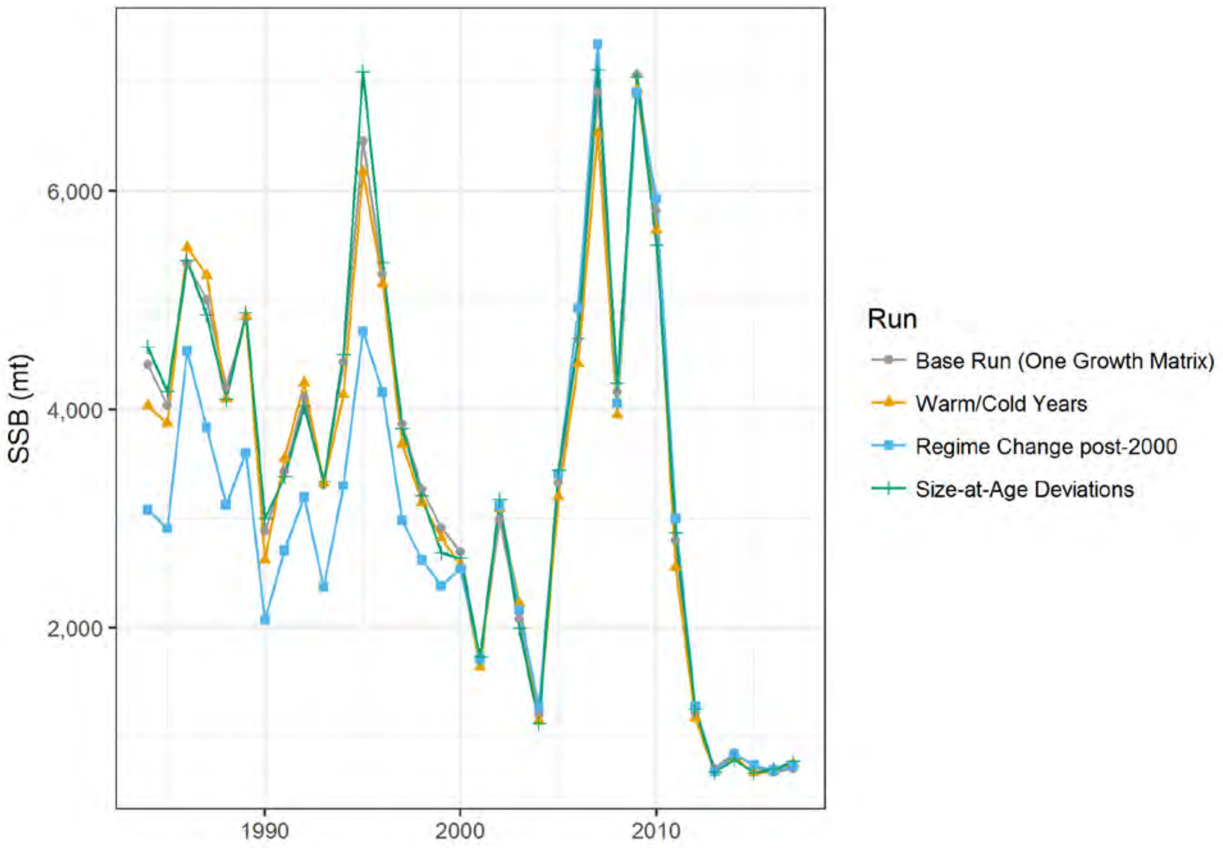


Figure 5.50. Estimates of SSB from the UME model under different growth block scenarios.

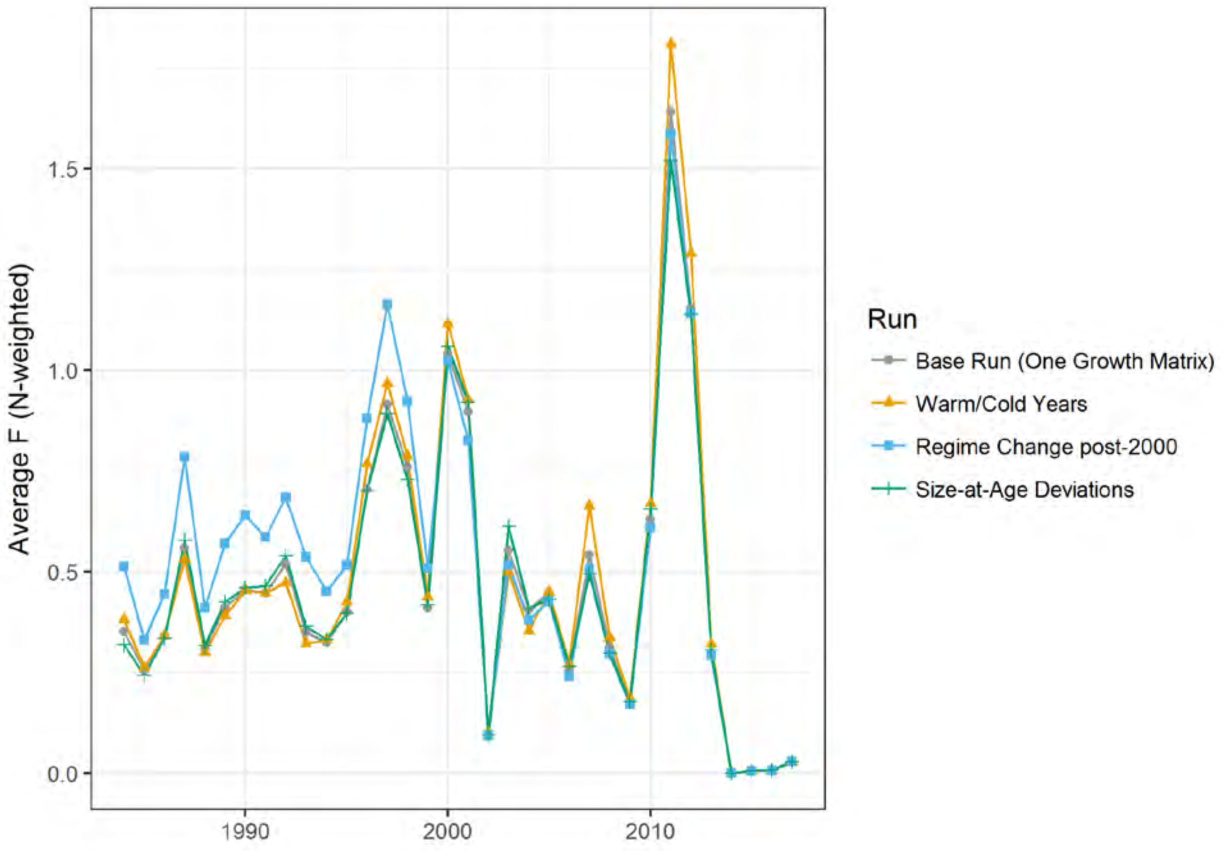


Figure 5.51. Estimates of average F from the UME model under different growth block scenarios.

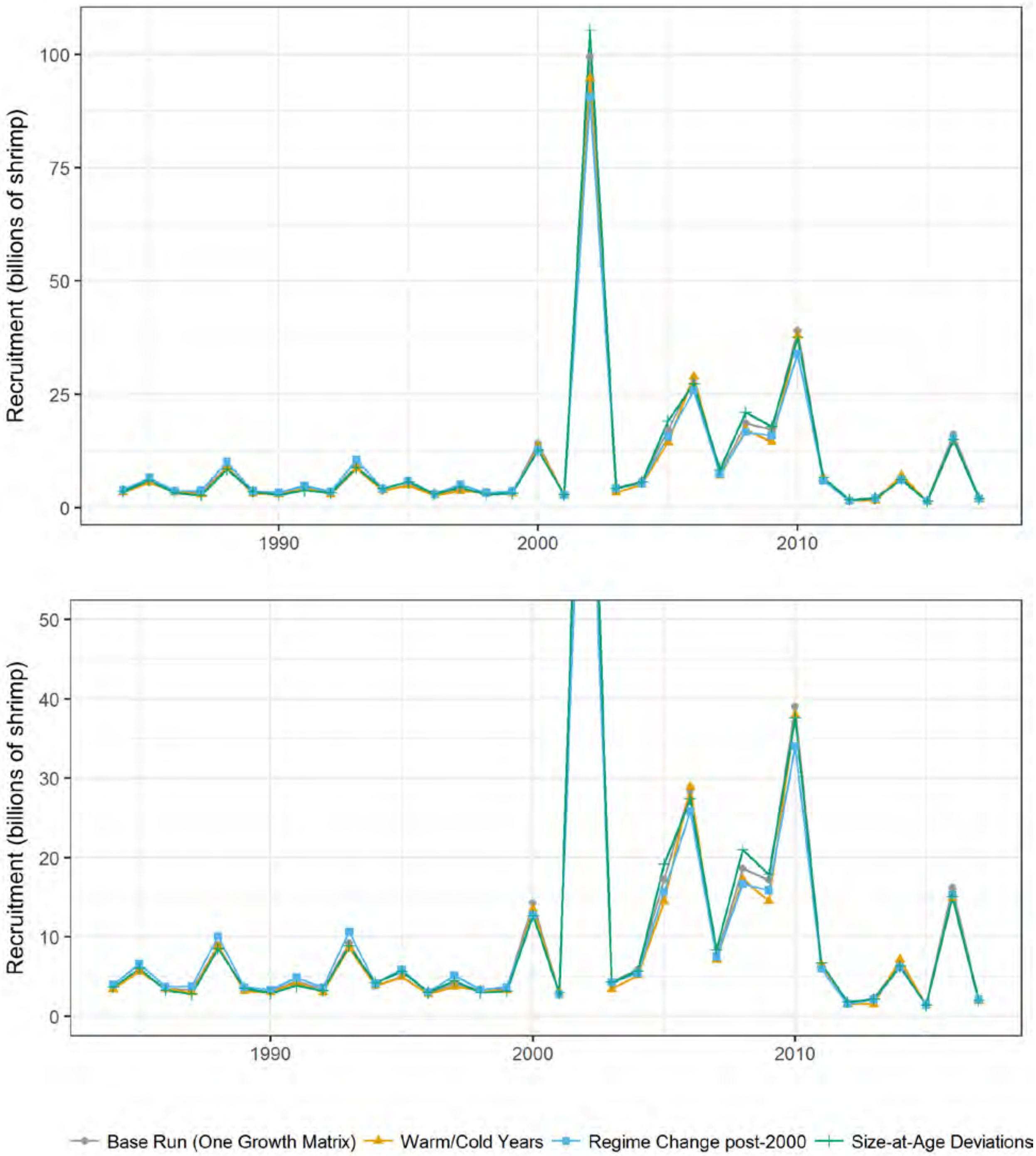


Figure 5.52. **Estimates of recruitment from the UME model under different growth block scenarios. The y-axis in the bottom graph is truncated to show detail.**

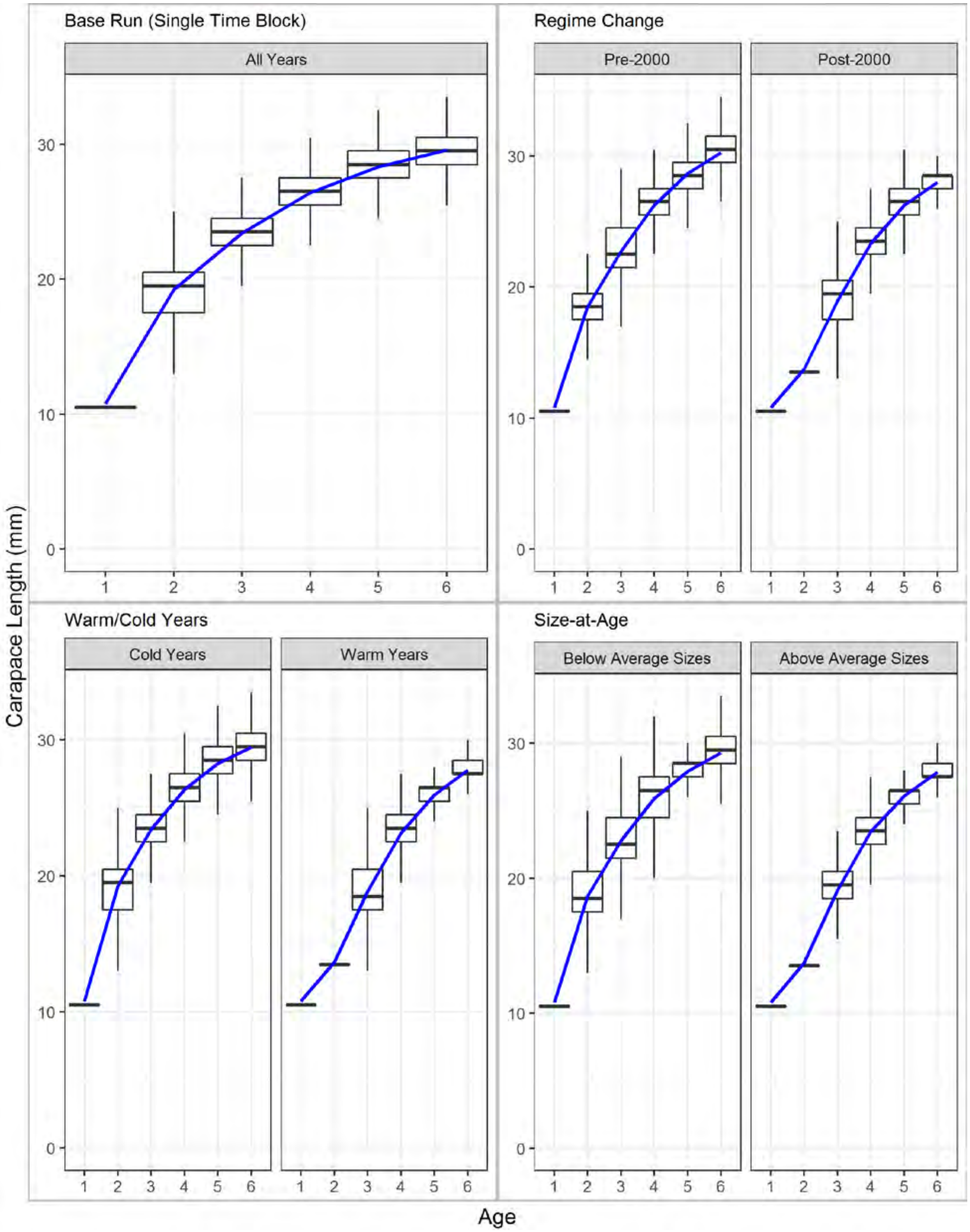


Figure 5.53. **Growth curves estimated by the UME model under different growth block scenarios.**

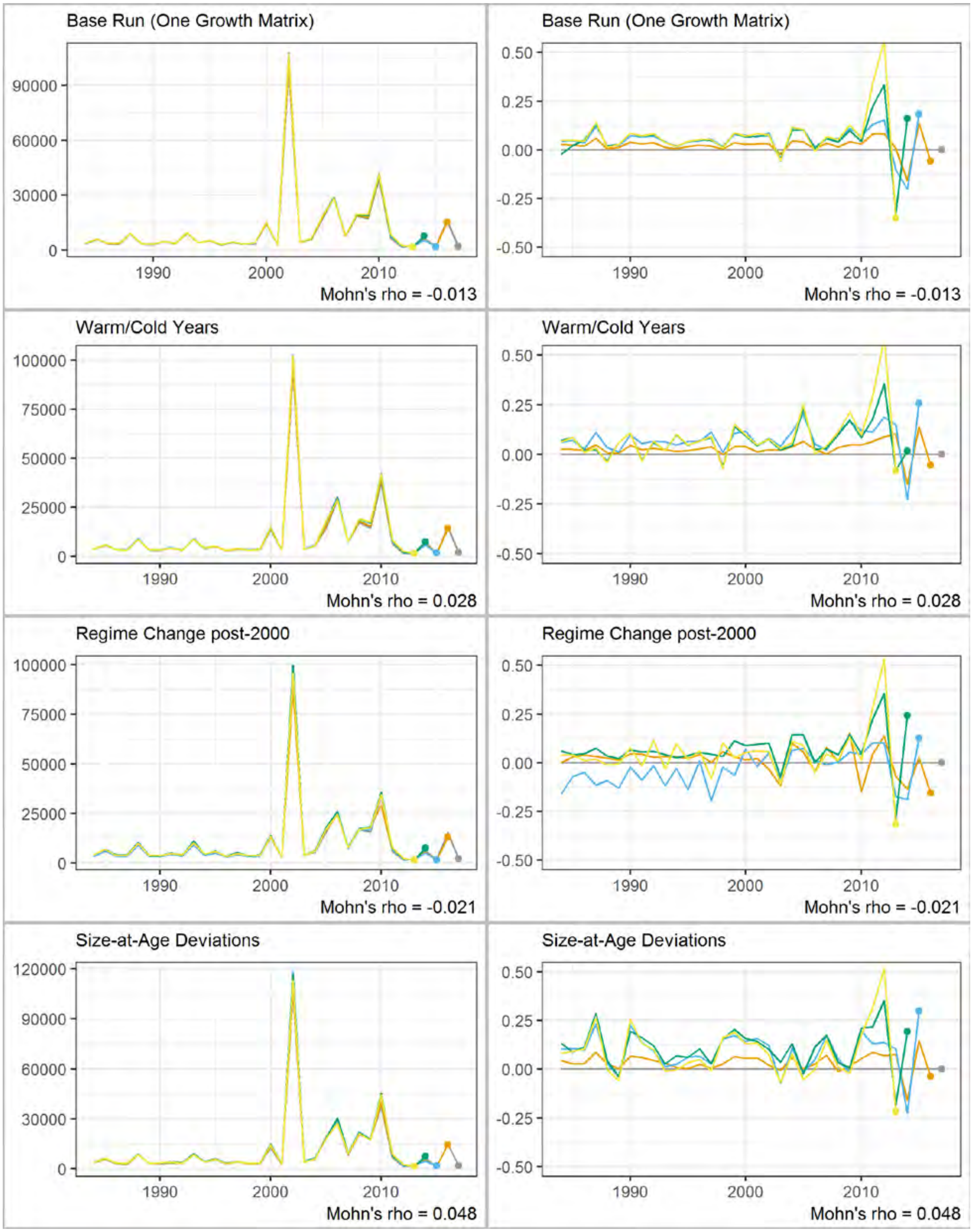


Figure 5.54. Recruitment retrospective patterns from the UME model under different growth block scenarios.

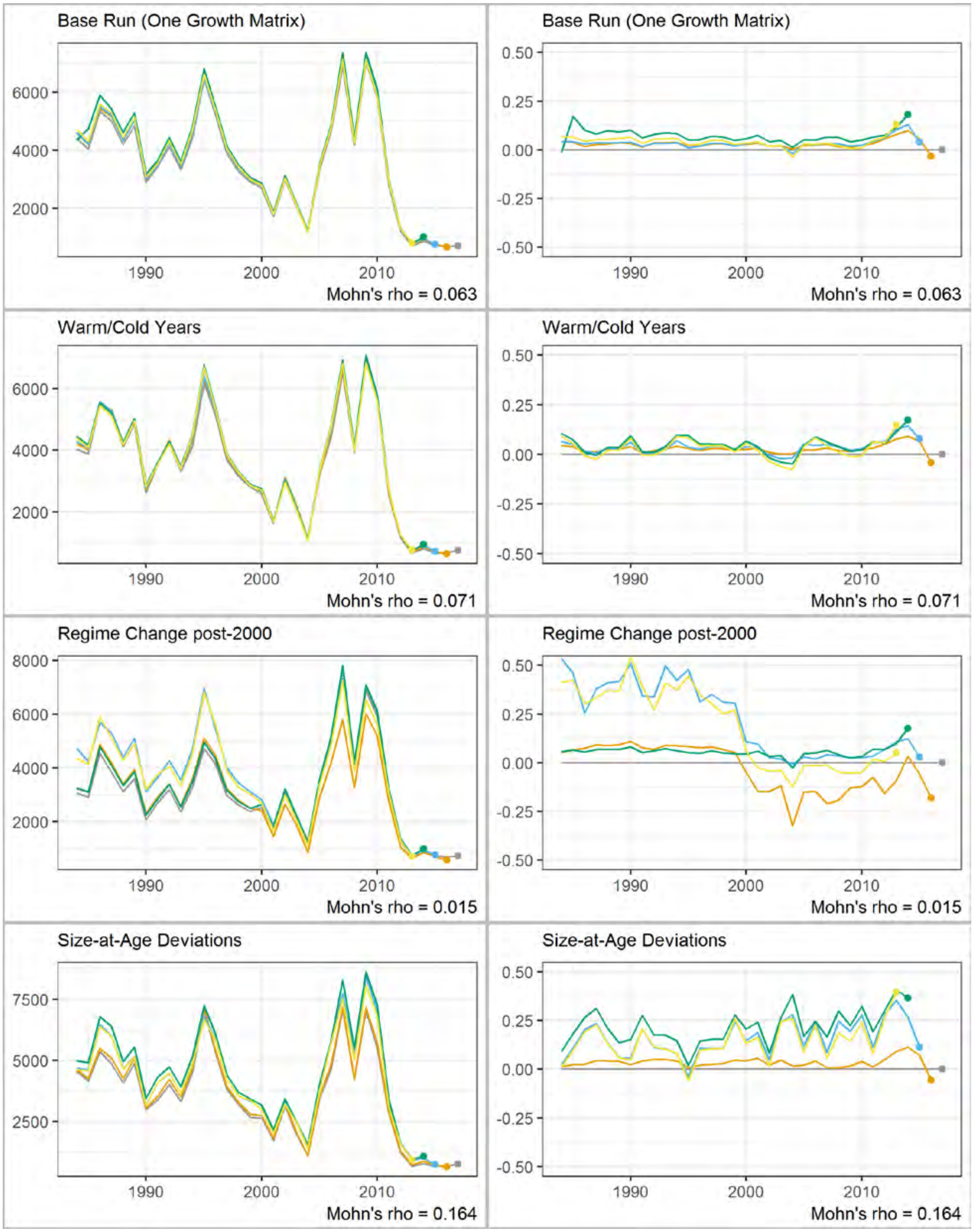


Figure 5.55. SSB retrospective patterns from the UME model under different growth block scenarios.

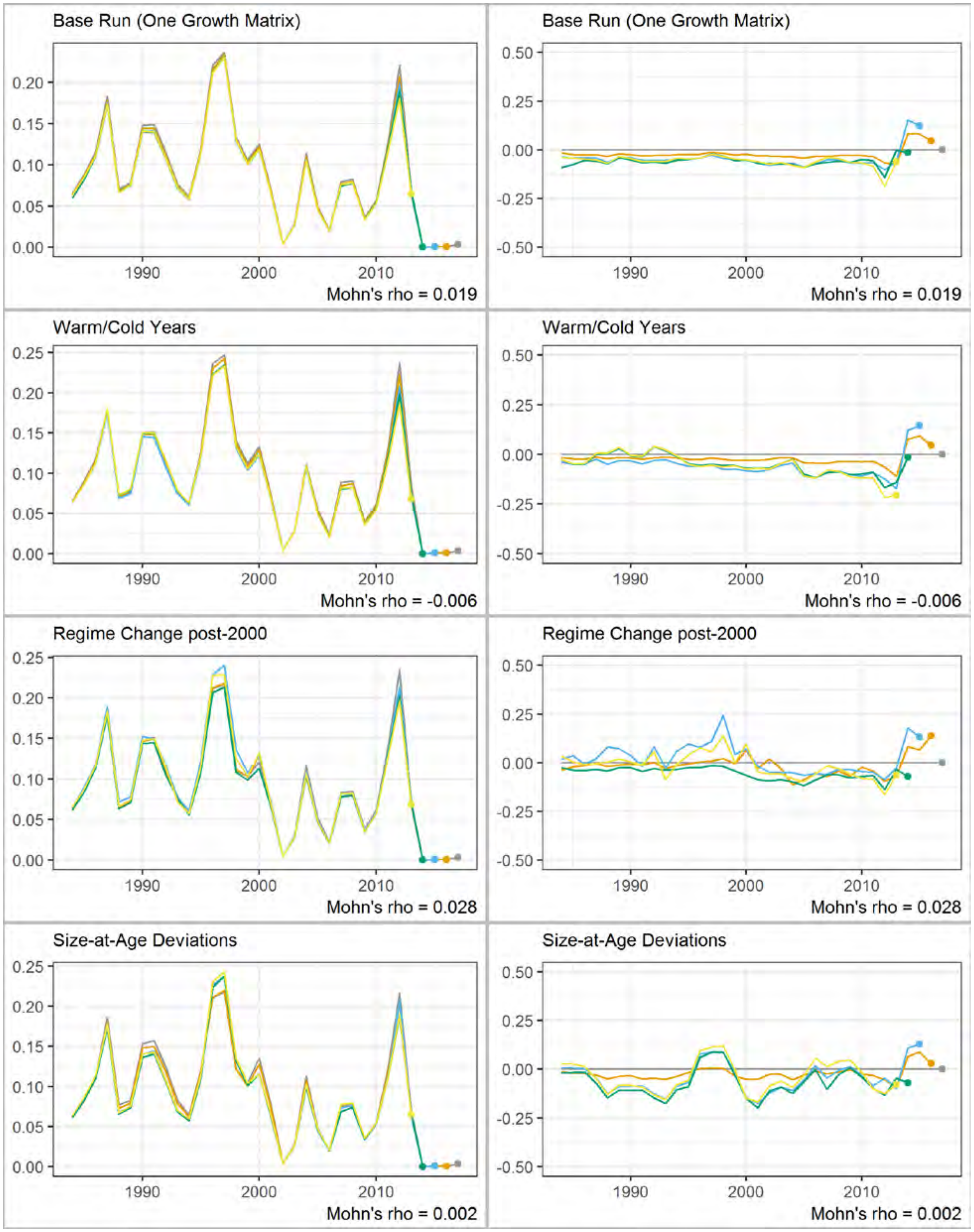
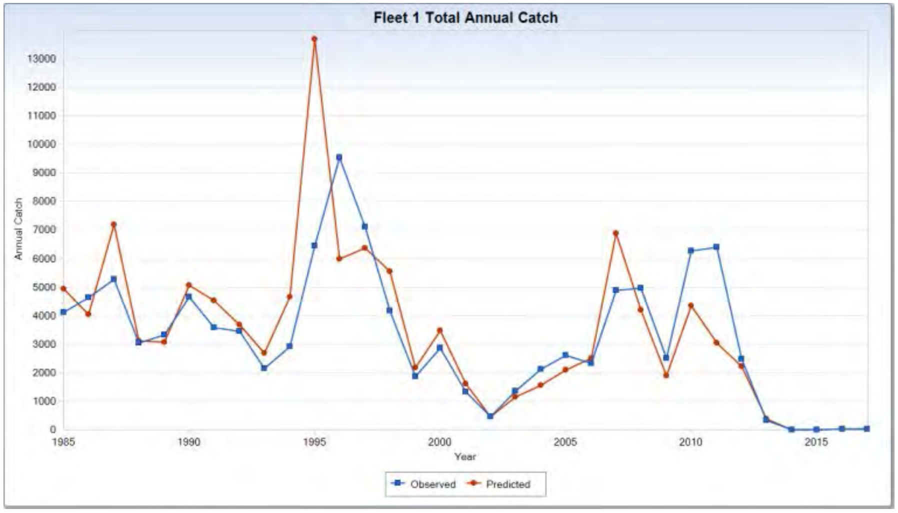


Figure 5.56. Exploitation rate retrospective patterns from the UME model under different growth block scenarios.

(a)


Fleet 1 Total Annual Catch
Annual Catch
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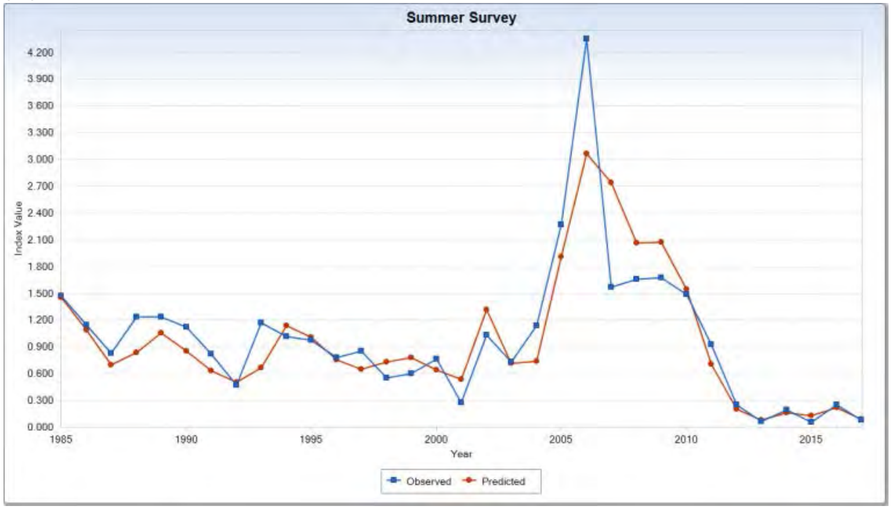
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1985
1990
1995
2000
2005
2010
2015
Year
Observed
Predicted

(b)


Summer Survey
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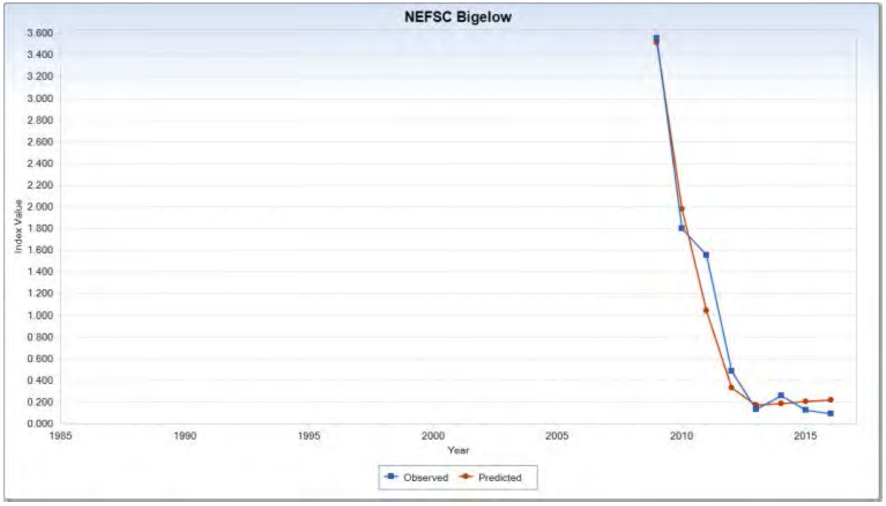
3.600
3.300
3.000
2.700
2.400
2.100
1.800
1.500
1.200
0.900
0.600
0.300
0.000
1985
1990
1995
2000
2005
2010
2015
Year
Observed
Predicted

(c)


NEFSC Bigelow
Index Value
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2.600
2.400
2.200
2.000
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
1985
1990
1995
2000
2005
2010
2015
Year
Observed
Predicted

(d)

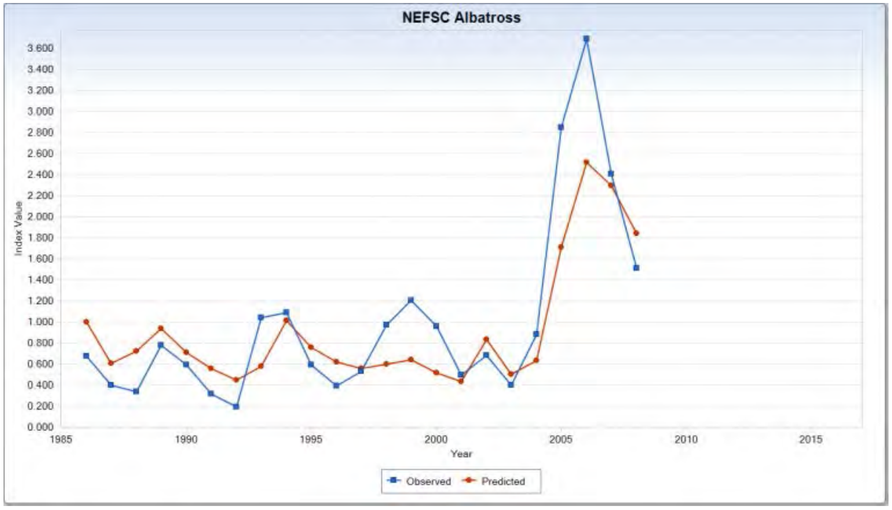
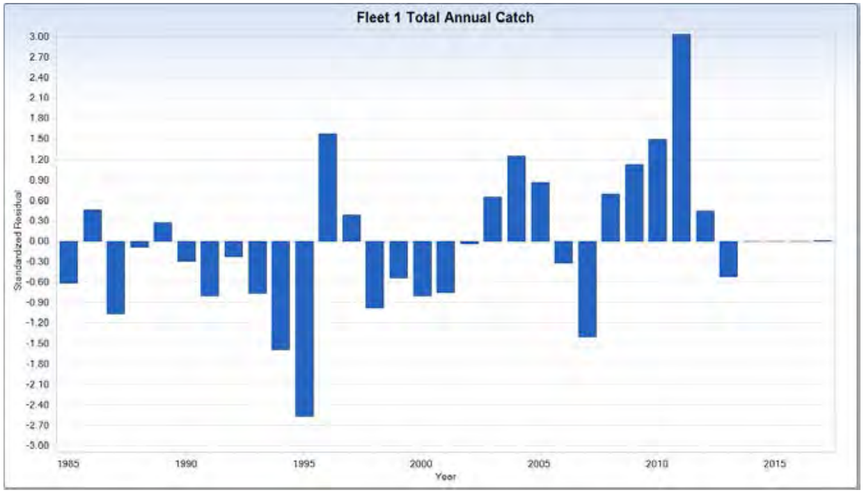
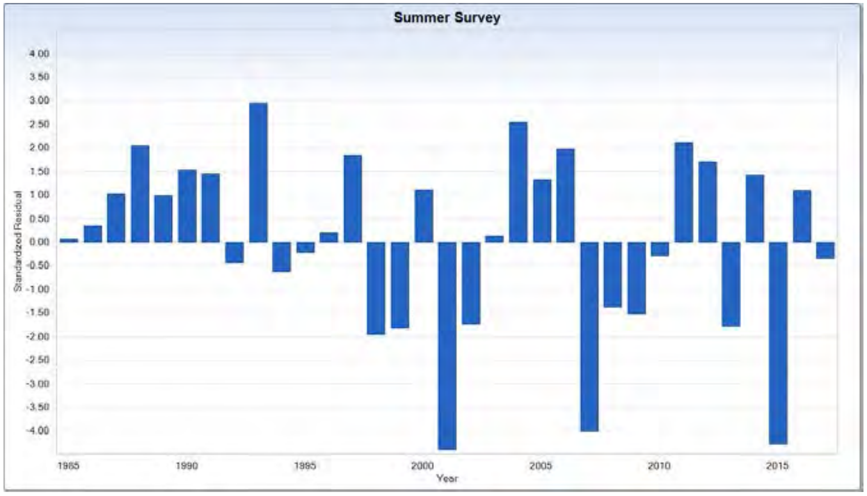


Figure 5.57 (a-d) ASAP model fits to survey indices and catch using model-based indices and age- and time-varying (PPI-scaled) M (based on M=0.5). (a) model fit to total annual catch; (b) model fit to ASMFC Summer Survey; (c) model fit to NEFSC Bigelow; (d) model fit to NEFSC Albatross.

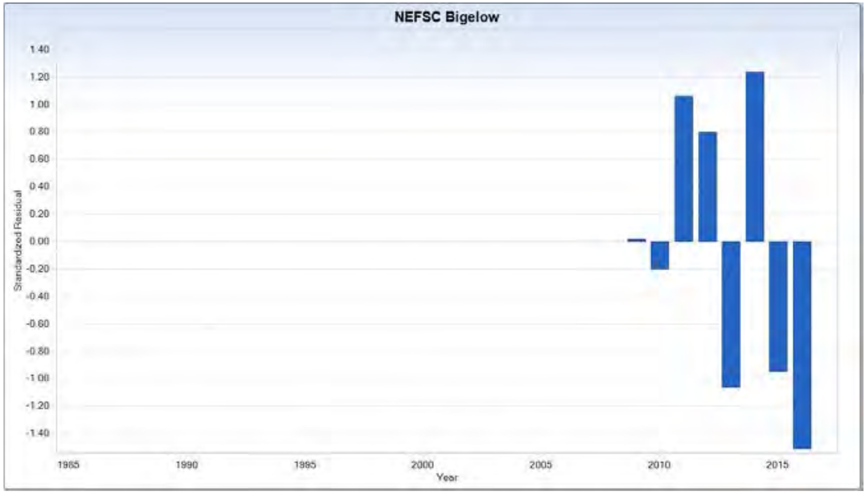
(a)


Fleet 1 Total Annual Catch
Standardized Residual
3.00
2.70
2.40
2.10
1.80
1.50
1.20
0.90
0.60
0.30
0.00
-0.30
-0.60
-0.90
-1.20
-1.50
-1.80
-2.10
-2.40
-2.70
-3.00
1985
1990
1995
2000
2005
2010
2015
Year

(b)


Summer Survey
Standardized Residual
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
1985
1990
1995
2000
2005
2010
2015
Year

(c)


NEFSC Bigelow
Standardized Residual
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
1985
1990
1995
2000
2005
2010
2015
Year

(d)

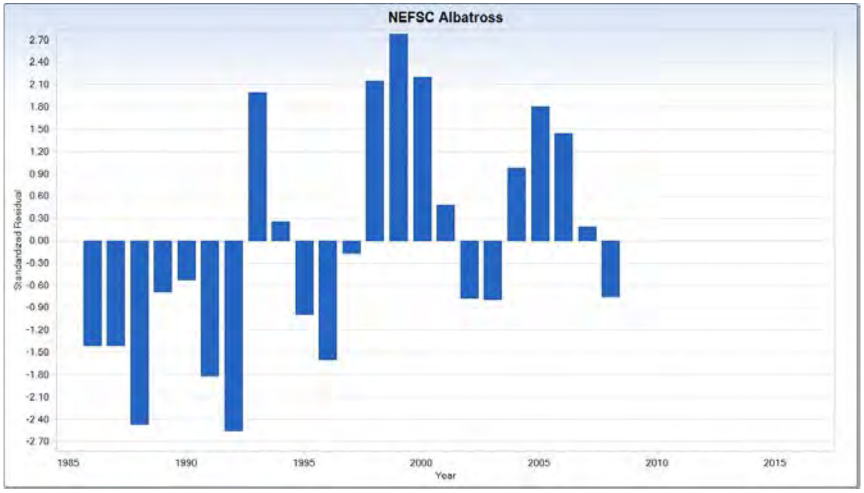
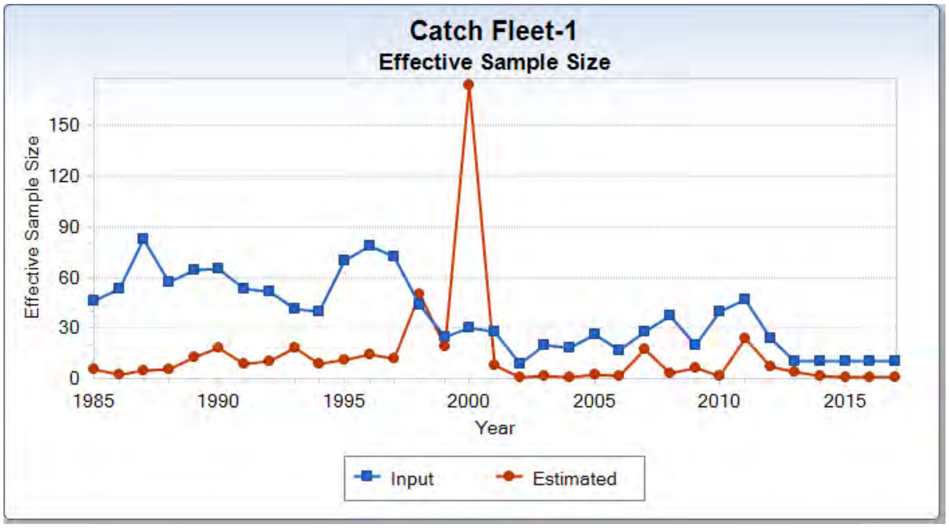
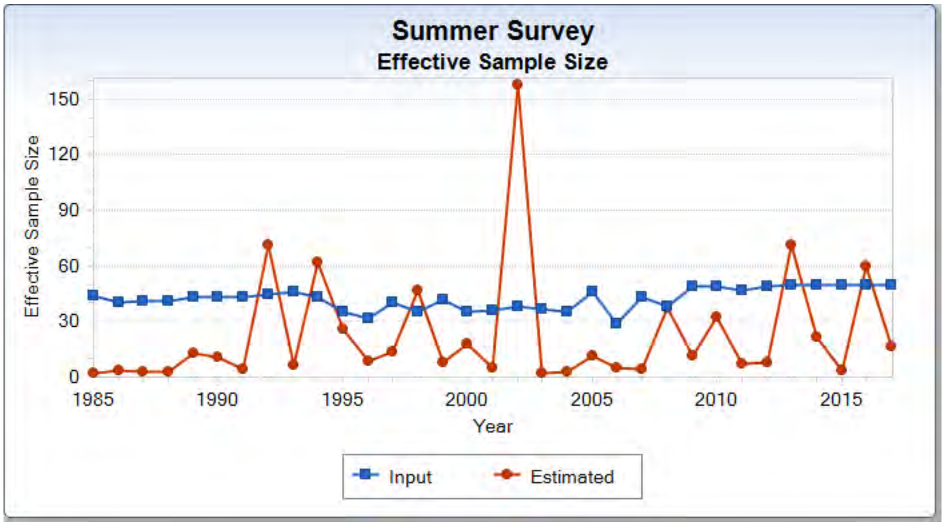


Figure 5.58 (a-d). Standardized residuals for the final ASAP model using model-based indices and age- and time-varying (PPI-scaled) M (based on M=0.5). (a) Total annual catch; (b) ASMFC Summer Survey; (c) NEFSC Bigelow; (d) NEFSC Albatross.

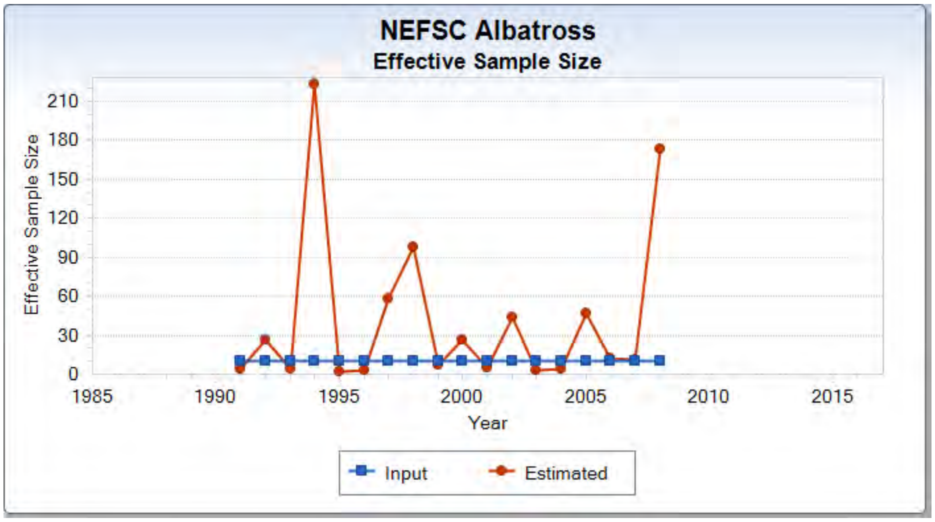
(a)


Catch Fleet-1
Effective Sample Size
Effective Sample Size
0
30
60
90
120
150
1985
1990
1995
2000
2005
2010
2015
Year
Input
Estimated

(b)


Summer Survey
Effective Sample Size
Effective Sample Size
0
30
60
90
120
150
1985
1990
1995
2000
2005
2010
2015
Year
Input
Estimated

(c)


NEFSC Albatross
Effective Sample Size
Effective Sample Size
0
30
60
90
120
150
180
210
1985
1990
1995
2000
2005
2010
2015
Year
Input
Estimated

(d)

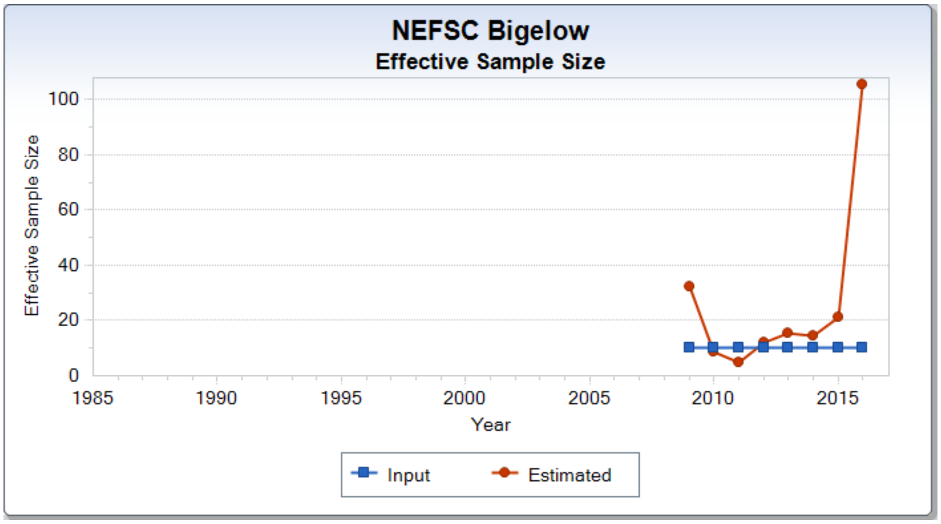


Figure 5.59 (a-d). **Input (observed) and model-estimated effective sample size of Gulf of Maine northern shrimp in the a) commercial catch, b) ASMFC Summer survey, c) NEFSC fall Albatross survey, and d) NEFSC fall Bigelow survey for the ASAP base run.**

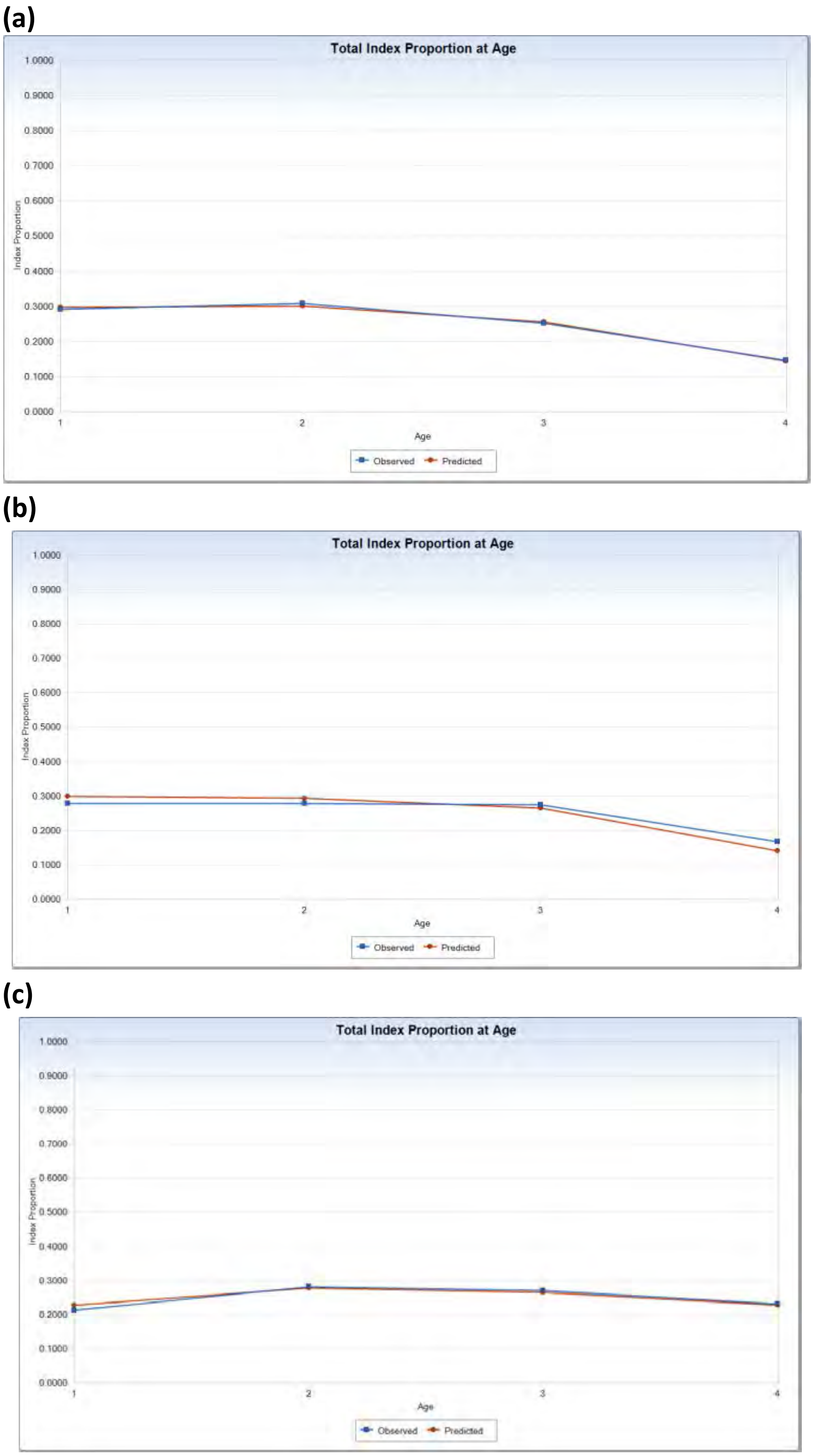
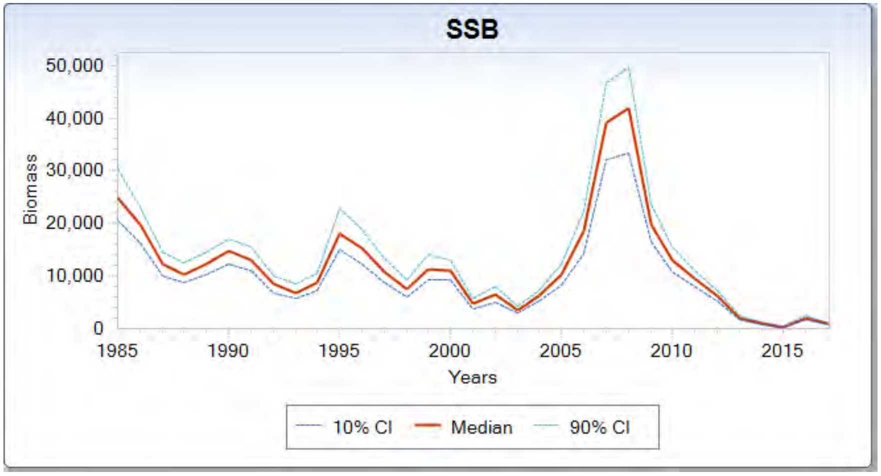
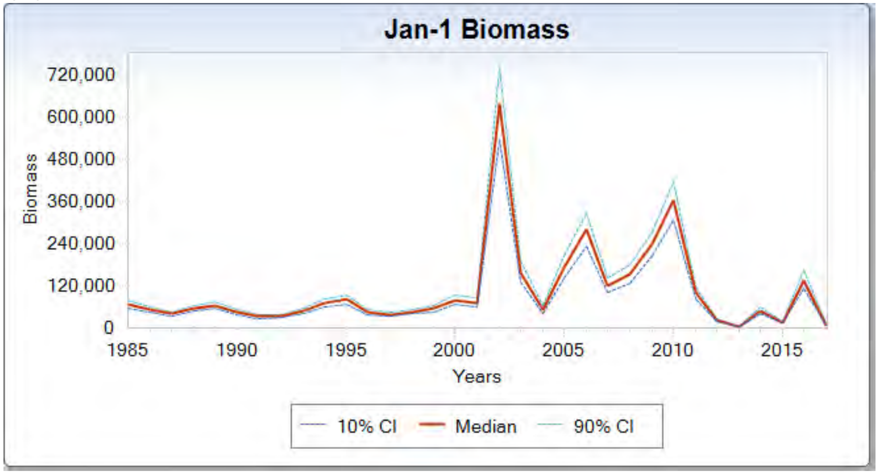


Figure 5.60 (a-c) ASAP model fits to proportion at age for survey indices a) Summer Survey, b) NEFSC Albatross, c) Bigelow, for time- and age-varying M (based on M=0.5).

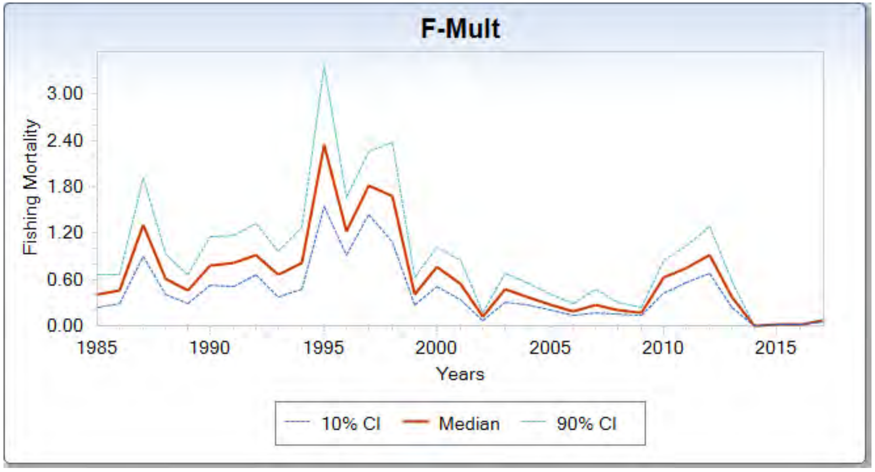
(a)


SSB
Biomass
50,000
40,000
30,000
20,000
10,000
0
1985
1990
1995
2000
2005
2010
2015
Years
10% CI
Median
90% CI

(b)


Jan-1 Biomass
Biomass
720,000
600,000
480,000
360,000
240,000
120,000
0
1985
1990
1995
2000
2005
2010
2015
Years
10% CI
Median
90% CI

(c)


F-Mult
Fishing Mortality
3.00
2.40
1.80
1.20
0.60
0.00
1985
1990
1995
2000
2005
2010
2015
Years
10% CI
Median
90% CI

(d)

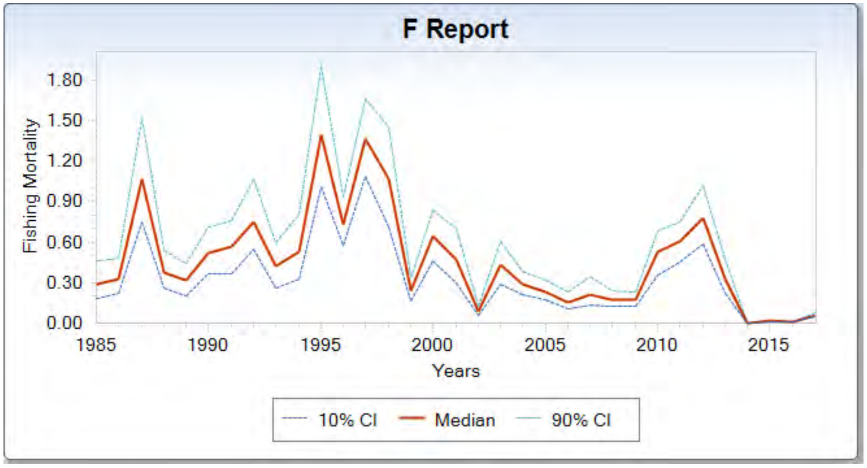


Figure 5.61.1 (a-d). MCMC-generated 90% confidence intervals from ASAP base model for a) SSB (mt), b) January 1 biomass (mt), and F, as c) full F and d) N-weighted average F.

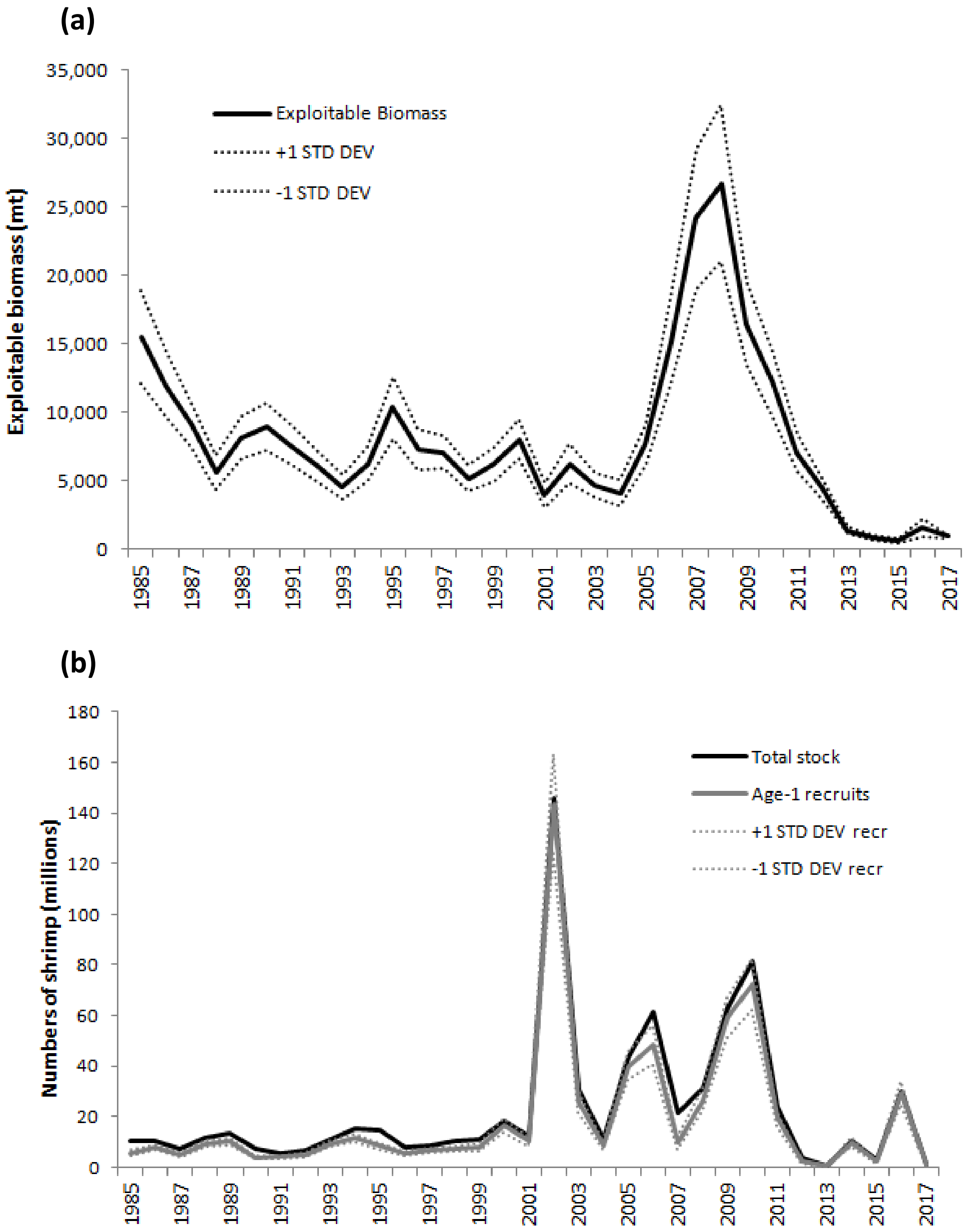
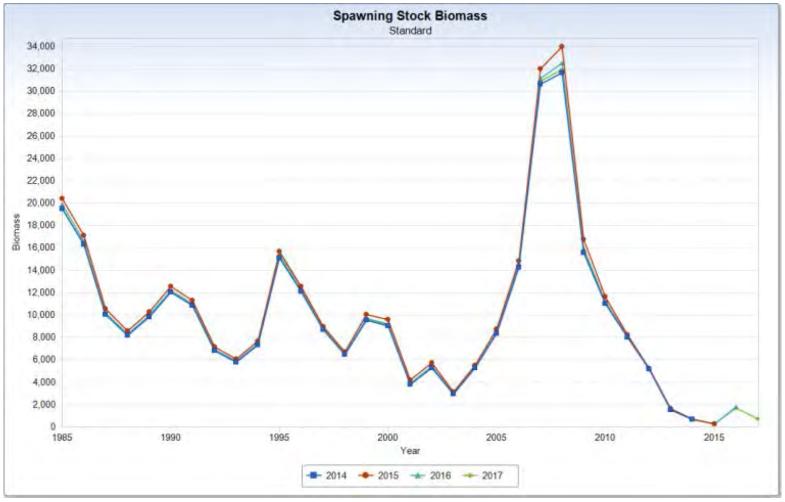
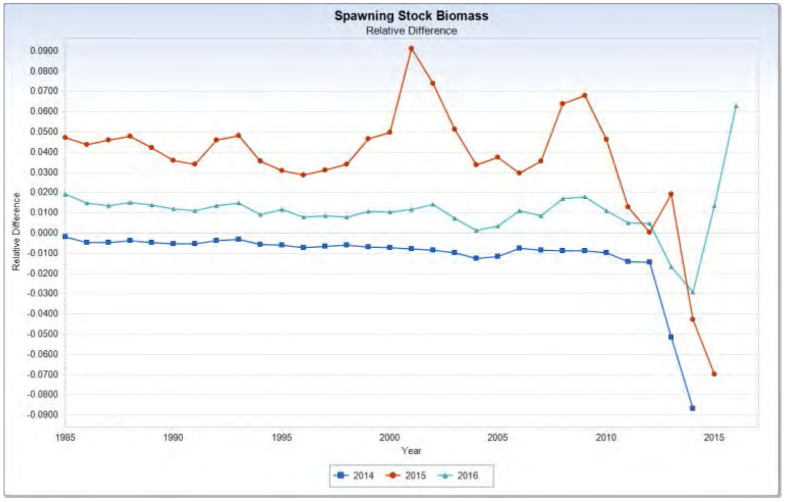


Figure 5.61.2 (a-b). ASAP base model estimates for a) exploitable biomass (+/- 1 std dev) and b) total stock abundance and Age-1 recruit abundance (+/-1 std dev).

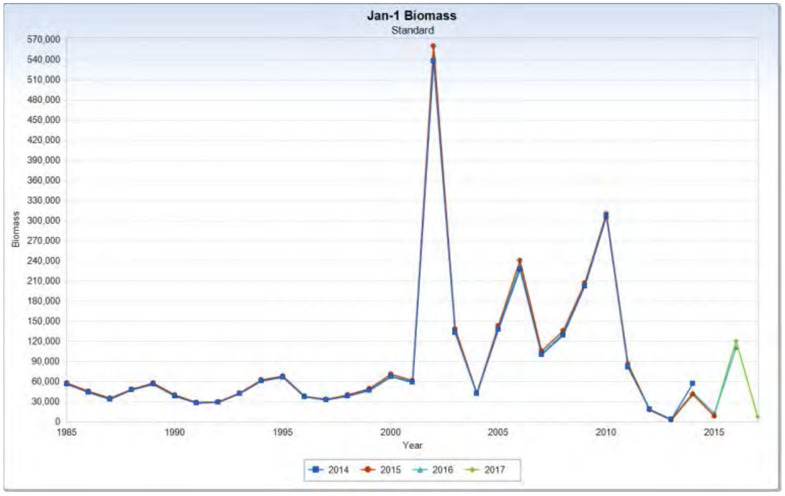
(a)


Spawning Stock Biomass
Standard
Biomass
34,000
32,000
30,000
28,000
26,000
24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1985
1990
1995
2000
2005
2010
2015
Year
2014
2015
2016
2017

(b)

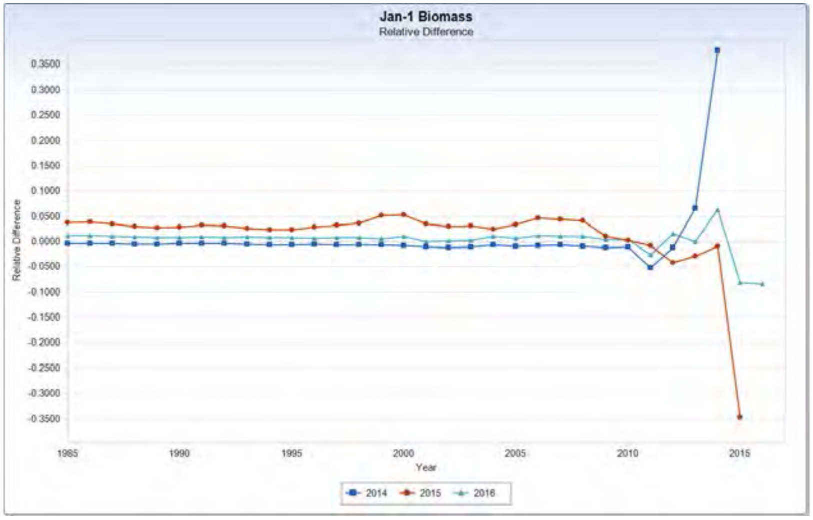

Spawning Stock Biomass
Relative Difference
Relative Difference
0.0900
0.0800
0.0700
0.0600
0.0500
0.0400
0.0300
0.0200
0.0100
0.0000
-0.0100
-0.0200
-0.0300
-0.0400
-0.0500
-0.0600
-0.0700
-0.0800
-0.0900
1985
1990
1995
2000
2005
2010
2015
Year
2014
2015
2016

(c)

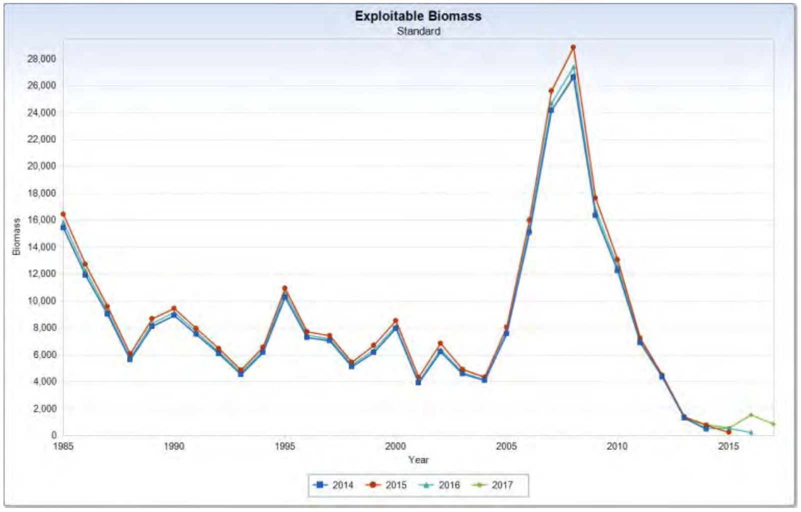

Jan-1 Biomass
Standard
Biomass
570,000
540,000
510,000
480,000
450,000
420,000
390,000
360,000
330,000
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
1985
1990
1995
2000
2005
2010
2015
Year
2014
2015
2016
2017

Continued

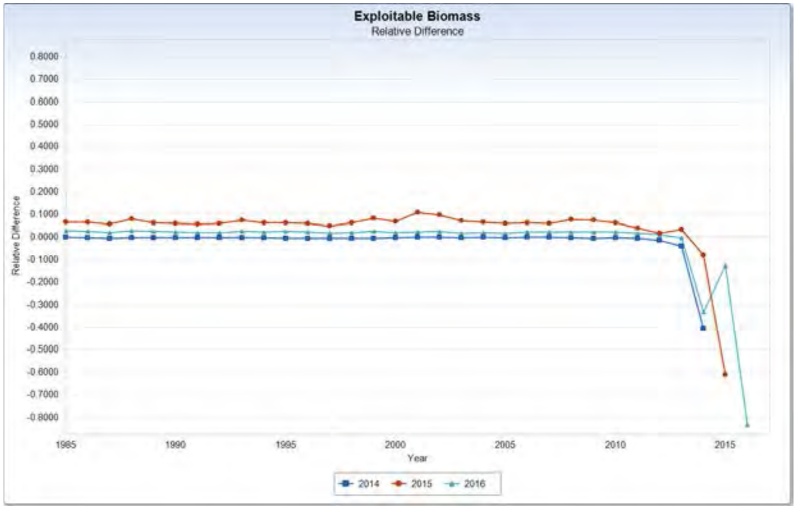
(d)



(e)

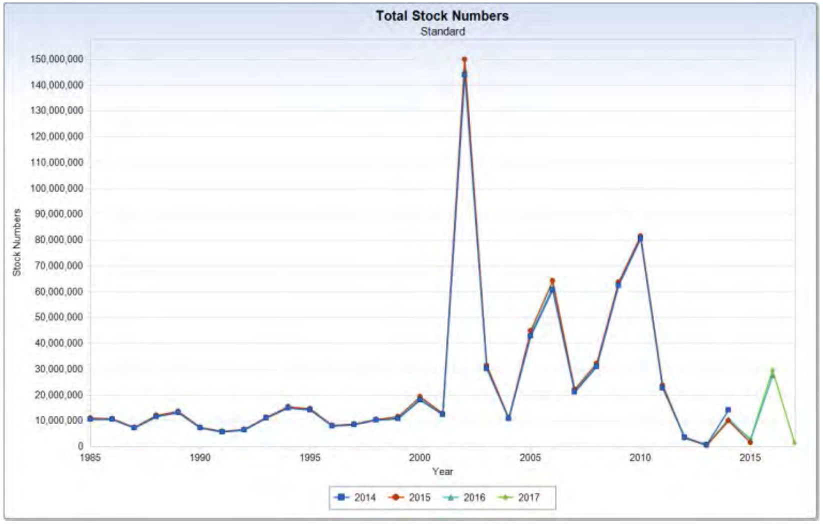


(f)

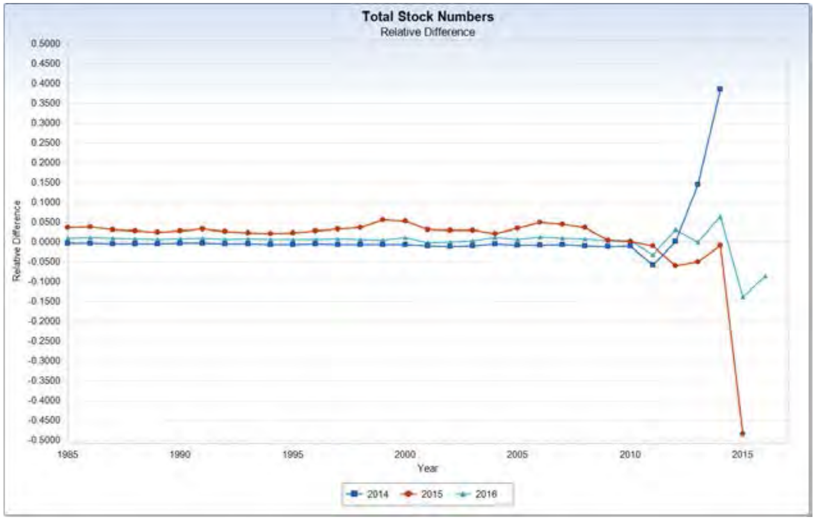


Continued

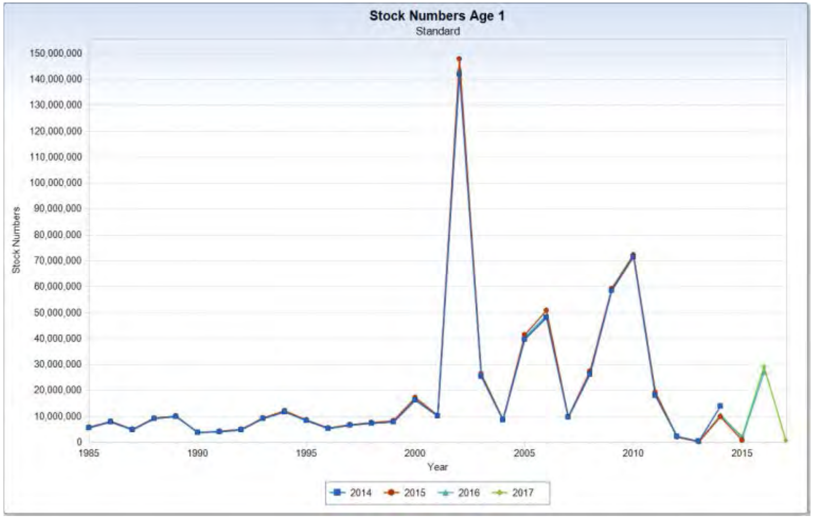
(g)



(h)



(i)



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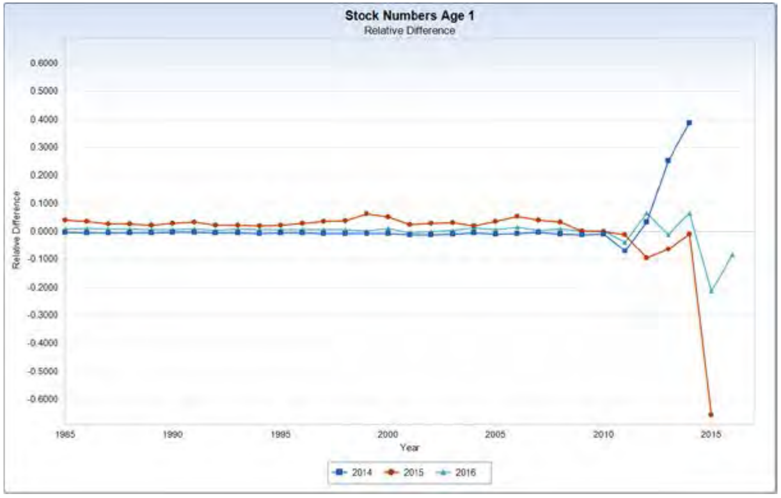
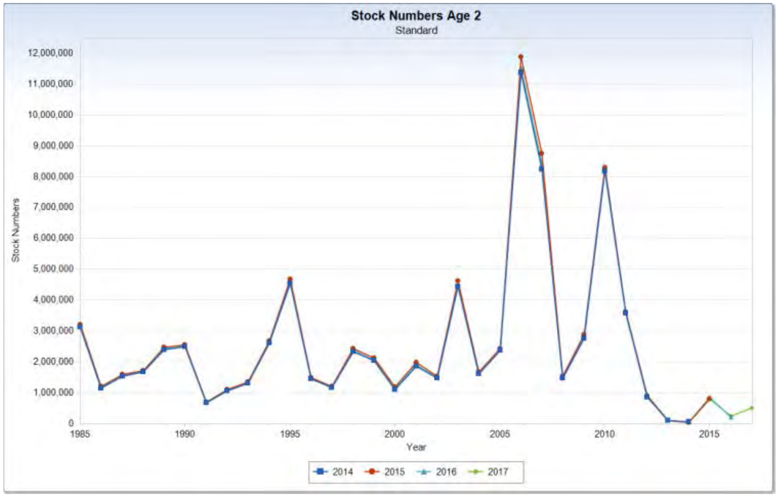
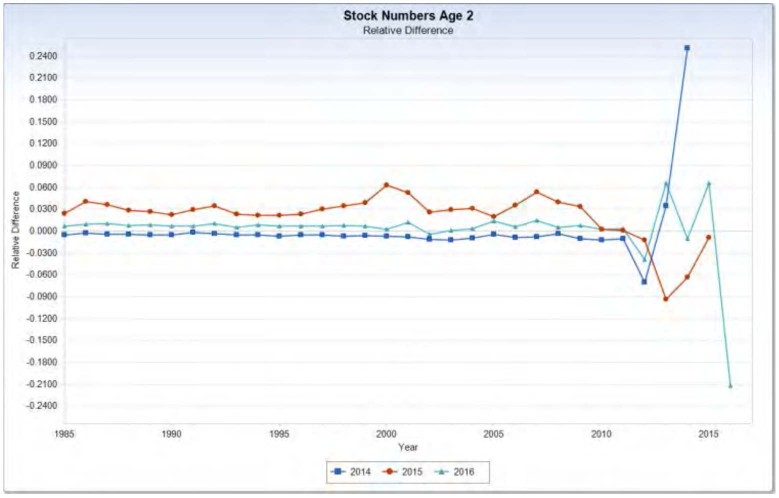
(j)



(k)

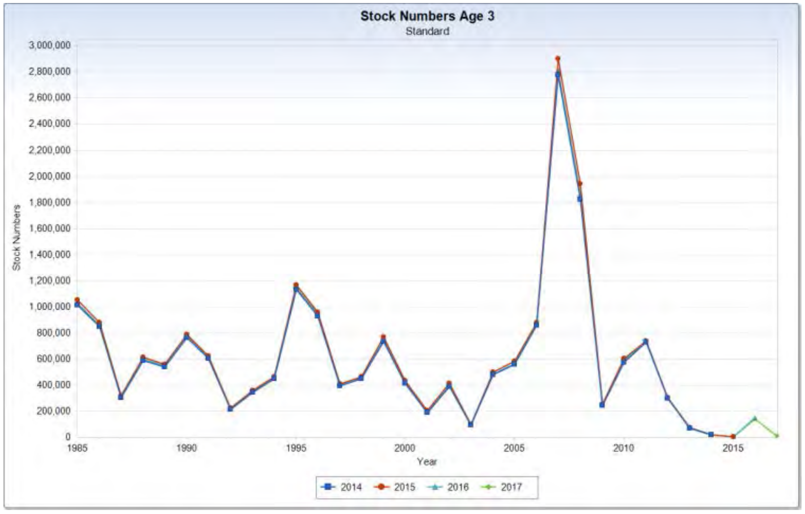


(l)

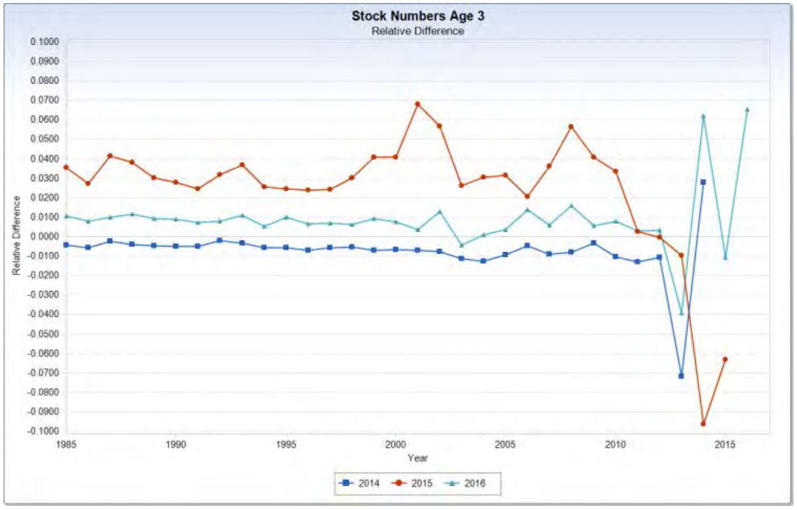


Continued

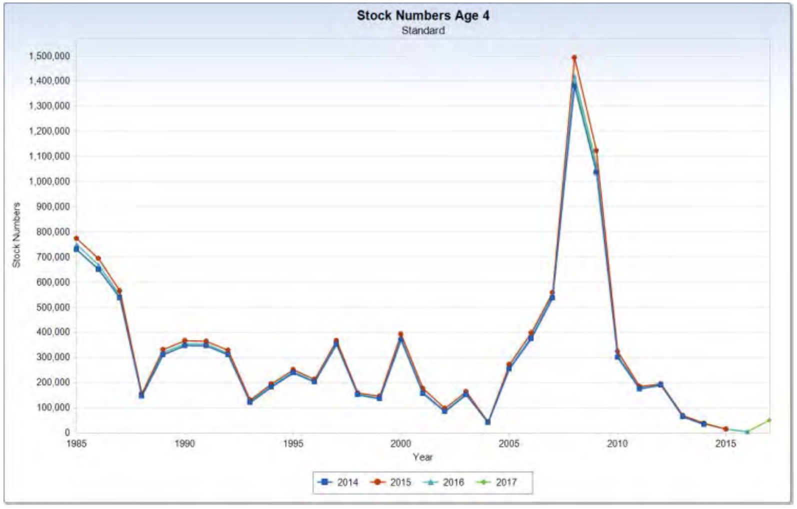
(m)



(n)

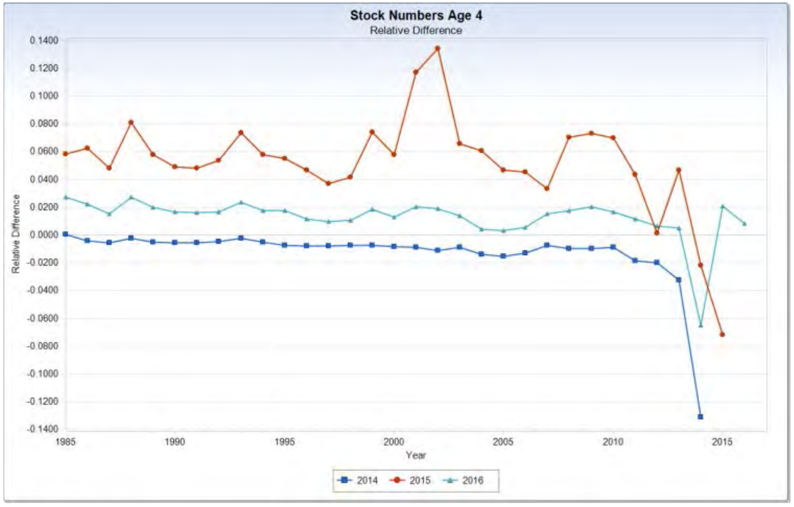


(o)

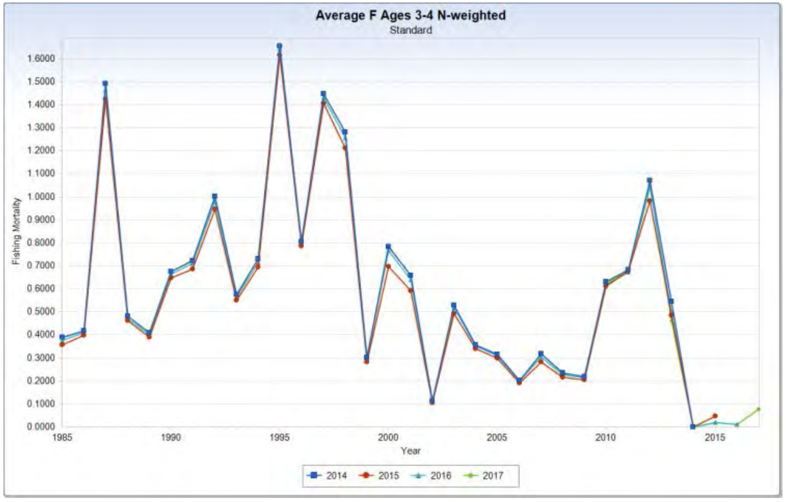


Continued

(p)



(q)



Continued

(r)

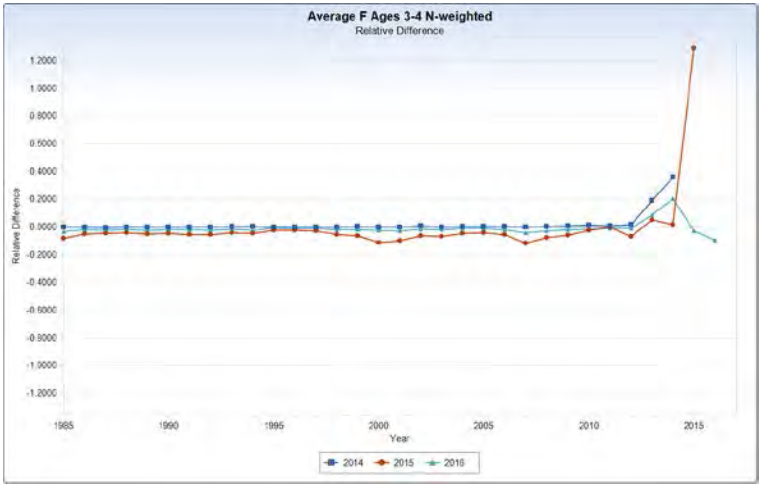


Figure 5.62 (a-r) Retrospective patterns for ASAP final run using model-based indices and age-varying and time varying (PPI scaled) M (based on M=0.5). (a) SSB; (b) relative change in estimates of SSB; (c) January 1 biomass; (d) relative change in estimates of January 1 biomass; (e) exploitable biomass; (f) relative change in estimates of exploitable biomass; (g) total stock numbers; (h) relative change in estimates of total stock numbers; (i) age 1 stock numbers; (j) relative change in estimates of age 1 stock numbers; (k) age 2 stock numbers; (l) relative change in estimates of age 2 stock numbers; (m) age 3 stock numbers; (n) relative change in estimates of age 3 stock numbers; (o) age 4 stock numbers; (p) relative change in estimates of age 4 stock numbers; (q) average F for ages 3-4; (r) relative change in estimates of average F for ages 3-4.

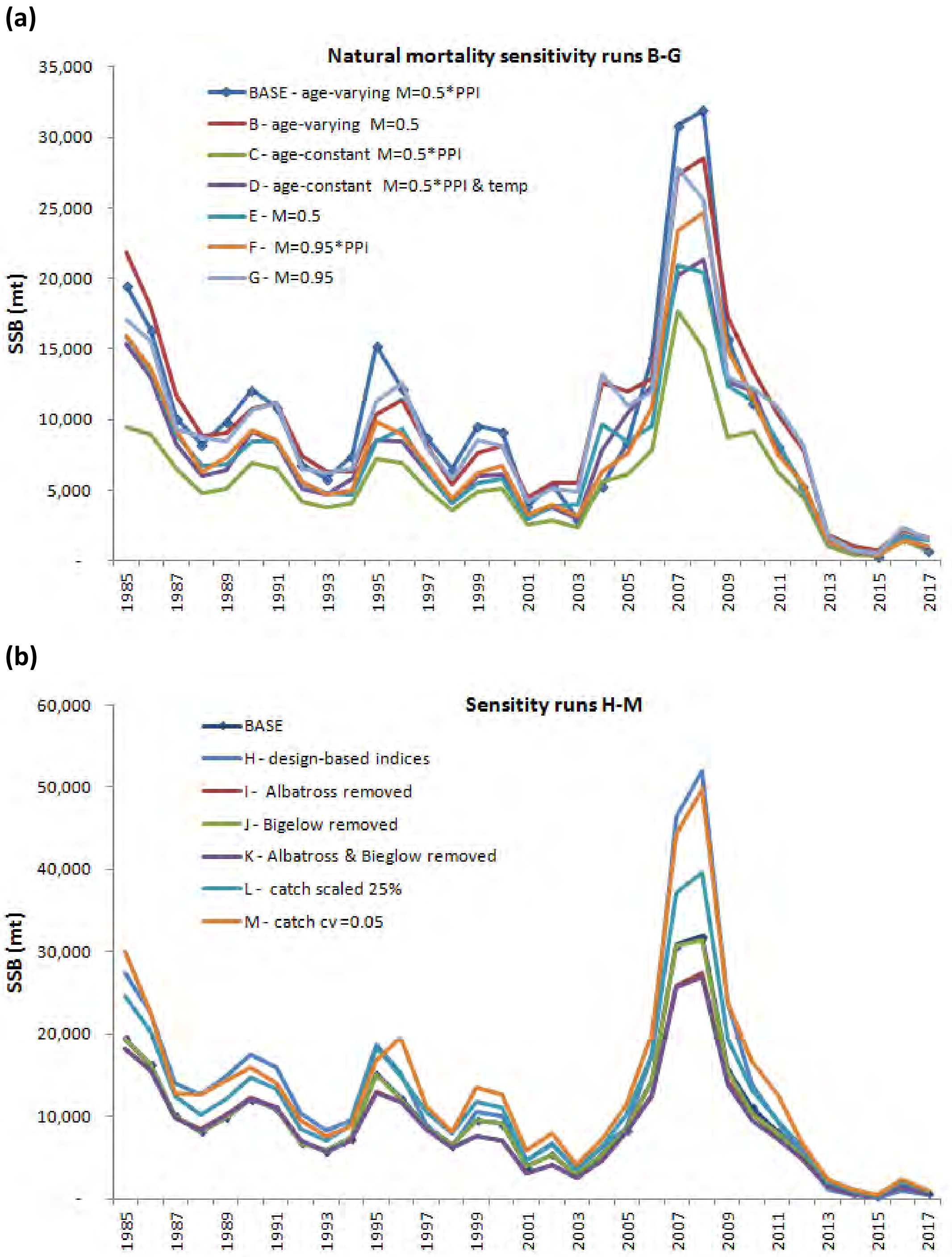


Figure 5.63. (a-b) ASAP model generated estimates of SSB for base and sensitivity runs. a) base model compared to alternative natural mortality scenarios; b) base model compared to runs with changes in survey indices, catch, and catch CVs; See Table 4.1 for descriptions of sensitivity runs (i.e. scenarios).

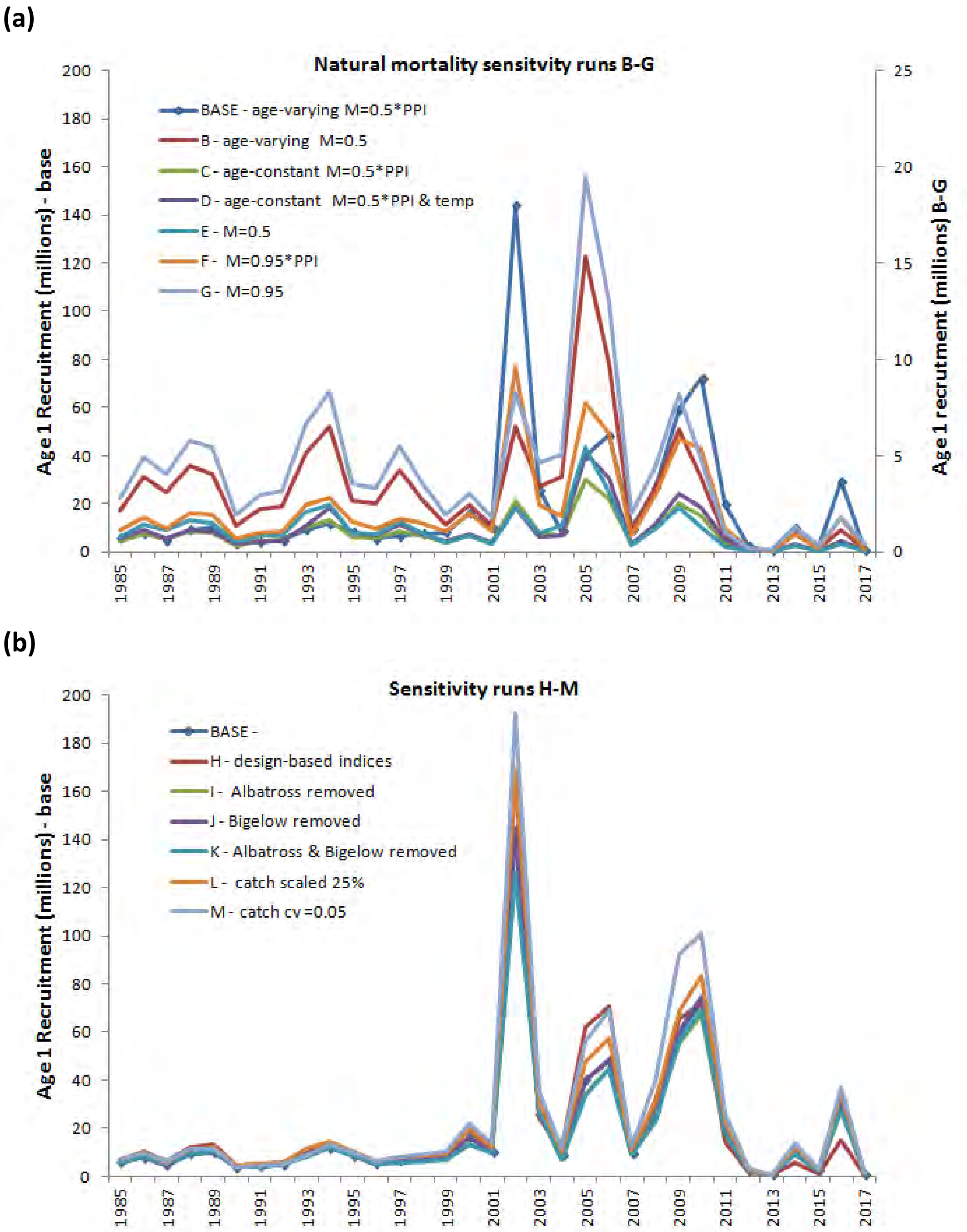


Figure 5.64 (a-b). **ASAP model estimates of Age-1 recruitment for base and sensitivity runs. a) base model compared to alternative natural mortality scenarios; b) base model compared to runs with changes in survey indices, catch, and catch CVs; See Table 4.1 for descriptions of sensitivity runs (i.e. scenarios).**

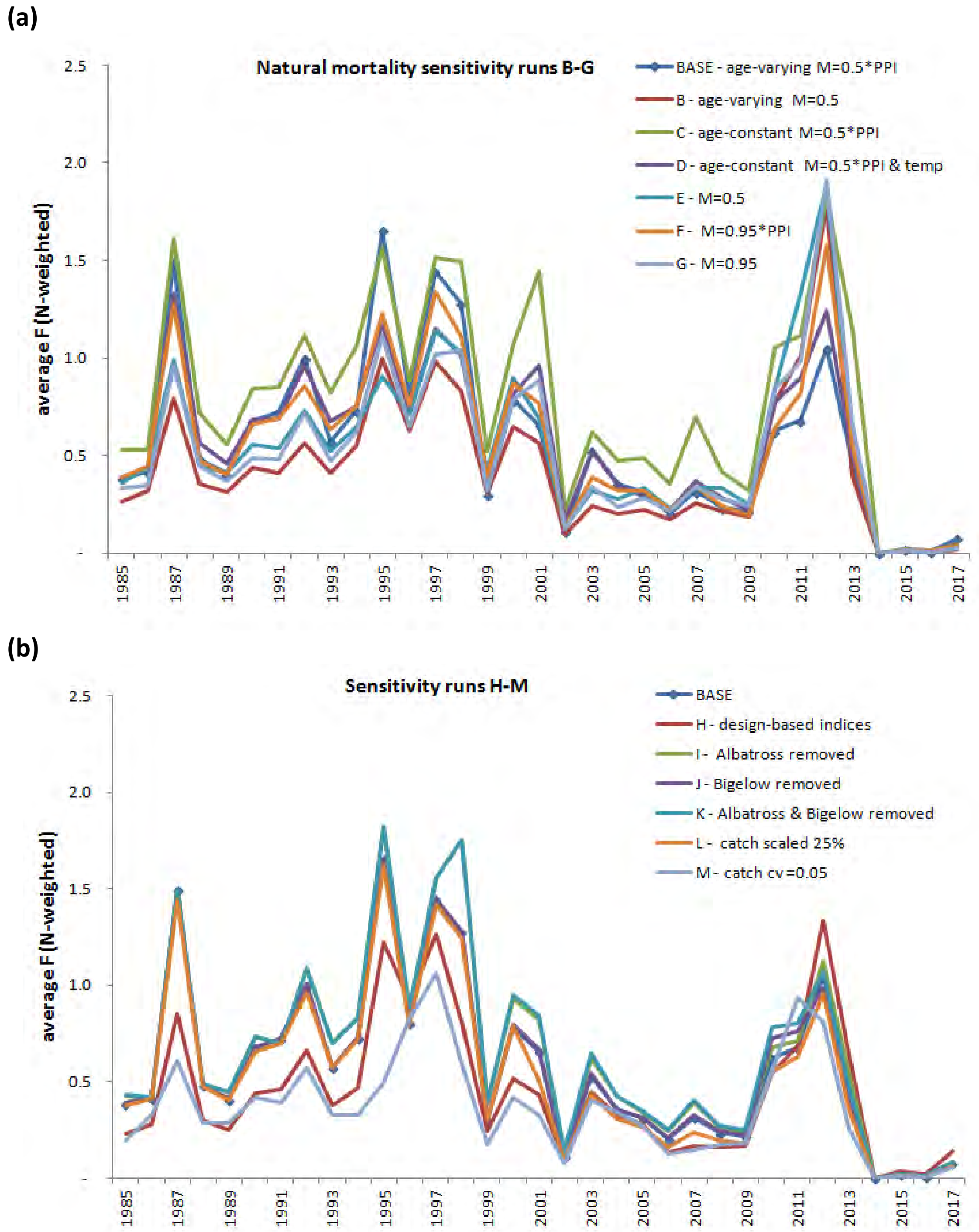


Figure 5.65 (a-b). **ASAP model generated estimates of average F for base and sensitivity runs. a) base model compared to alternative natural mortality scenarios; b) base model compared to runs with changes in survey indices, catch, and catch CVs; See Table 4.1 for descriptions of sensitivity runs (i.e. scenarios).**

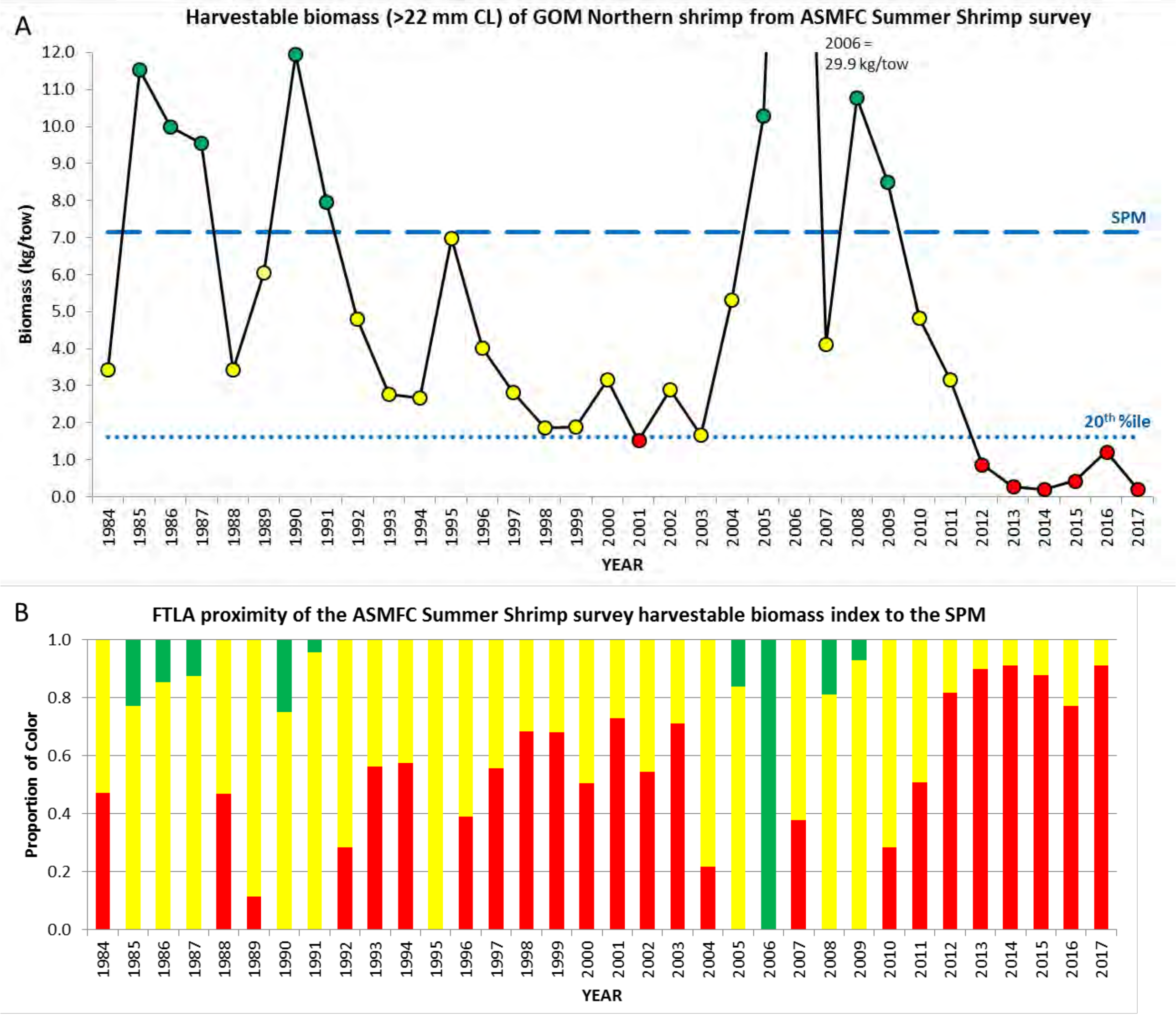


Figure 5.66 Traffic light analysis for harvestable biomass. (A) Harvestable biomass of Gulf of Maine northern shrimp from the ASMFC Summer Shrimp survey 1984–2017, with 'stable period' (1985–1994) mean (SPM) (dashed) and 20th percentile of the time series from 1984–2017 (dotted) indicated. Green values ≥ SPM; red values ≤ 20th percentile; yellow values > 20th percentile and < SPM. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

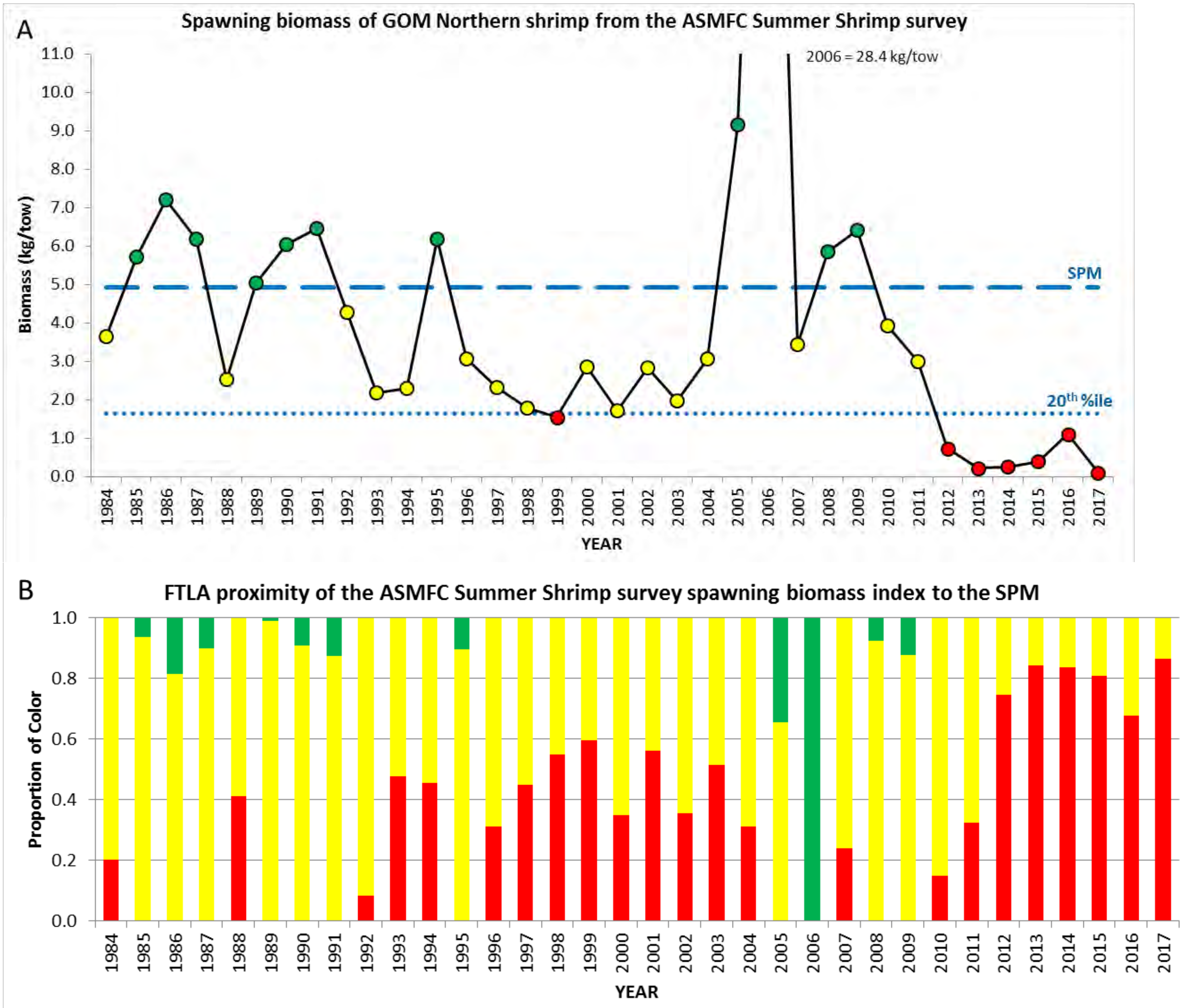


Figure 5.67 Traffic light analysis of SSB. (A) Spawning biomass of Gulf of Maine northern shrimp from the ASMFC Summer Shrimp survey 1984–2017, with ‘stable period’ (1985–1994) mean (SPM) (dashed) and 20th percentile of the time series from 1984– 2017 (dotted) indicated. Green values ≥ SPM; red values ≤ 20th percentile; yellow values > 20th percentile and < SPM. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

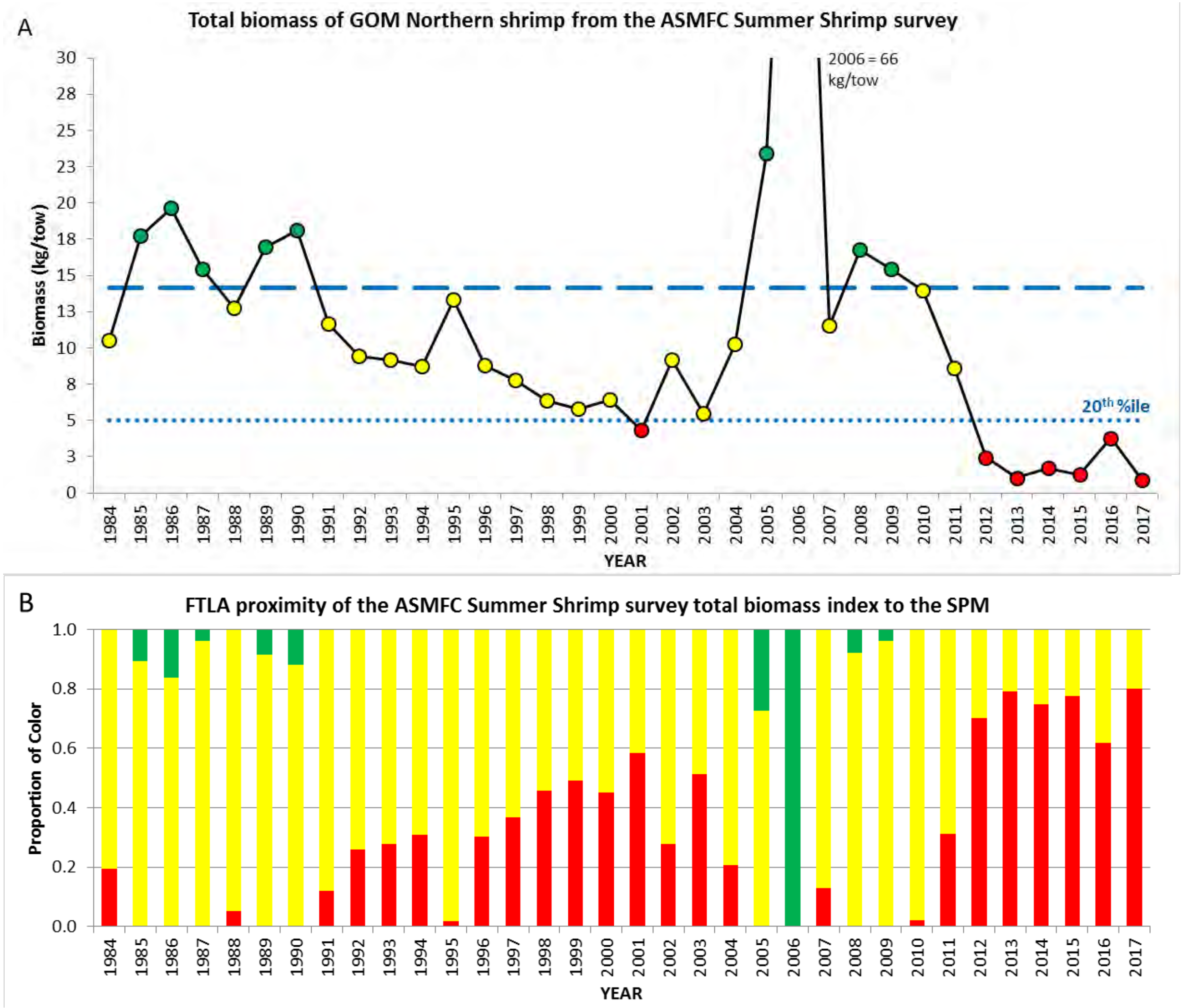


Figure 5.68 **Traffic light analysis for total biomass. (A) Total biomass of Gulf of Maine northern shrimp from the ASMFC Summer Shrimp survey 1984–2017, with the 'stable period' (1985–1994) mean (SPM) (dashed) and 20th percentile of the time series from 1984– 2017 (dotted) indicated. Green values ≥ SPM; red values ≤ 20th percentile; yellow values > 20th percentile and < SPM. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).**

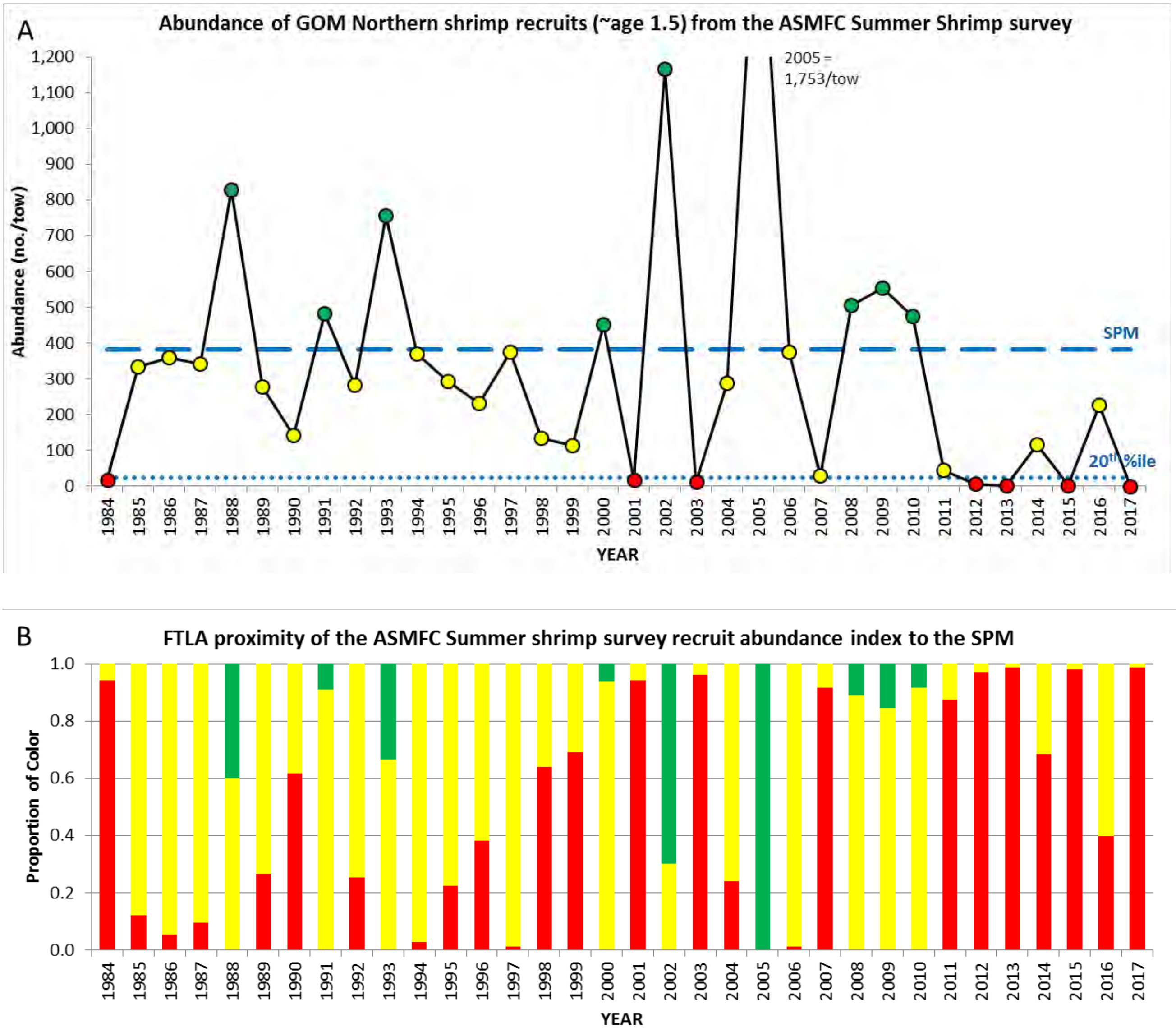


Figure 5.69 Traffic light analysis of northern shrimp recruitment. (A) Recruit abundance of Gulf of Maine northern shrimp from the ASMFC Summer shrimp survey 1984–2017, with ‘stable period’ (1985–1994) mean (SPM) (dashed) and 20th percentile of the time series from 1984–2017 (dotted) indicated. Green values ≥ SPM; red values ≤ 20th percentile; yellow values > 20th percentile and < SPM. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

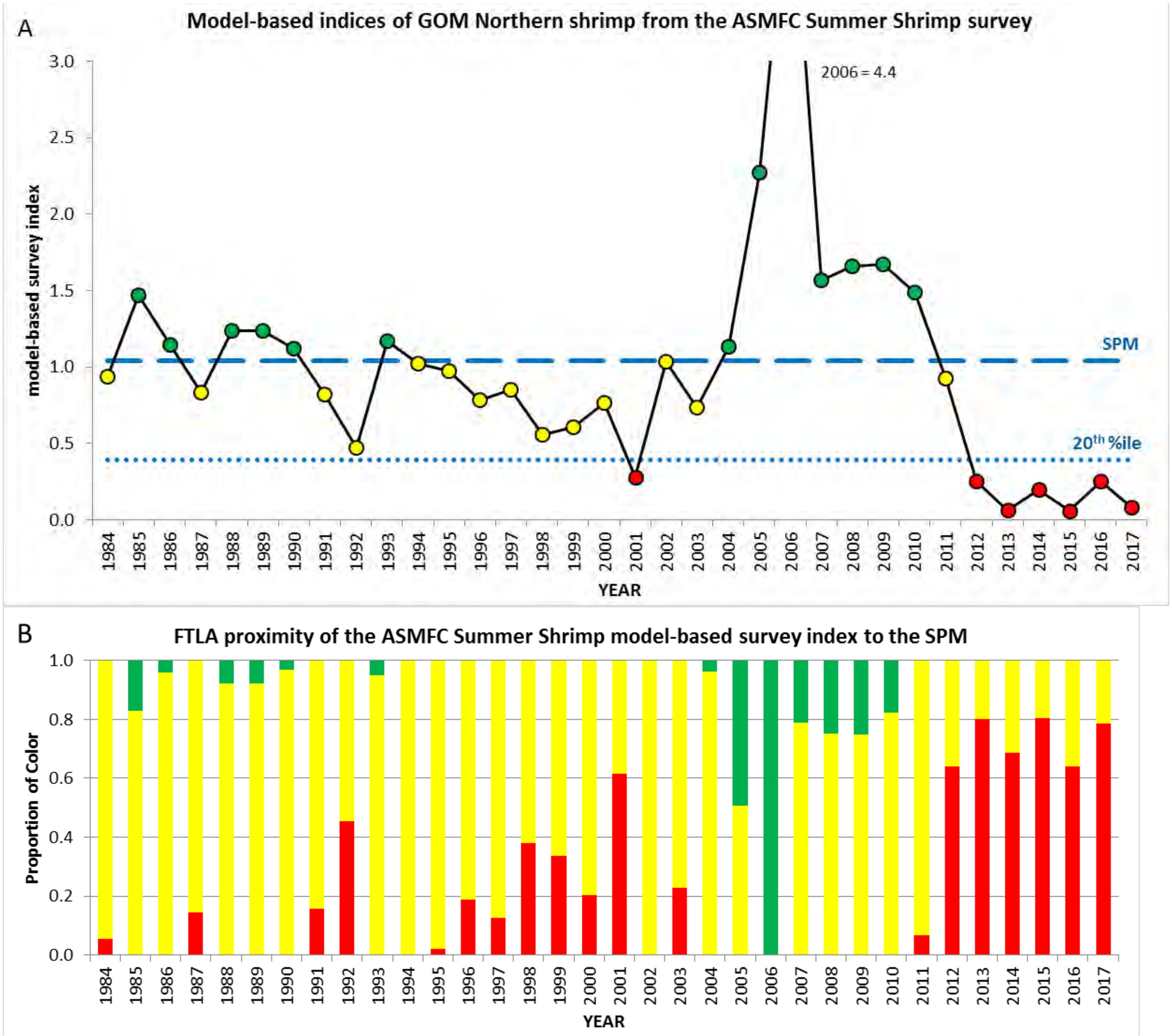


Figure 5.70 Traffic light analysis of model-based summer survey index. (A) Model-based index of Gulf of Maine northern shrimp from the ASMFC Summer shrimp survey 1984–2017, with 'stable period' (1985–1994) mean (SPM) (dashed) and 20th percentile of the time series from 1984–2017 (dotted) indicated. Green values ≥ SPM; red values ≤ 20th percentile; yellow values > 20th percentile and < SPM. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

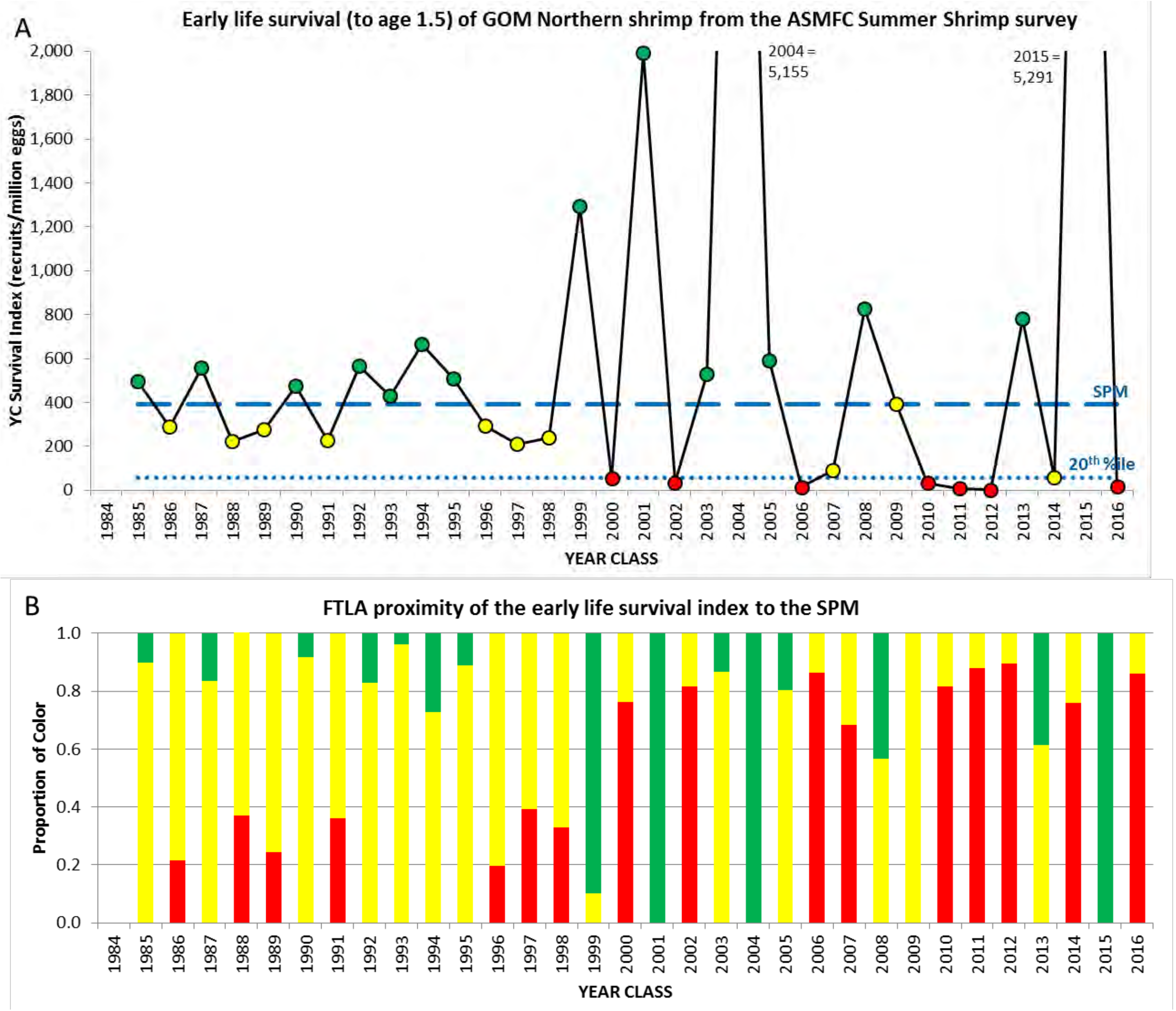


Figure 5.71 Traffic light analysis of northern shrimp early life survival. (A) Early life survival (to age 1.5) by year class of Gulf of Maine northern shrimp from the ASMFC Summer Shrimp survey 1984–2016, with 'stable period' (1985–1994) mean (SPM) (dashed) and 20th percentile of the time series by year class 1985–2016 (dotted) indicated. Green values ≥ SPM; red values ≤ 20th percentile; yellow values > 20th percentile and < SPM. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

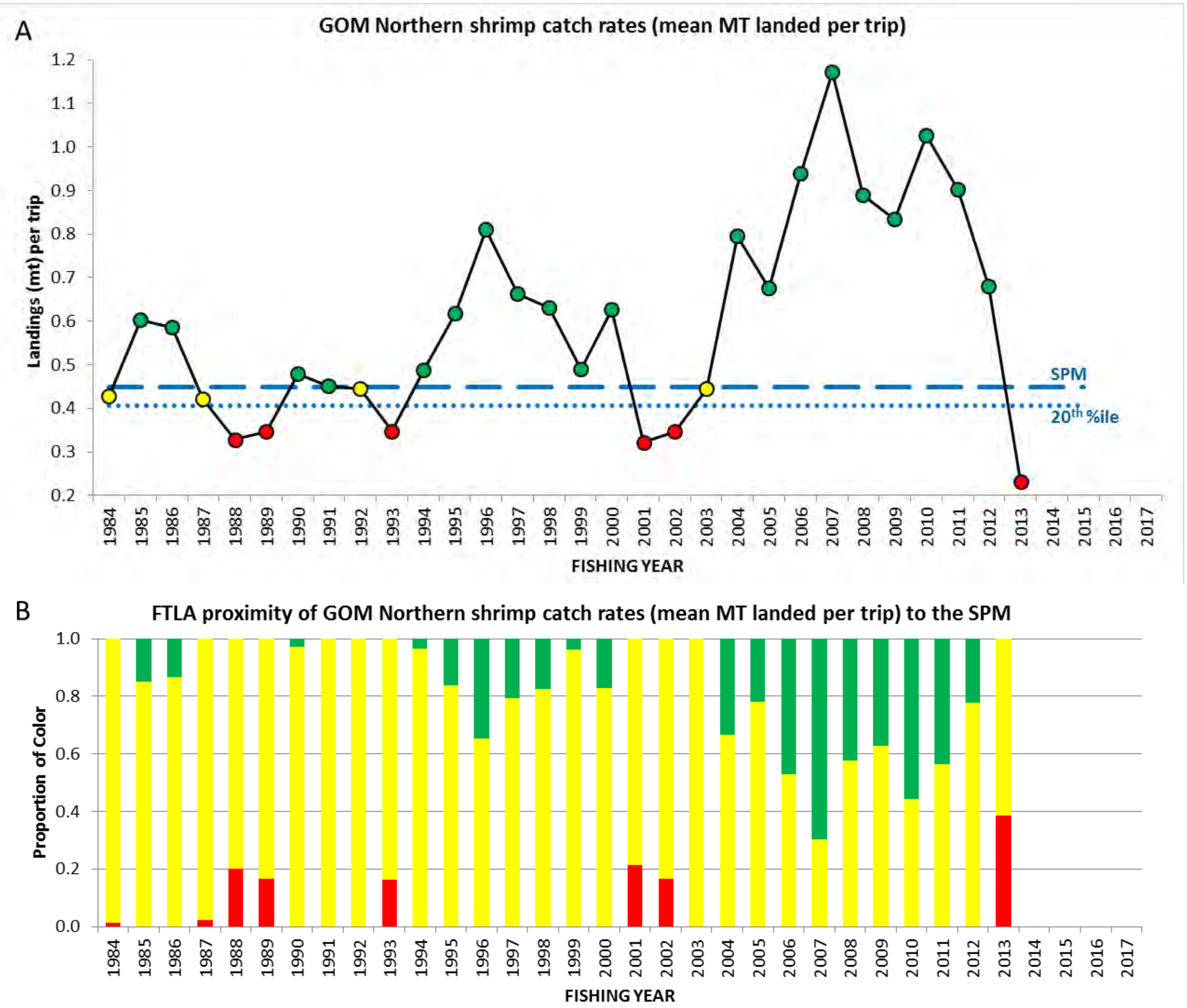


Figure 5.72 Traffic light analysis of northern shrimp commercial CPUE. (A) Gulf of Maine northern shrimp fishery catch rates (mt of landings per trip) by fishing year from 1984–2013 (fishery closed 2014–2017), with 'stable period' (1985–1994) mean (SPM) (dashed) and 20th percentile of the time series from 1984–2013 (dotted) indicated. Green values ≥ SPM; red values ≤ 20th percentile; yellow values > 20th percentile and < SPM. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

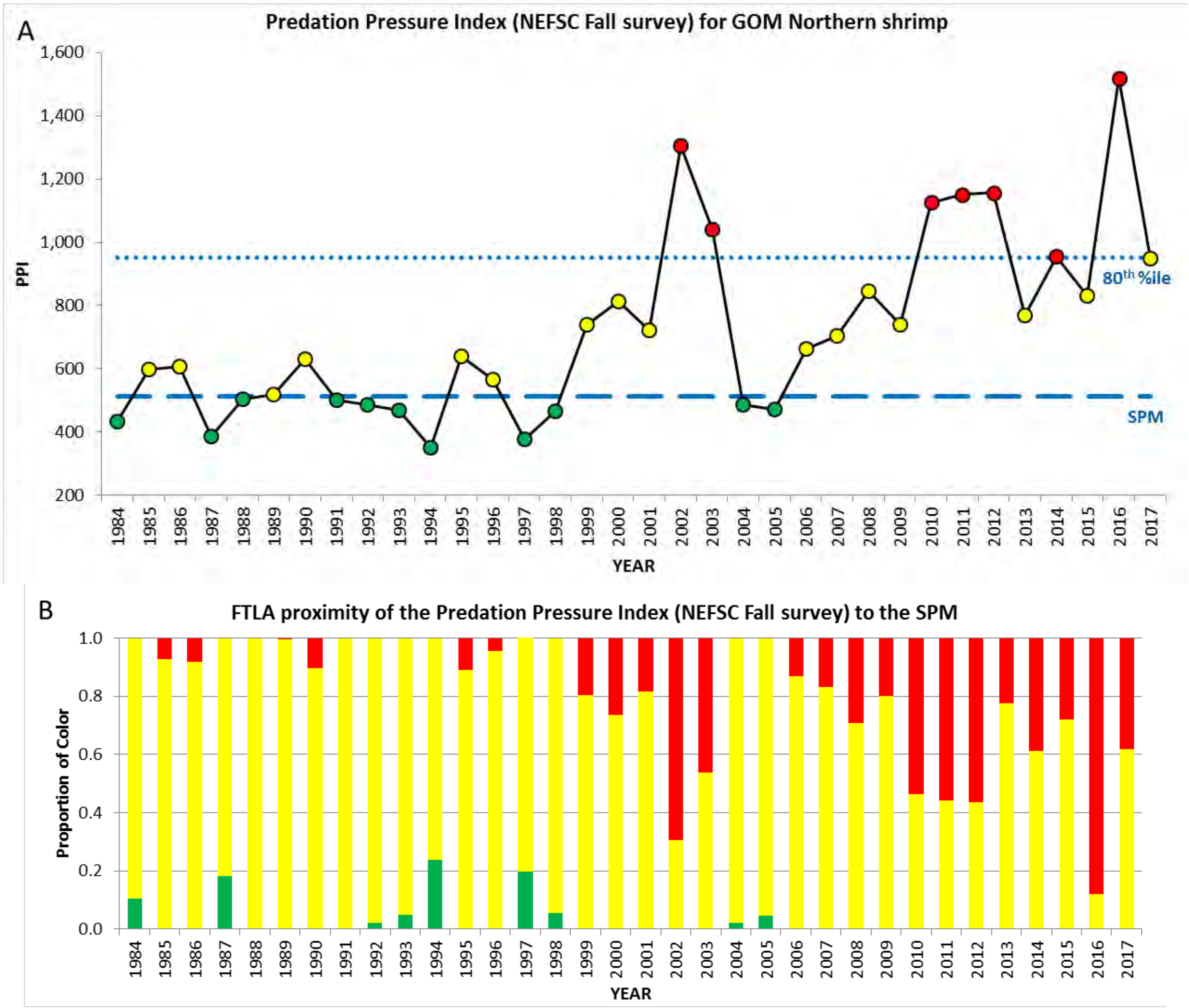


Figure 5.73 Traffic light analysis of northern shrimp predation pressure index. (A) Predation Pressure Index (PPI) for Gulf of Maine northern shrimp from 1984–2017, with 'stable period' (1985–1994) mean (SPM) (dashed) and 80th percentile of the time series from 1984–2017 (dotted) indicated. Green values ≤ SPM; red values ≥ 80th percentile; yellow values > SPM and < 80th percentile. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

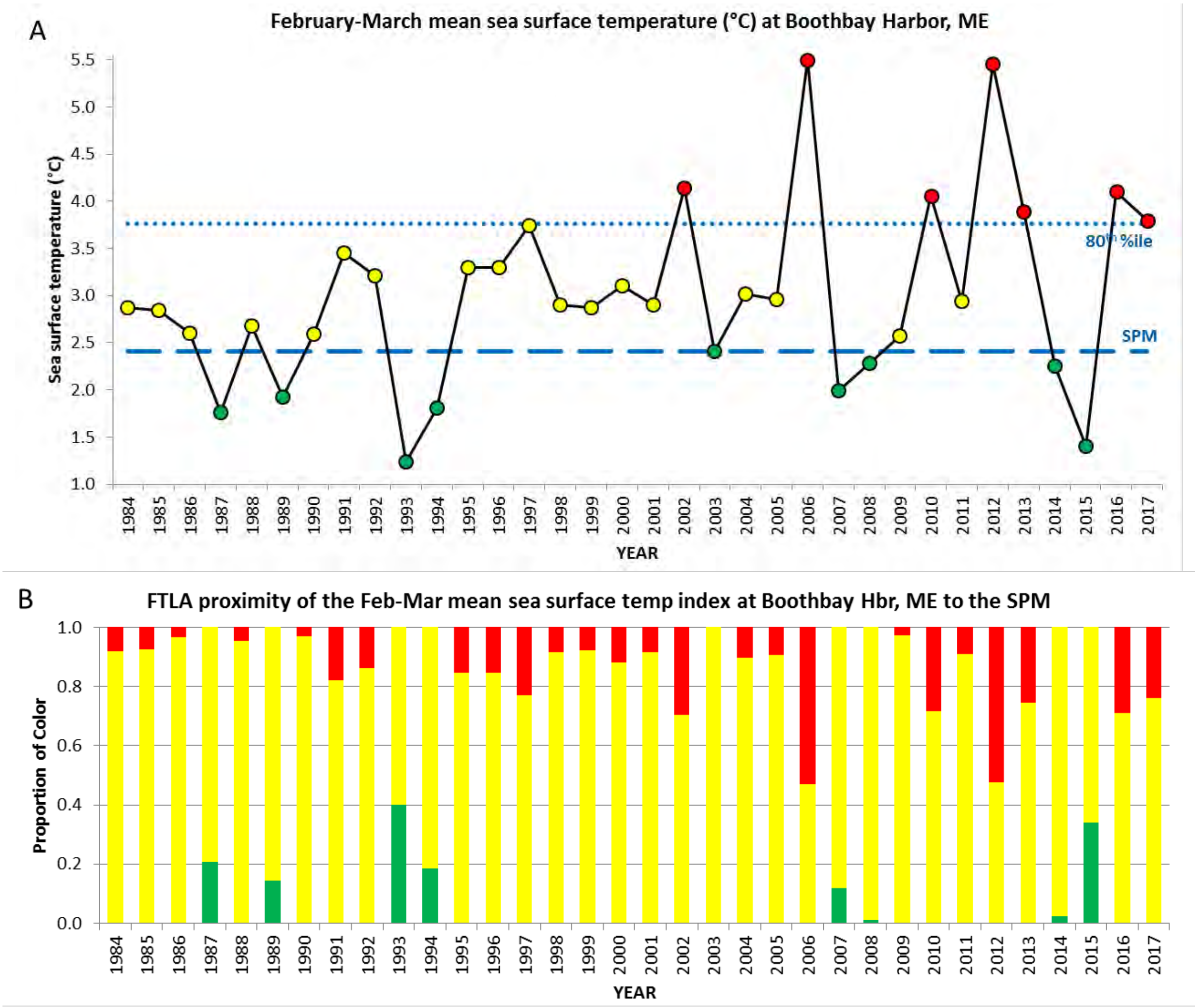


Figure 5.74 Traffic light analysis of Feb-Mar sea surface temperature at Boothbay Harbor, ME. (A) February to March mean sea surface temperature (°C) at Boothbay Harbor, ME from 1984–2017, with 'stable period' (1985–1994) mean (SPM) (dashed) and 80th percentile of the time series from 1984–2017 (dotted) indicated. Green values ≤ SPM; red values ≥ 80th percentile; yellow values > SPM and < 80th percentile. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

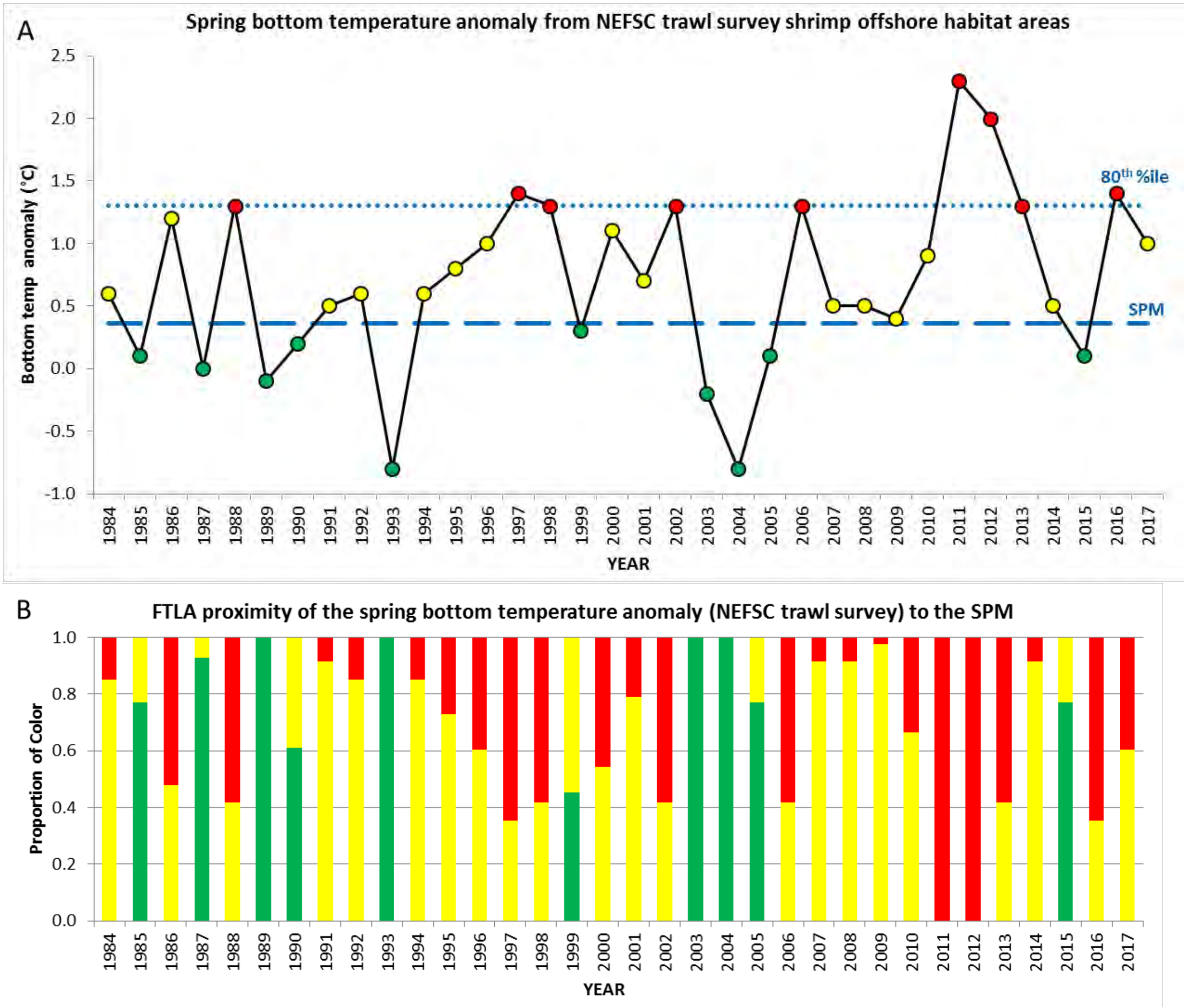


Figure 5.75 **Traffic light analysis of spring bottom temperature anomalies from the NEFSC trawl survey. (A) Spring bottom temperature anomaly (°C) from the NEFSC trawl survey in shrimp offshore habitat areas from 1984–2017, with 'stable period' (1985–1994) mean (SPM) (dashed) and 80th percentile of the time series from 1984–2017 (dotted) indicated. Green values ≤ SPM; red values ≥ 80th percentile; yellow values > SPM and < 80th percentile. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).**

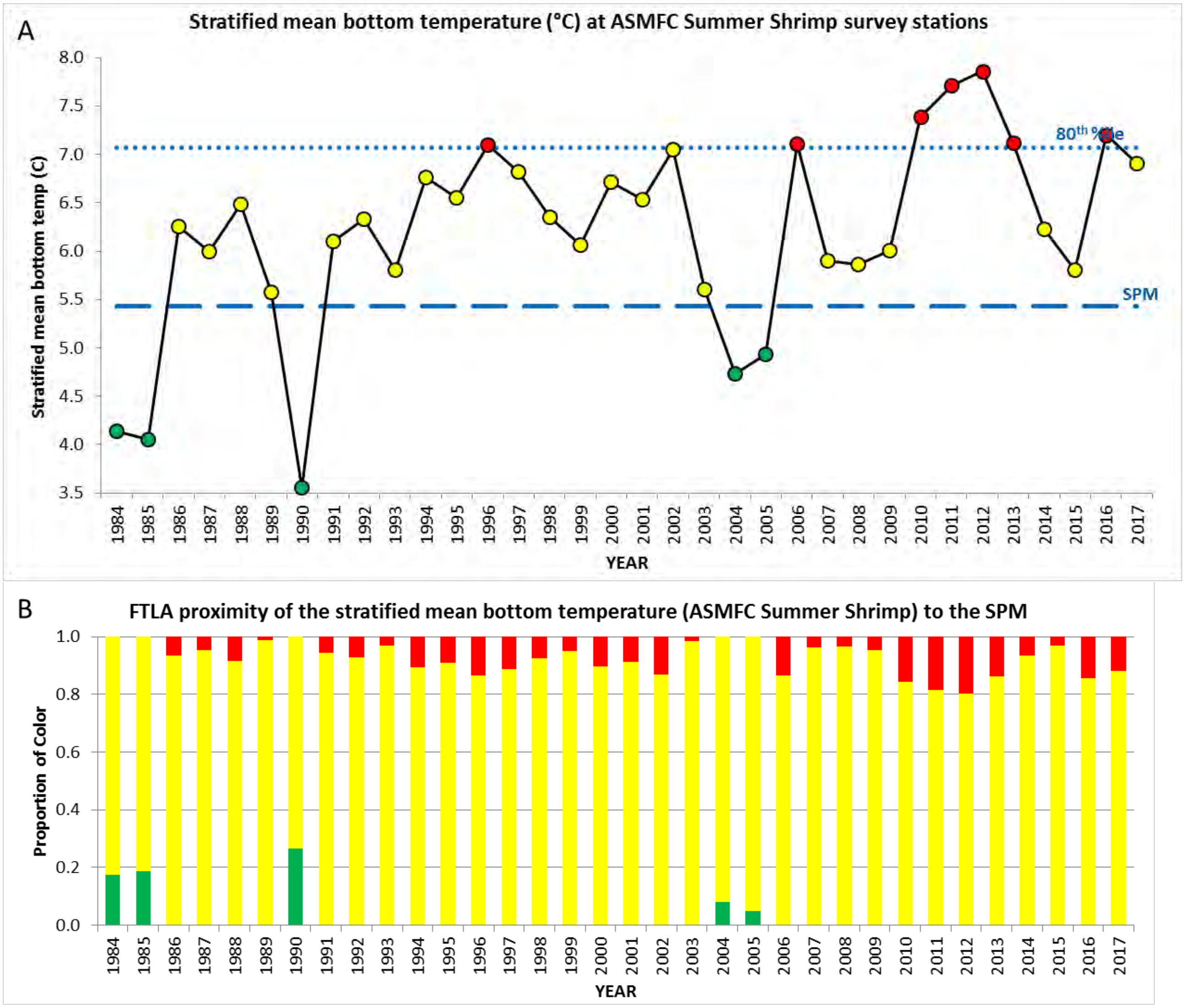


Figure 5.76 Traffic light analysis of summer bottom temperature from the ASMFC summer survey. (A) summer stratified mean bottom temperature (°C) at ASMFC Summer Shrimp survey stations from 1984–2017, with 'stable period' (1985–1994) mean (SPM) (dashed) and 80th percentile of the time series from 1984–2017 (dotted) indicated. Green values ≤ SPM; red values ≥ 80th percentile; yellow values > SPM and < 80th percentile. (B) Fuzzy Traffic Light Analysis (FTLA) color proportions indicate proximity of annual indices to the SPM (red = unfavorable; green = favorable).

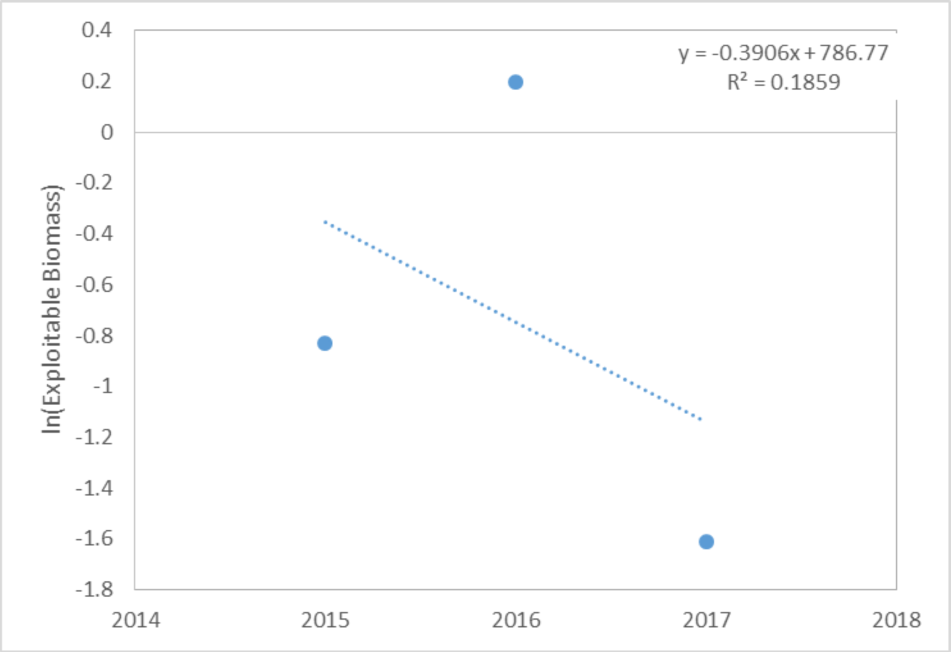


Figure 5.77. Slope of the log-index of exploitable biomass over the last 3 years used for the data poor quota calculation.

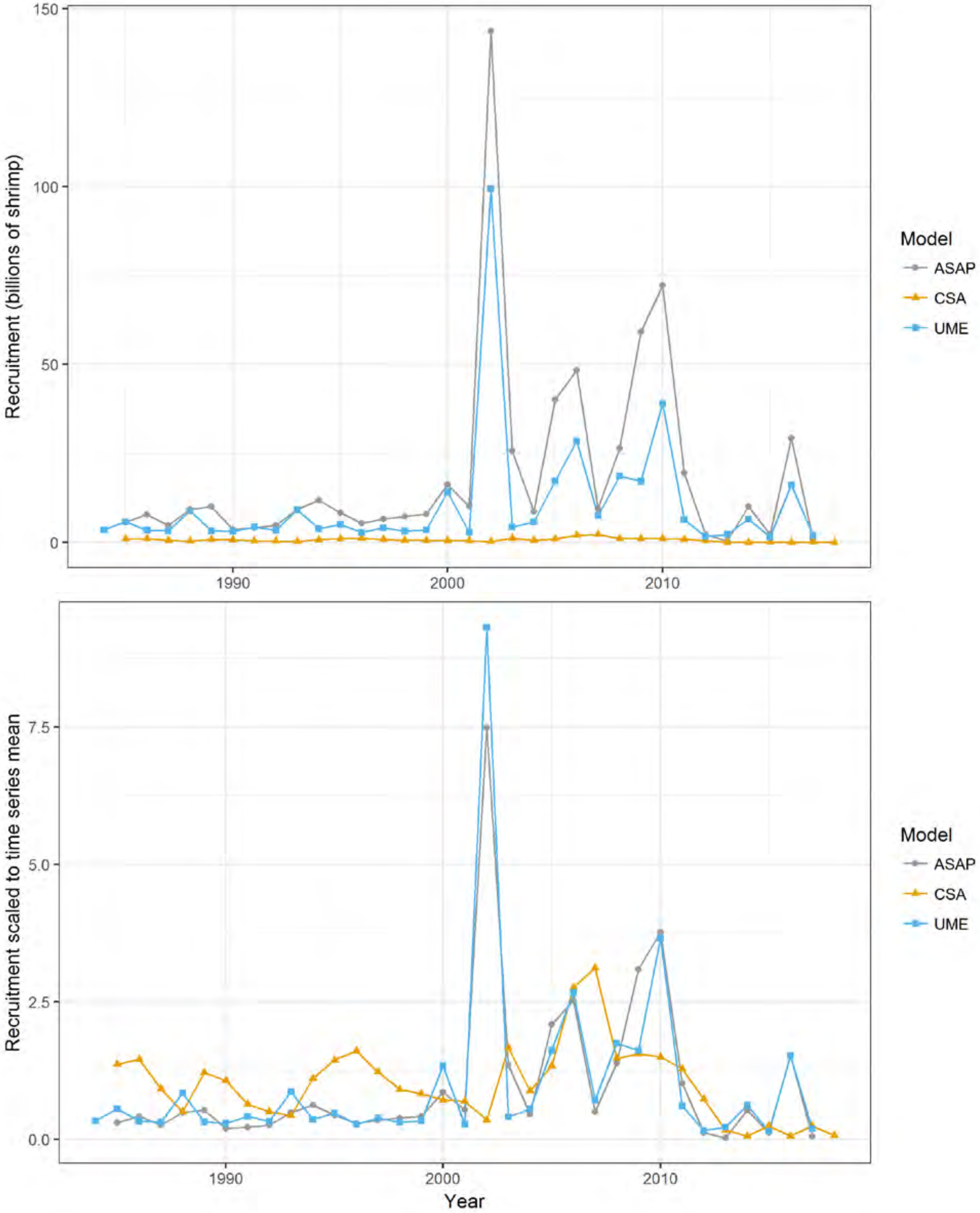


Figure 5.78. Comparison of recruitment estimates from ASAP, CSA, and UME model. Top panel is absolute numbers of recruits; bottom panel is scaled to the respective time series means.

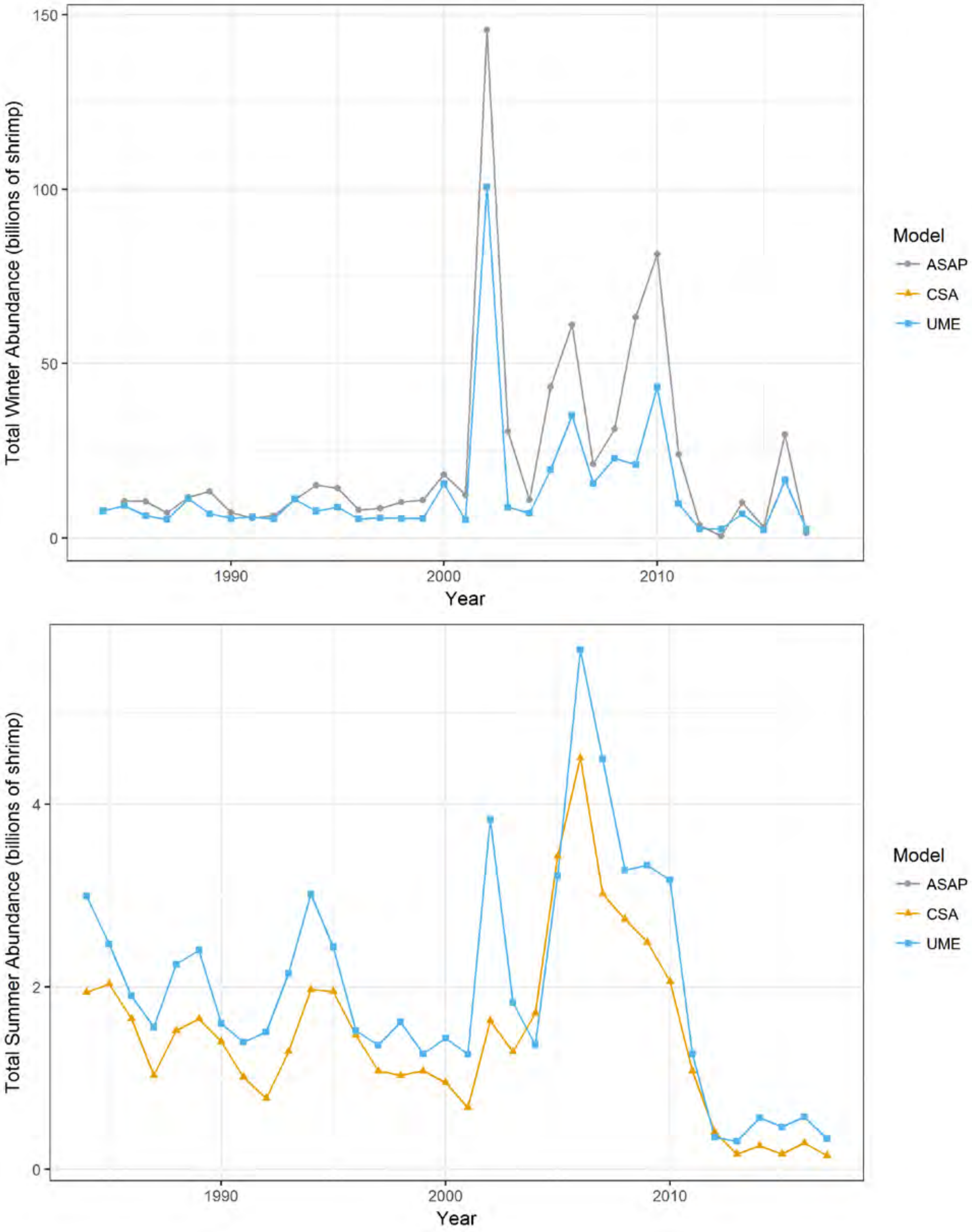


Figure 5.79. Comparison of total abundance estimates from the ASAP, CSA, and UME models for the winter (top) and summer (bottom).

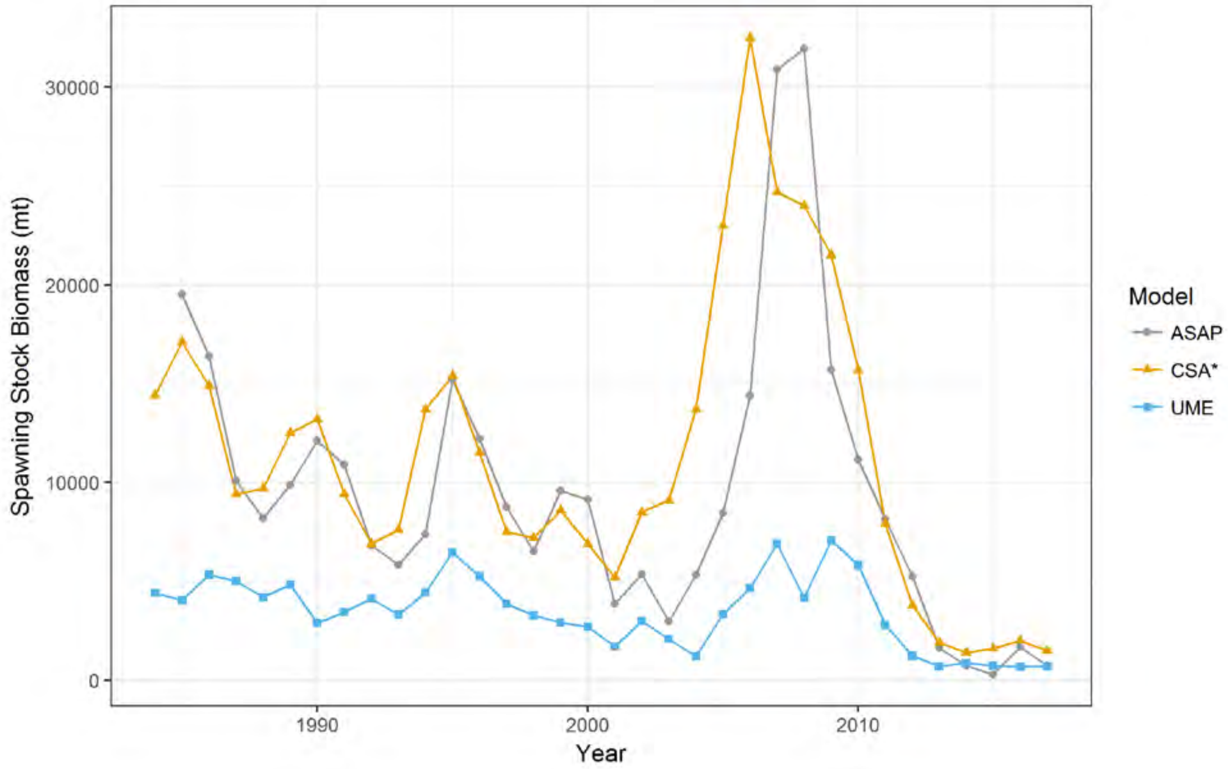


Figure 5.80. Comparisons of spawning stock biomass estimates from the ASAP, CSA, and UME models. *: Exploitable biomass is used as a proxy for SSB for the CSA model, as the CSA model does not calculate SSB.

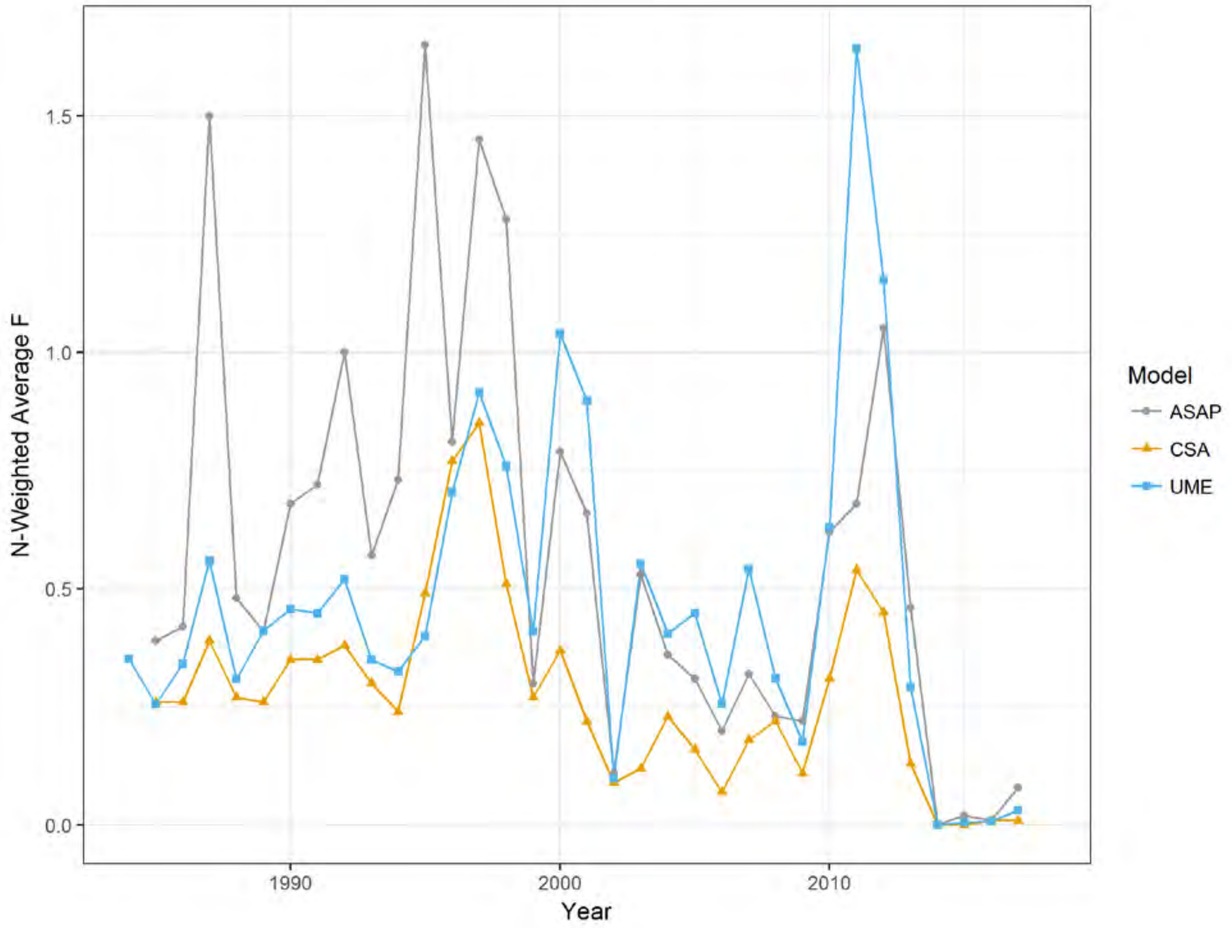


Figure 5.81. Comparison of fishing mortality estimates from the ASAP, CSA, and UME models.

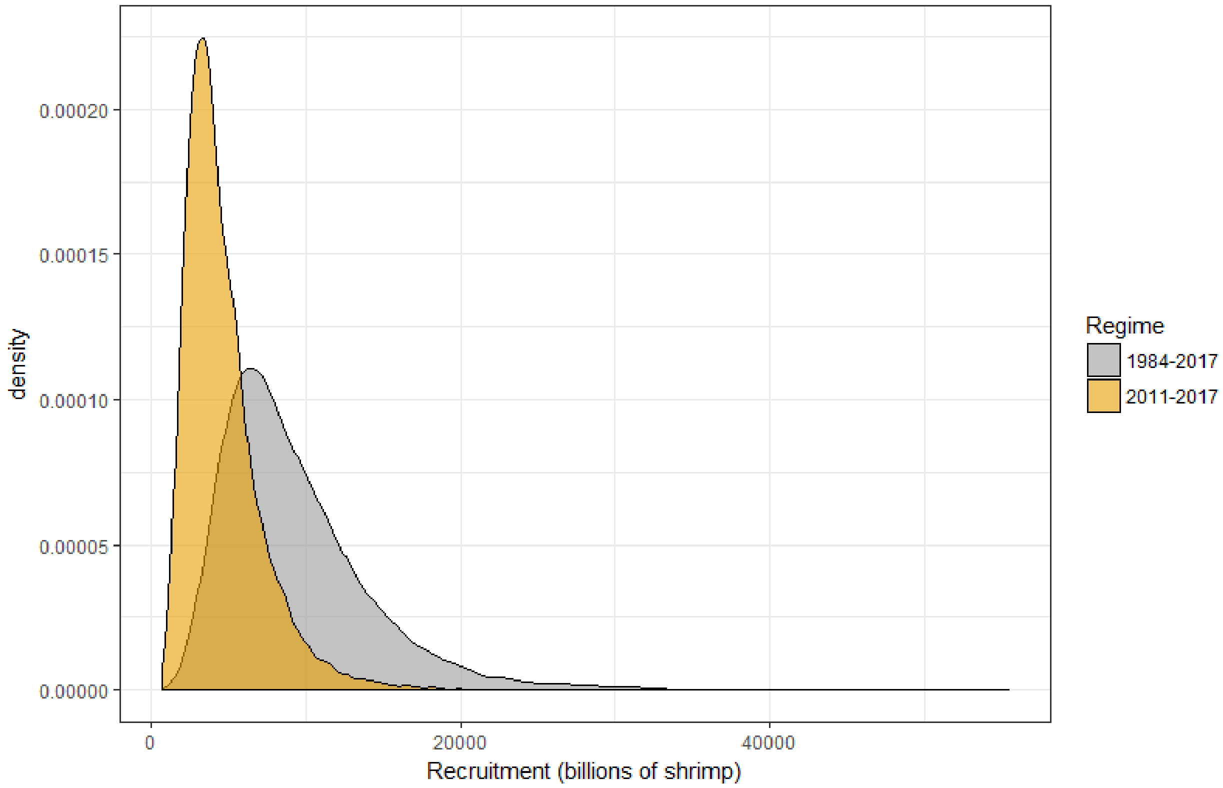


Figure 6.1. **Distributions of recruitment used in projections from the UME model**

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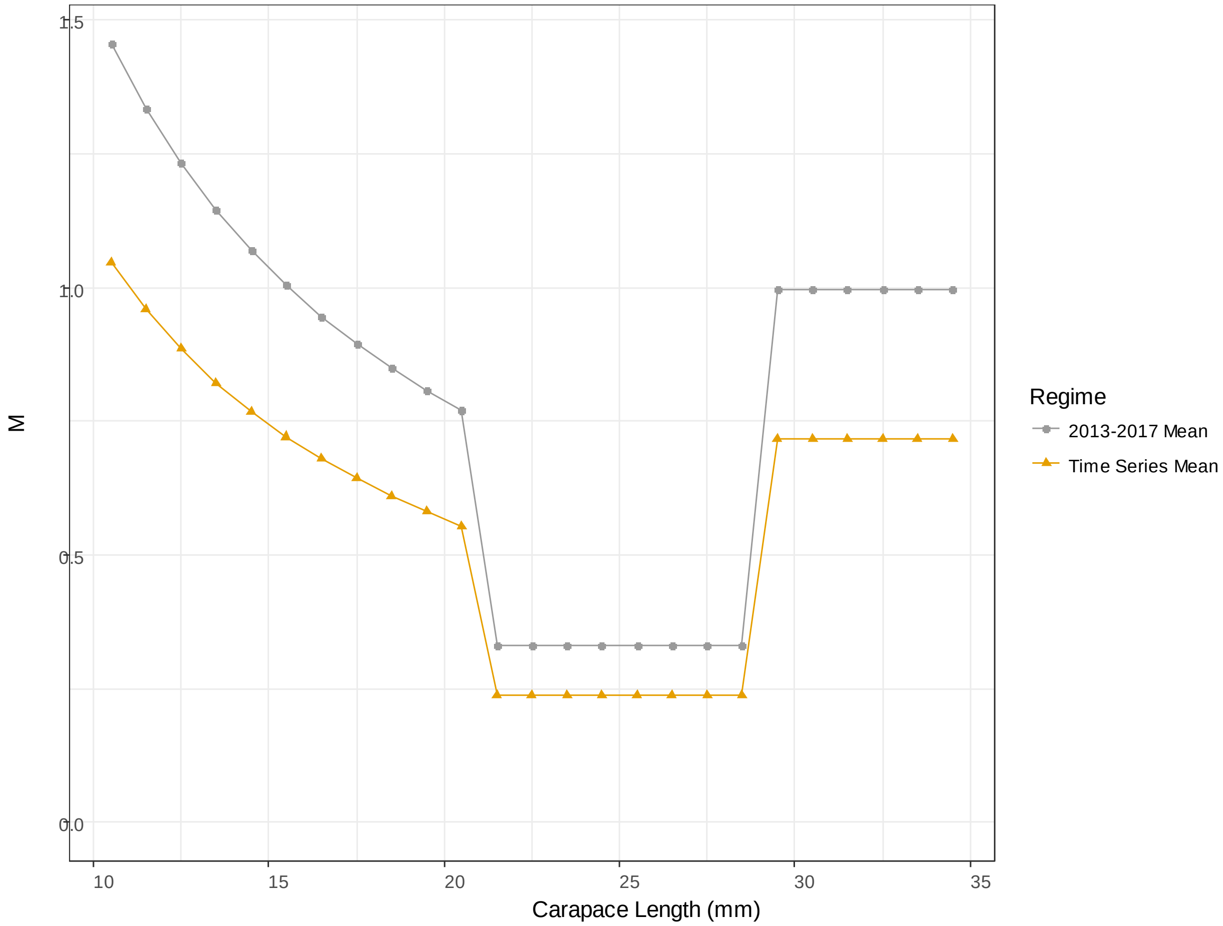

Figure 6.2. **M at size used in the UME model projections.**

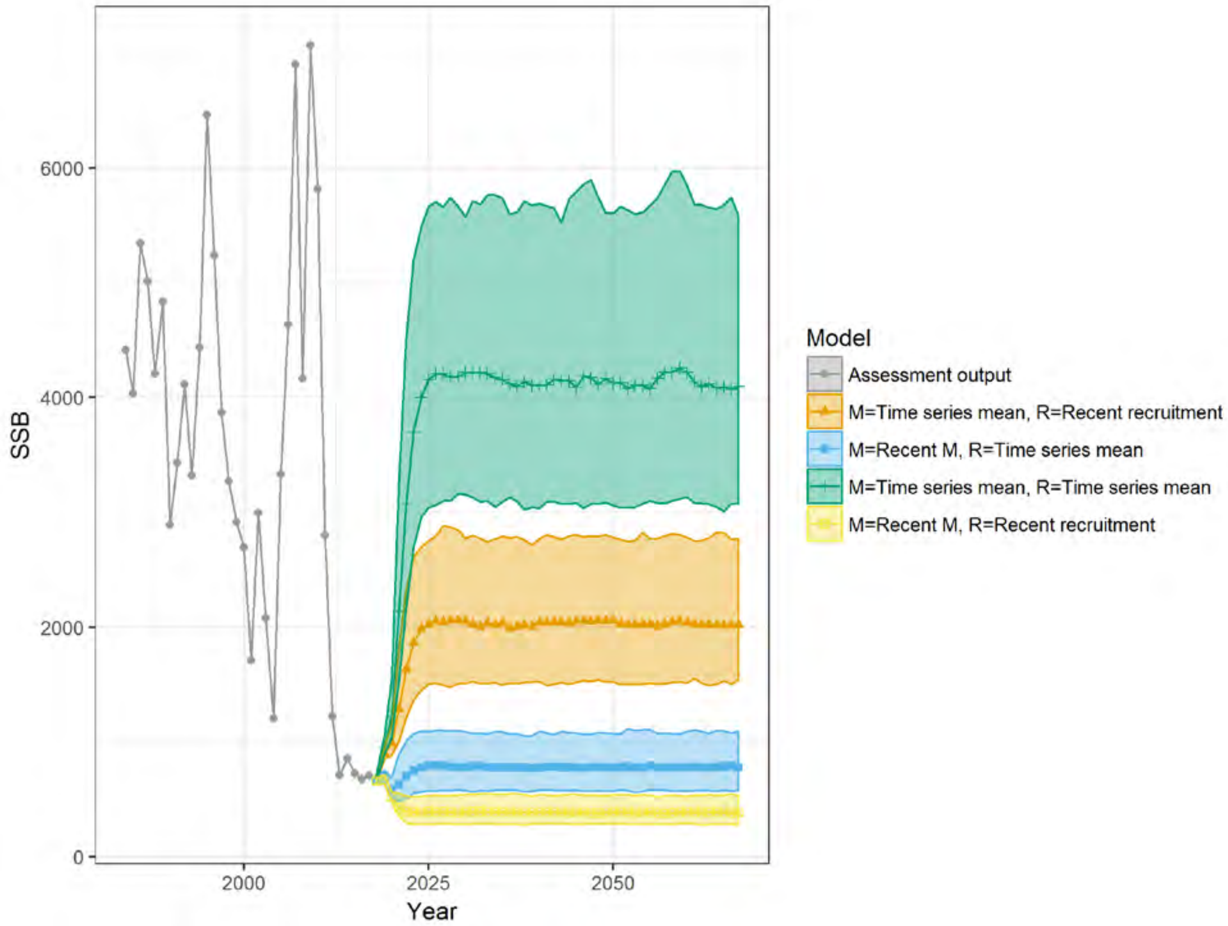

Figure 6.3. Projected population trajectories from the UME model under no fishing for different natural mortality and recruitment scenarios. Shaded areas indicate the 10th and 90th percentiles of the stochastic projections.

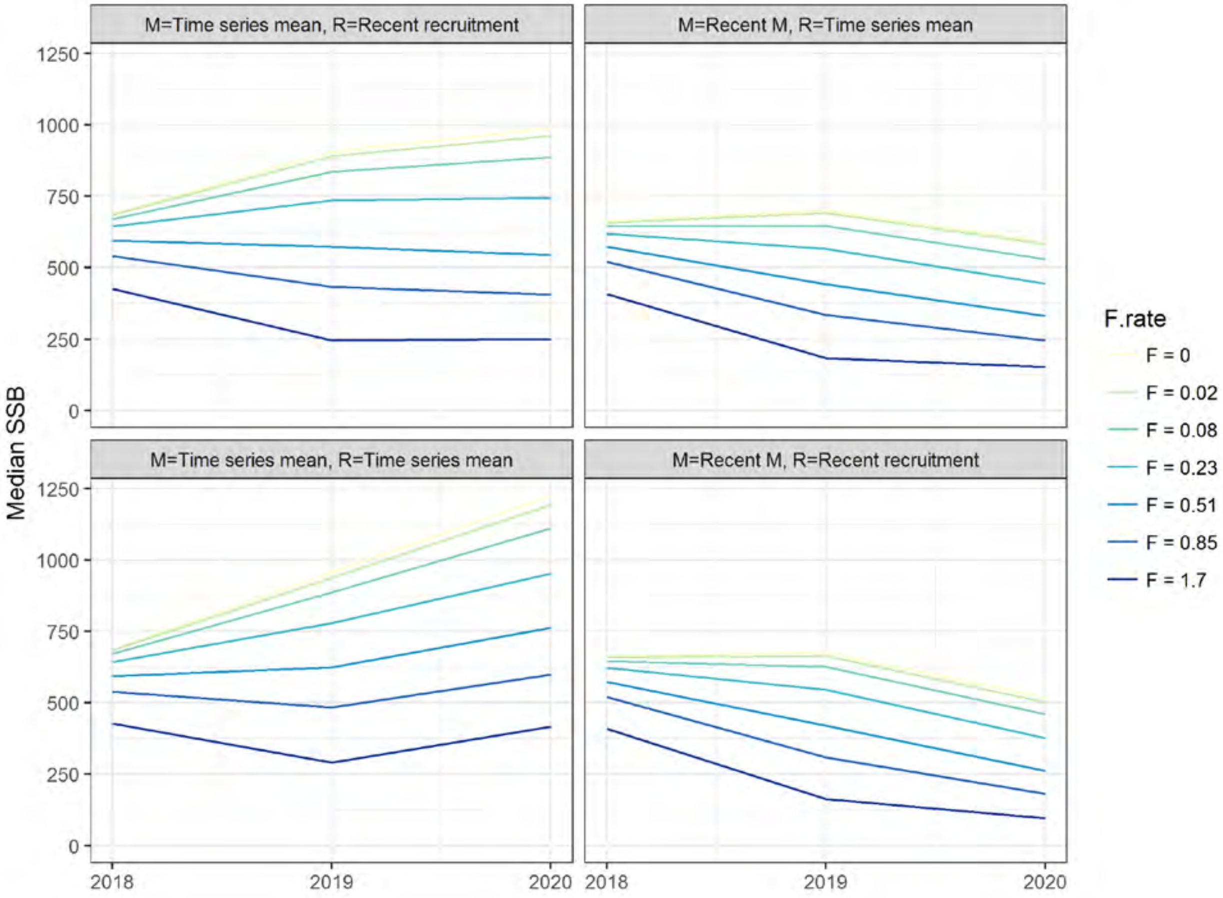

Figure 6.4. **Projected SSB trajectories from the UME model under different levels of F for different M and recruitment scenarios.**

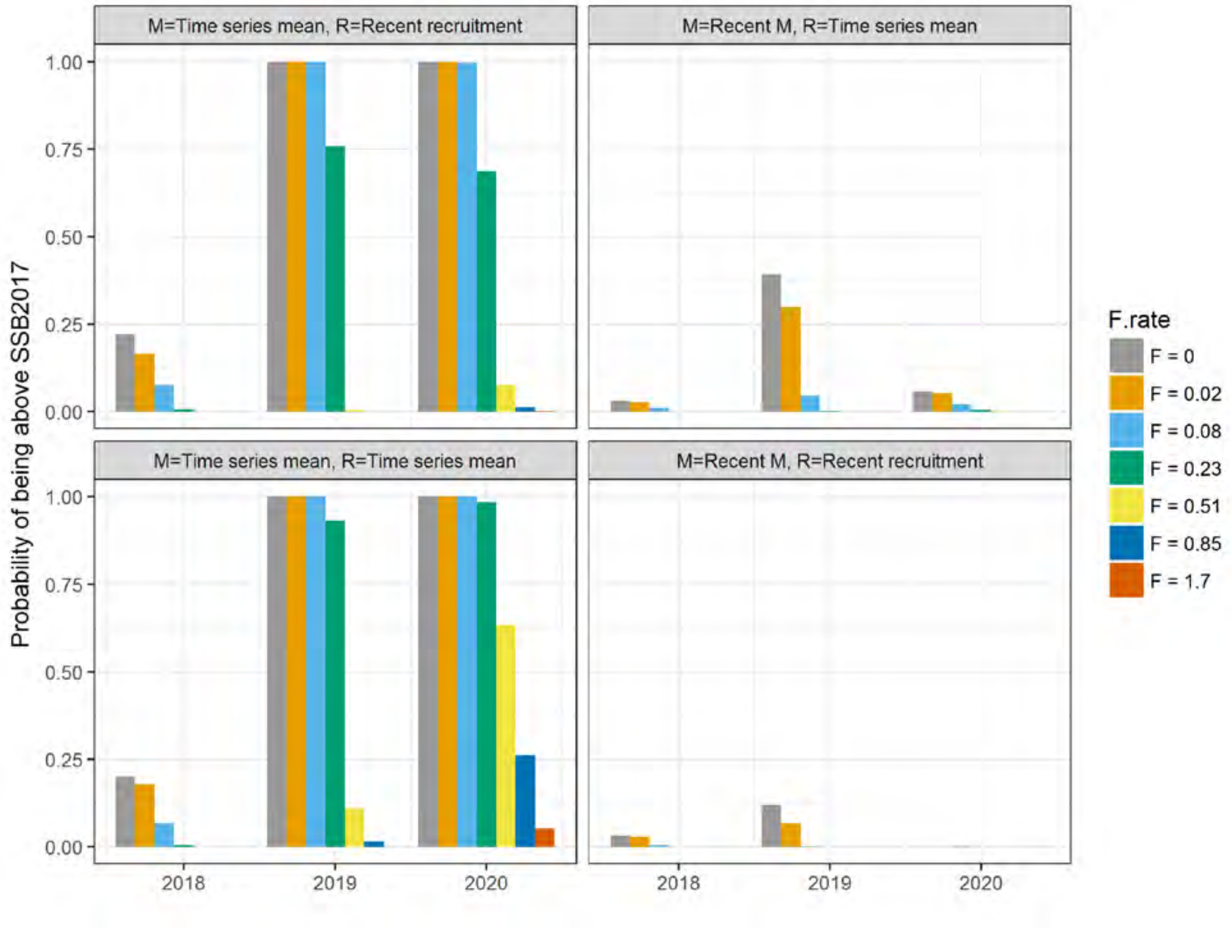

Figure 6.5. Probability of SSB being above SSB_{2017} in 2020 from the UME model for different F levels under different M and recruitment scenarios.

APPENDIX 1: ANALYSIS ON RECENT REGIME SHIFTS AND IMPACTS ON THE NORTHERN SHRIMP POPULATIONS

Identification of Potential Regime Shifts Relevant to Northern Shrimp

To address the question of whether we may be in a new ‘productivity regime’ for northern shrimp in the Gulf of Maine, a statistical method for regime shift detection was applied to time series of environmental (temperature) and biological data relevant to northern shrimp.

Methods

The STARS (Sequential t-test Analysis of Regime Shifts) method for regime shift detection was used to evaluate possible regime shifts (Rodionov 2004; Rodionov and Overland 2005). The method is based on a series of sequential t-tests comparing the current (most recent) value to the mean of the time series for the current regime to identify potential change points. A significantly different value indicates a potential regime shift, and subsequent observations are used to confirm this. Many methods for regime shift detection have difficulty detecting shifts near the end of the time series, thus shifts cannot be detected in a timely fashion. The STARS method was developed the address this problem.

The time series examined are shown in Tables 1 (temperature data) and 2 (biological data). The data were prewhitened to correct for auto-regression in the time series so that the correlation between successive years did not influence the results. Autocorrelation can lead to spurious detection of regime shifts (Rodionov 2006). Huber’s h=1.345 (Huber 1964) was used for down-weighting outliers.

Two parameters determine the sensitivity of regime detection by STARS – (1) the significance level used for the t-tests (the lower the P level, the larger the magnitude of the shift must be in order to be detected), and (2) the cut-off length. The implications of cut-off length are described by Rodionov (http://www.beringclimate.noaa.gov/regimes/help.html): “The regimes that are longer than the cut-off length will all be detected. If the regimes are shorter than the cut-off length, the probability for them to be detected reduces proportionally to their length. Some of them, however, may still be selected if the magnitude of the shift is significant enough. Generally speaking, the shorter the cut-off length, the shorter the regimes that will be selected (and vice versa), but it's not always true.”

As a base case, a cut-off length of 5 years and a P value of 0.10 for significance of the t-tests were used. To test the sensitivity to these parameters, the analysis was repeated using a 10-year cut-off, and P=0.05 or P=0.10.

Results

Temperature Data

Using the base case parameters, regime shifts were detected for all temperature variables except spring bottom temperature anomaly (BTA) and Feb-Mar average sea surface temperature (SST) at Boothbay Harbor (Figure 1). A regime change point was detected in 2010 for spring sea surface temperature anomaly (SSTA), summer shrimp survey bottom temperature (BT), fall BTA, PC1 (composite temperature index), and day of year (DOY) of spring thermal transition. A change point was detected in 2009 for the length of summer. Earlier change points were identified in some series, but did not occur at the same time in different time series.

When the cut-off length was increased to 10 years (with P=0.10), several changes in timing of change points were seen (shaded plots in Figure 2), but change points were still identified in 2010 for summer BT, fall BTA and PC1. The change point for spring SSTA changed from 2010 to 2008, for spring transition from 2010 to 2009, and for summer length from 2009 to 2008. An additional regime shift was detected in 2011 for spring BTA.

When the P value for significance was reduced to P=0.05 (cut-off length held at 10 yr), the change point identified at 2010 for summer BT was no longer significant (Figure 3). No other changes were seen.

Biological Data

Under the base case scenario, no regime shifts were detected for shrimp recruitment or survival indices (Figure 4). The mean size of presumed age 1.5 shrimp (recruits) showed a possible change point in 2014. The spring and fall PPI indices showed change points in 2000 and 1999, respectively, and potential change points near the end of the time series as well (2015, 2016).

With a cut-off length of 10 years and P=0.10, the only changes from the base case results were a possible regime shift to lower recruitment starting in 2011 (recruitment index estimated using the geostatistical method), and a possible change point in survival (higher) identified in 2015 (Figure 5).

With a cut-off length of 10 years and P=0.05, the possible regime shift in 2011 to lower recruitment was no longer identified (Figure 6). No other changes were seen.

Discussion

Identifying possible regimes is not an exact science. Choice of methods and parameters can affect whether a time period is identified as a regime. In addition, though the STARS method can identify potential change points near the ends of time series, these change points should be viewed as provisional until more years are added.

A regime shift was detected at or near 2010 in several of the temperature time series (spring SSTA, fall BTA, summer shrimp survey BT, PC1, DOY of spring thermal transition, length of summer). It should be noted that PC1 is somewhat redundant with several individual time series, since it is a composite of spring SSTA, spring BTA and fall BTA. The temperature series that did not show a change point near 2010 were winter SST at Boothbay Harbor and spring BTA, which is consistent with other studies showing that the recent warming in the Gulf of Maine has been stronger during summer and fall than winter and spring (Friedland and Hare 2007; Thomas et al. 2017).

For the five shrimp variables, two of the identified change points (in mean size at age 1.5 and early life survival) are very recent and thus bear watching to determine whether a regime shift has occurred. It should be noted that the survival indices (which are ratios of recruitment indices to indices of population fecundity) may not be very meaningful at the low current abundance. The possible regime shift to lower recruitment indices in 2011 was seen under only one set of parameters, so also bears watching.

The results for the spring and fall predation pressure indices suggest a change point near the ends of the time series, which will need to be evaluated as more years of data are added. Overall, the results suggest a shift in temperature regime occurring around 2010, but no clear effect on shrimp as yet.

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Thomas, AC, Pershing, AJ, Friedland, KD, Nye, JA, Mills, KE, Alexander, MA, Record, NR, Weatherbee,R and Elisabeth Henderson, M. 2017. Seasonal trends and phenology shifts in sea surface temperature on the North American northeastern continental shelf. Elem Sci Anth, 5: 48, DOI: https://doi.org/10.1525/elementa.240

Table 1. Temperature-related time series tested for regime shifts. SST=surface temperature, BT=bottom temperature, SSTA=surface temperature anomaly, BTA=bottom temperature anomaly, DOY=day of year. PC1 is composite temperature index from principal components analysis of NEFSC spring SSTA, spring BTA and fall BTA. BBY is Boothbay Harbor daily SST. Spring thermal transition and summer length is for western Gulf of Maine, provided by Kevin Friedland (personal communication).

Year	Temperature PC1	BBY Feb-Mar avg SST	BBY-Jul 15-Sep 1 avg SST	NEFSC Spring SSTA	NEFSC Spring BTA	NEFSC Fall BTA	Shrimp Survey BT	DOY spring thermal transition	Summer length (days)
1984	-0.226	2.9	15.7	-0.1	0.6	0.8	4.1	155	180
1985	-0.628	2.8	16.3	0.1	0.1	0.6	4.0	154	173
1986	0.851	2.6	15.5	0.8	1.2	0.7	6.3	153	161
1987	-1.712	1.8	14.2	-0.6	0.0	0.0	6.0	150	161
1988	-0.460	2.7	15.9	-0.2	1.3	-0.1	6.5	151	159
1989	-2.028	1.9	15.2	-0.6	-0.1	-0.3	5.6	144	176
1990	-1.020	2.6	16.5	0.0	0.2	0.1	3.6	158	156
1991	-0.329	3.4	15.5	0.6	0.5	0.1	6.1	142	169
1992	-1.622	3.2	15.7	-0.9	0.6	-0.2	6.3	158	144
1993	-2.657	1.2	15.6	-0.7	-0.8	-0.3	5.8	158	149
1994	0.396	1.8	17.4	0.2	0.6	1.3	6.8	157	166
1995	-0.154	3.3	16.4	0.1	0.8	0.5	6.6	156	166
1996	0.252	3.3	15.9	-0.2	1.0	1.1	7.1	151	162
1997	0.245	3.7	16.0	0.0	1.4	0.5	6.8	157	159
1998	-0.167	2.9	16.4	0.5	1.3	-0.4	6.3	146	160
1999	0.135	2.9	16.9	0.9	0.3	0.6	6.1	144	177
2000	0.847	3.1	18.0	0.9	1.1	0.7	6.7	150	175
2001	-0.322	2.9	17.8	0.4	0.7	0.1	6.5	153	167
2002	1.707	4.1	19.2	1.2	1.3	1.3	7.1	154	170
2003	-1.949	2.4	18.2	-0.6	-0.2	-0.1	5.6	160	159
2004	-3.441	3.0	19.0	-0.9	-0.8	-1.1	4.7	160	151
2005	-0.632	3.0	19.7	0.2	0.1	0.5	4.9	157	163
2006	1.401	5.5	20.2	0.9	1.3	1.2	7.1	147	170
2007	-1.099	2.0	17.9	0.0	0.5	-0.3	5.9	149	164
2008	0.362	2.3	18.0	1.2	0.5	0.4	5.9	150	174
2009	-0.085	2.6	17.2	0.4	0.4	0.7	6.0	147	182
2010	2.085	4.1	17.9	1.7	0.9	1.7	7.4	140	186
2011	2.350	2.9	18.2	0.9	2.3	1.4	7.7	147	189
2012	3.344	5.5	18.3	1.9	2.0	2.0	7.9	136	207
2013	2.082	3.9	16.2	1.8	1.3	1.2	7.1	133	192
2014	0.623	2.2	16.4	0.5	0.5	1.4	6.2	141	193
2015	-0.866	1.4	17.3	0.1	0.1	0.3	5.8	145	194
2016	2.718	4.1	17.8	1.7	1.4		7.2	143	199
2017		3.8	16.3						

Table 2. Time series of biological data tested for regime shifts.

Year	Recruitment index	Geostatistical recruit index ('000)	Recruit average size (mm CL)	Transitional mean size (mm CL)	Survival-Recruits per million eggs (YC)	Fall Predation Pressure Index	Spring Predation Pressure Index
1984	18.4	0.016	15.1			475	286
1985	332.2	0.246	15.8	21.61	496	629	810
1986	358.1	0.243	15.3	23.36	287	622	420
1987	342.0	0.189	15.4	20.62	559	417	338
1988	827.9	0.826	16.3	24.27	222	538	269
1989	276.3	0.175	15.9	20.48	274	573	292
1990	141.7	0.090	15.6	20.63	476	665	231
1991	482.1	0.288	16.1	22.02	226	517	253
1992	281.6	0.143	16.2	20.20	565	489	413
1993	756.6	0.733	15.5	19.89	431	534	267
1994	368.1	0.397	16.4	20.13	664	510	227
1995	292.1	0.186	14.7	20.65	506	805	223
1996	231.9	0.257	15.9	21.66	294	561	243
1997	373.8	0.438	15.3	21.64	212	567	533
1998	134.0	0.153	15.9	19.51	239	492	303
1999	113.7	0.174	16.0	20.64	1294	802	437
2000	450.3	0.460	16.0	19.63	57	1101	904
2001	17.6	0.010	15.1	18.55	1992	776	559
2002	1164.5	0.808	16.7	17.99	35	1688	576
2003	10.7	0.014	15.3	17.90	527	1136	706
2004	286.4	0.354	15.8	19.87	5155	625	504
2005	1752.5	1.134	15.5	18.71	589	856	529
2006	374.3	0.146	15.2	18.78	15	1185	209
2007	28.3	0.049	15.3	19.87	91	1161	691
2008	505.7	0.444	16.3	21.38	828	919	731
2009	554.5	0.580	15.5	21.57	391	1167	275
2010	474.7	0.522	16.3	20.88	34	1268	632
2011	43.7	0.047	15.2	20.11	8	1267	782
2012	6.7	0.014	14.6	19.59	2	1118	804
2013	0.9	0.002	15.0	19.44	779	888	406
2014	116.2	0.201	17.4	20.92	17	1005	613
2015	2.7	0.003	16.4	19.25	5291	890	960
2016	225.8	0.190	16.7	18.78	16	1913	1207
2017	1.2		17.2	19.15			932

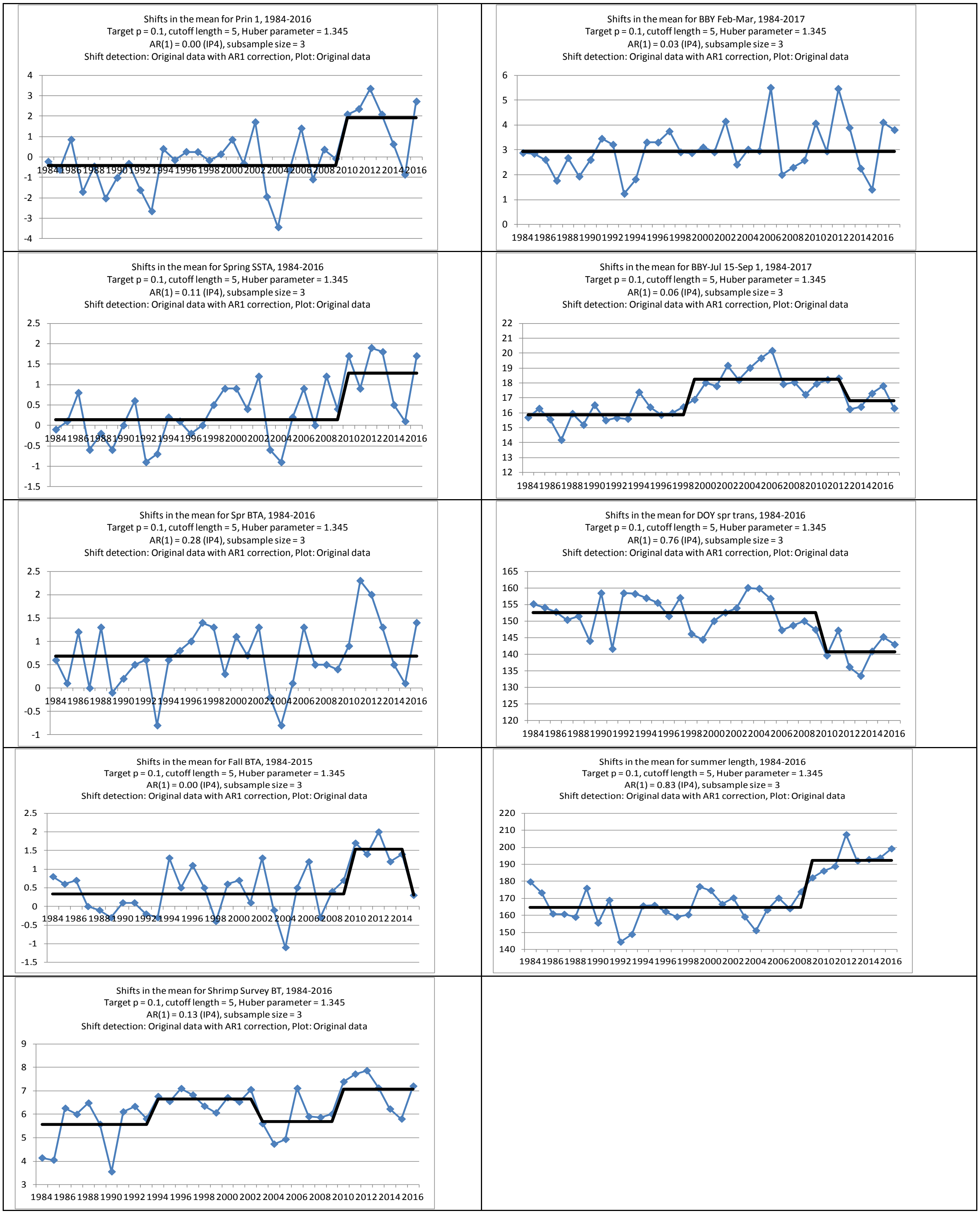


Figure 1. Shift detection results for temperature data. Blue lines represent original data, black line indicates mean for ‘regimes’ detected using 5-year windows, Huber’s weight=1.345 and P=0.10 for detecting significance.

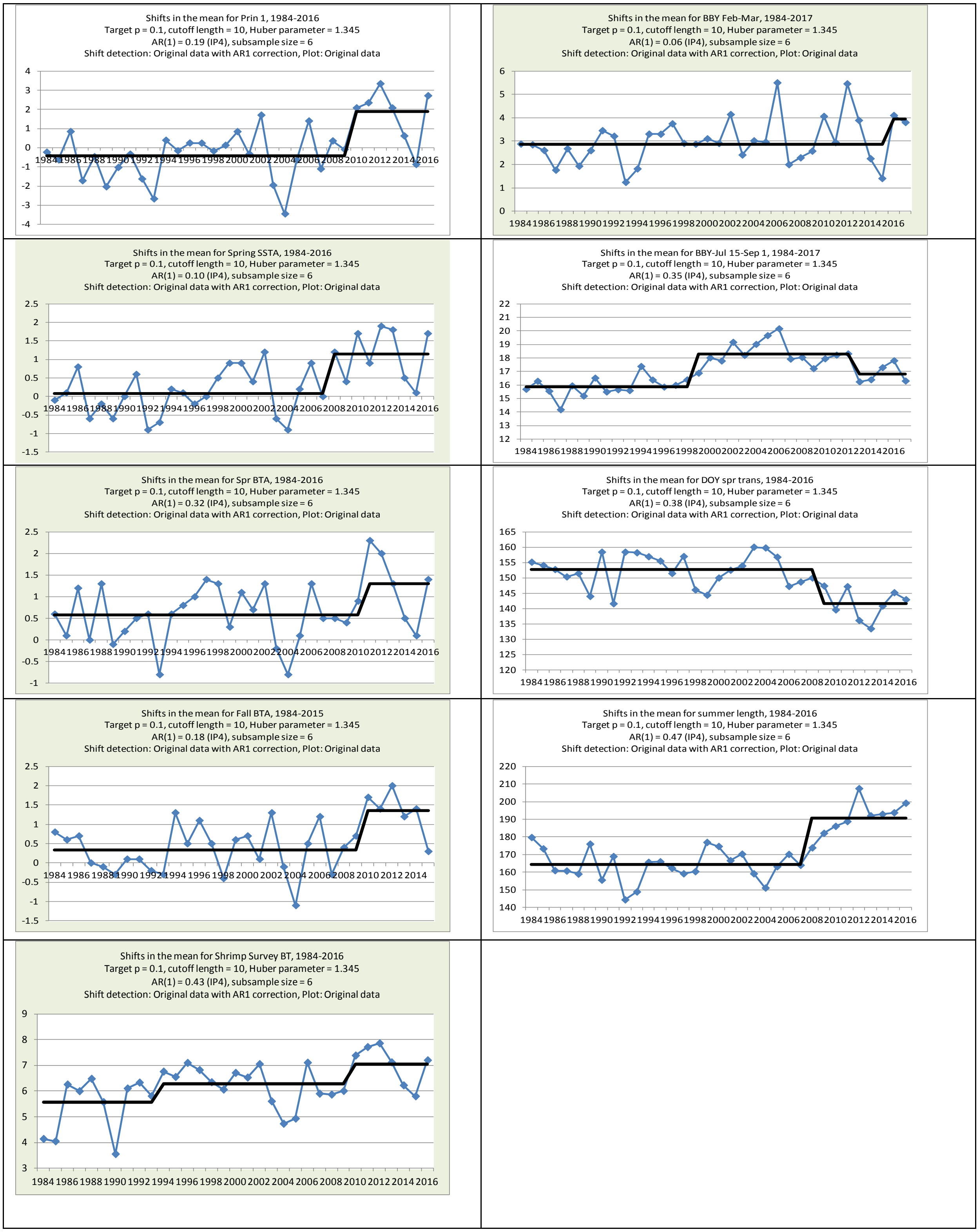


Figure 2. Shift detection results for temperature data. Blue lines represent original data, black line indicates mean for ‘regimes’ detected using 10-year windows, Huber’s weight=1.345 and P=0.10 for detecting significance. Green shaded charts are series that have different regimes identified than the runs in Figure 1 (due to changing from 5-year to 10-year windows).

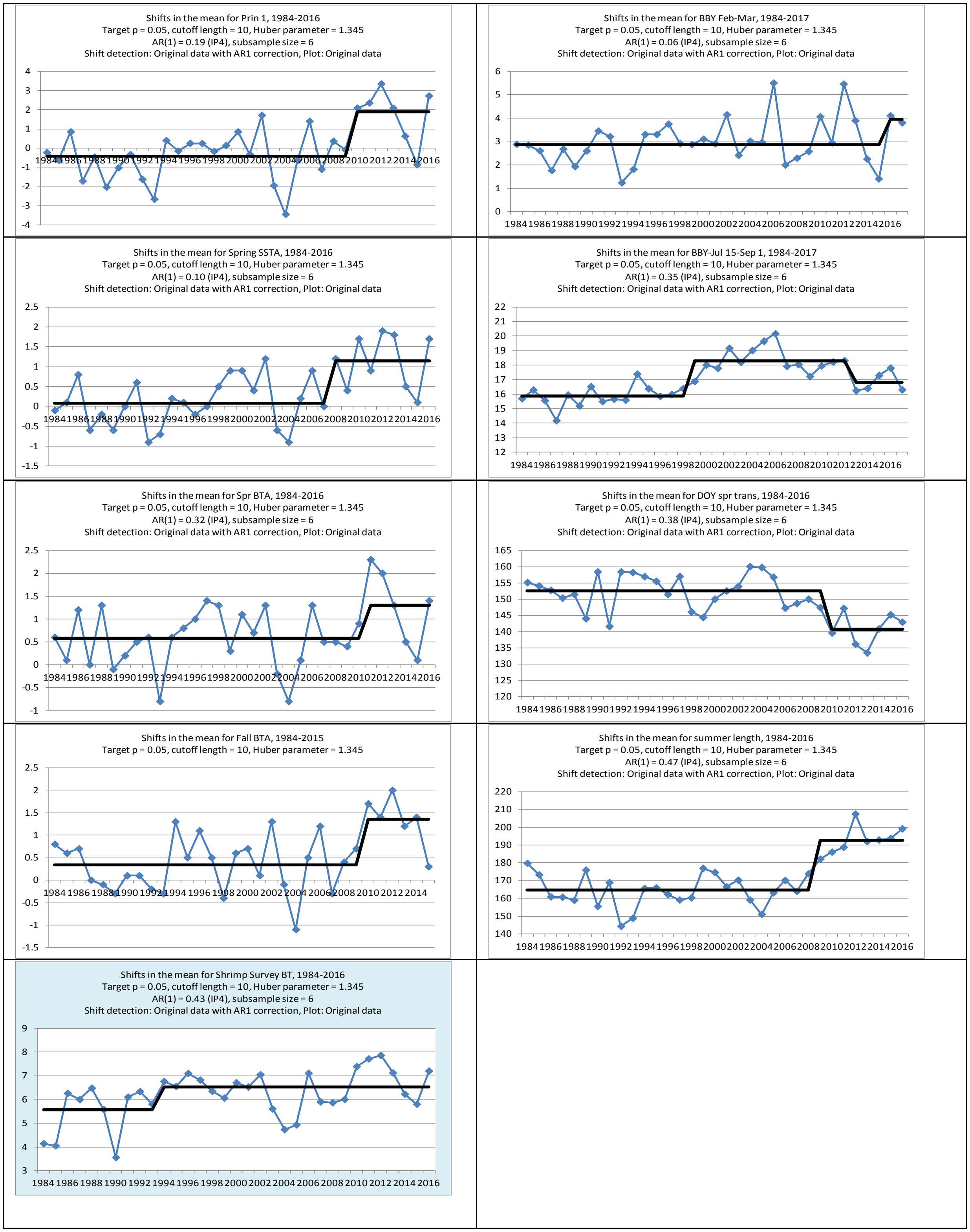


Figure 3. Shift detection results for temperature data. Blue lines represent original data, black line indicates mean for ‘regimes’ detected using 10-year windows, Huber’s weight=1.345 and P=0.05 for detecting significance. Blue shaded chart is series that has different regimes identified than the runs in Figure 3 (due to changing P value from 0.10 to 0.05).

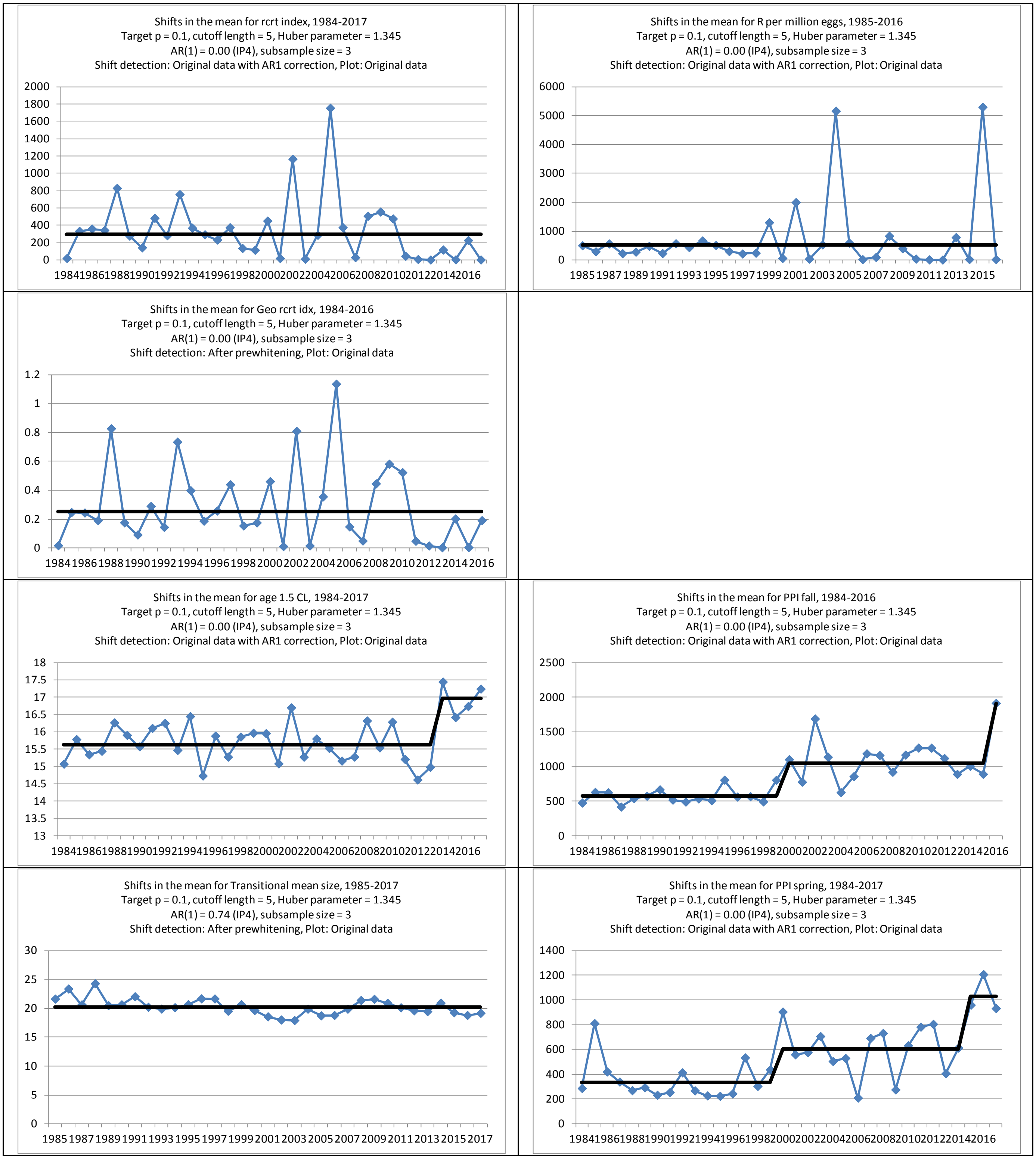


Figure 4. Shift detection results for biological data. Blue lines represent original data, black line indicates mean for ‘regimes’ detected using 5-year windows, Huber’s weight=1.345 and P=0.10 for detecting significance.

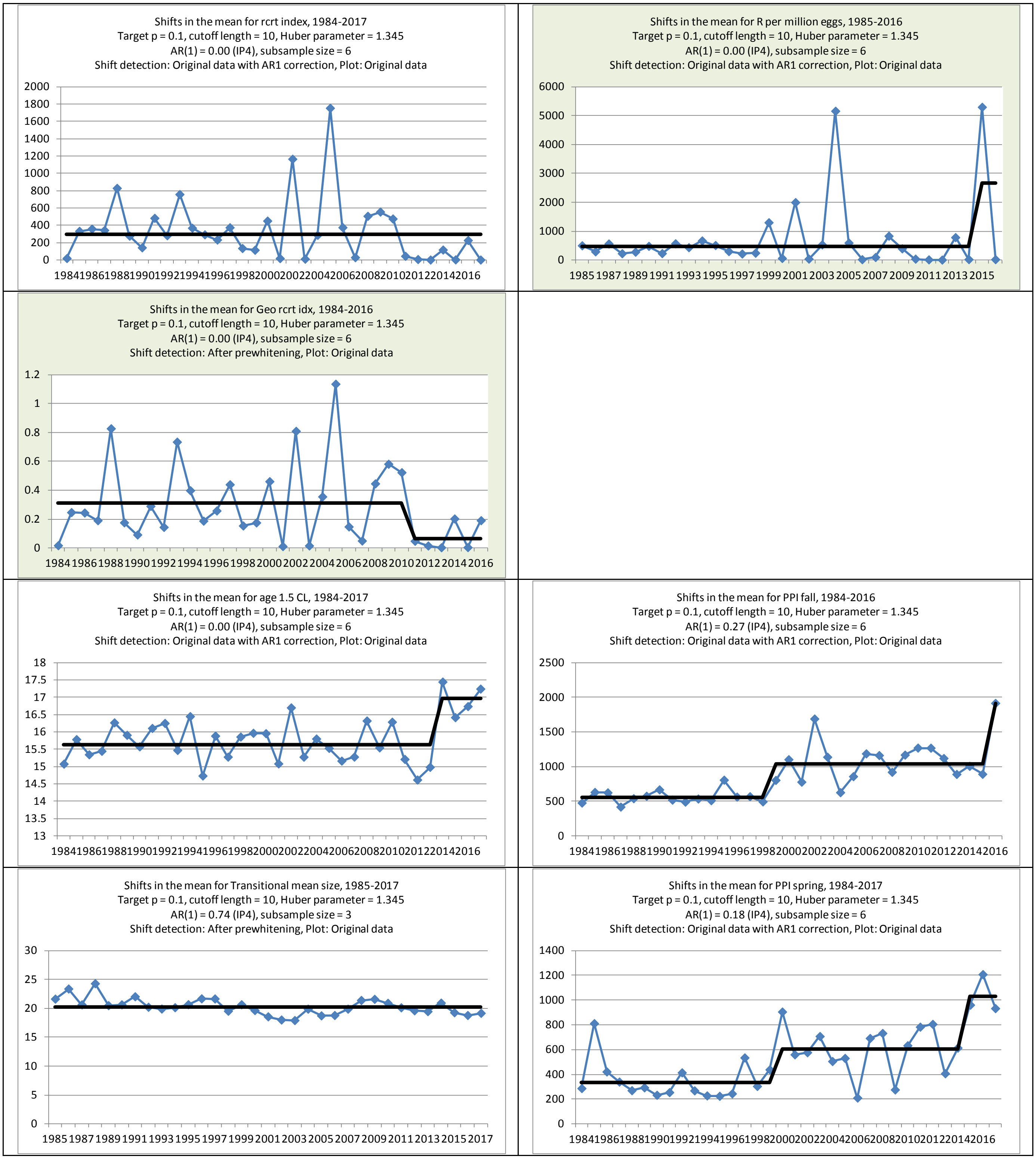


Figure 5. Shift detection results for biological data. Blue lines represent original data, black line indicates mean for ‘regimes’ detected using 10-year windows, Huber’s weight=1.345 and P=0.10 for detecting significance. Green shaded charts are series that have different regimes identified than the runs in Figure 4 (due to changing from 5-year to 10-year windows).

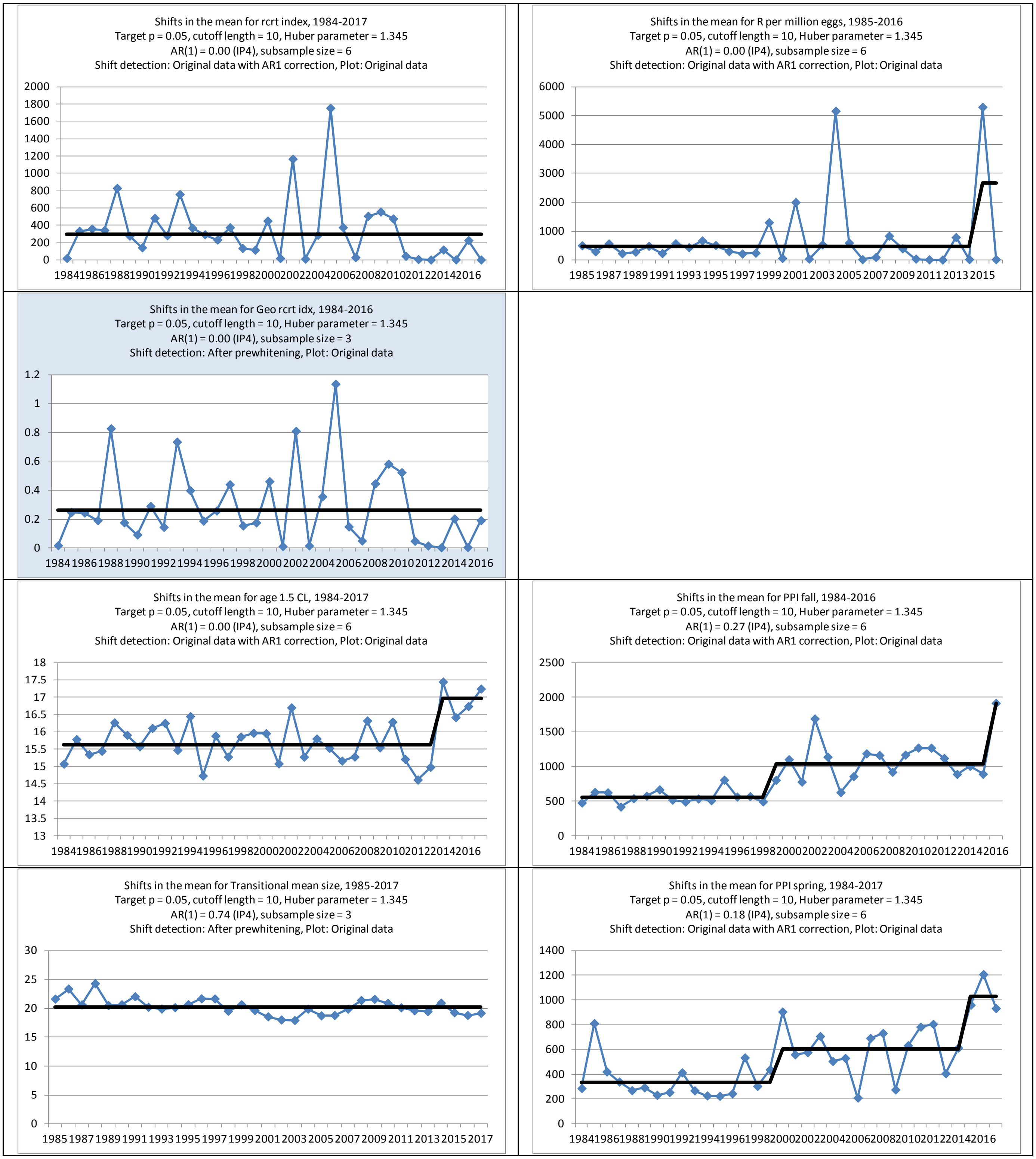


Figure 6. Shift detection results for biological data. Blue lines represent original data, black line indicates mean for 'regimes' detected using 10-year windows, Huber's weight=1.345 and P=0.05 for detecting significance.

APPENDIX 2. Preliminary Results from NEFSC/ASMFC Summer Shrimp Survey Door Calibration aboard the RV Gloria Michelle, July 2017

The first week of the 2017 NEFSC/ASMFC summer shrimp survey (July 9-13) aboard the *RV Gloria Michelle* was dedicated to performing comparison tows between the standard ("old") 350KG Portuguese doors and new Bison size 7+ doors. Non-random station locations were selected based on historical survey tows (Figure 3). Each plotted station was sampled once with each door type to obtain catch comparison data. All operational protocols were the same as for the regular survey. Results are plotted below (Figures 1-2). The new Bison doors were used for the rest of the 2017 survey. More calibrations tows are planned for 2018.

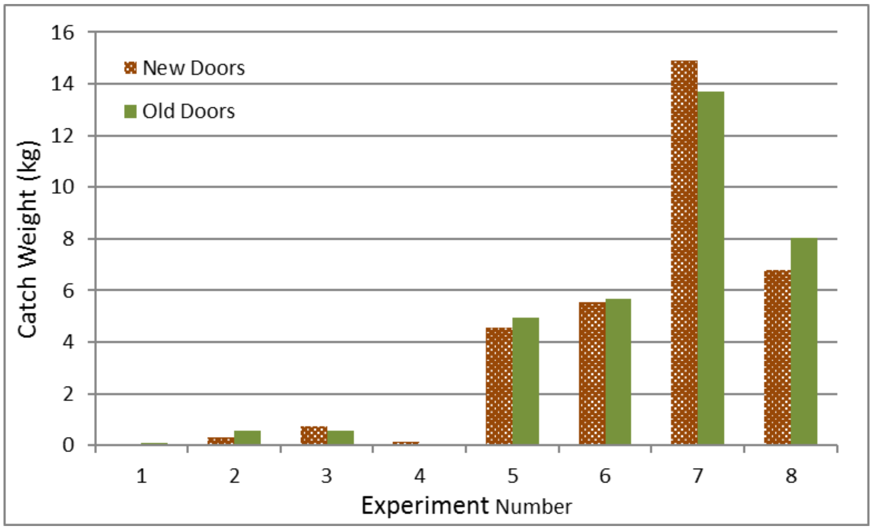


Figure 1. Northern shrimp catch (kg/tow) for the eight paired calibration tows.

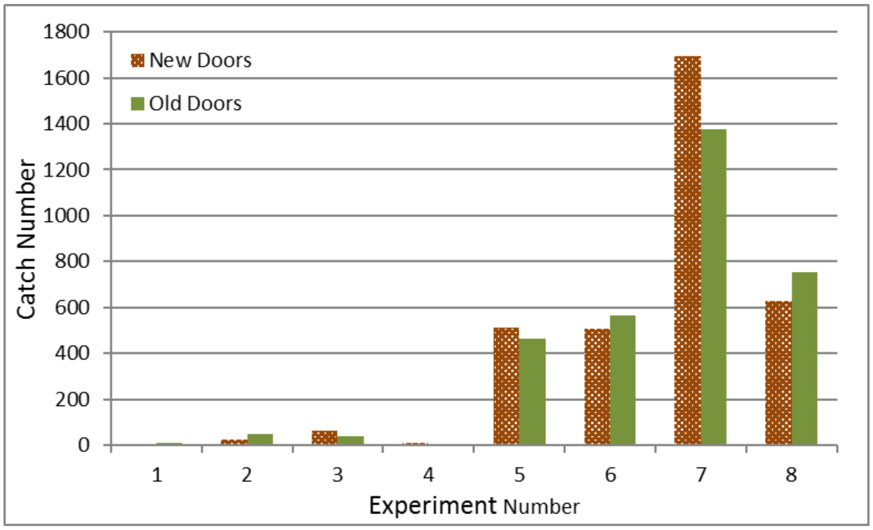


Figure 2. Northern shrimp catch (numbers/tow) for the eight paired calibration tows.

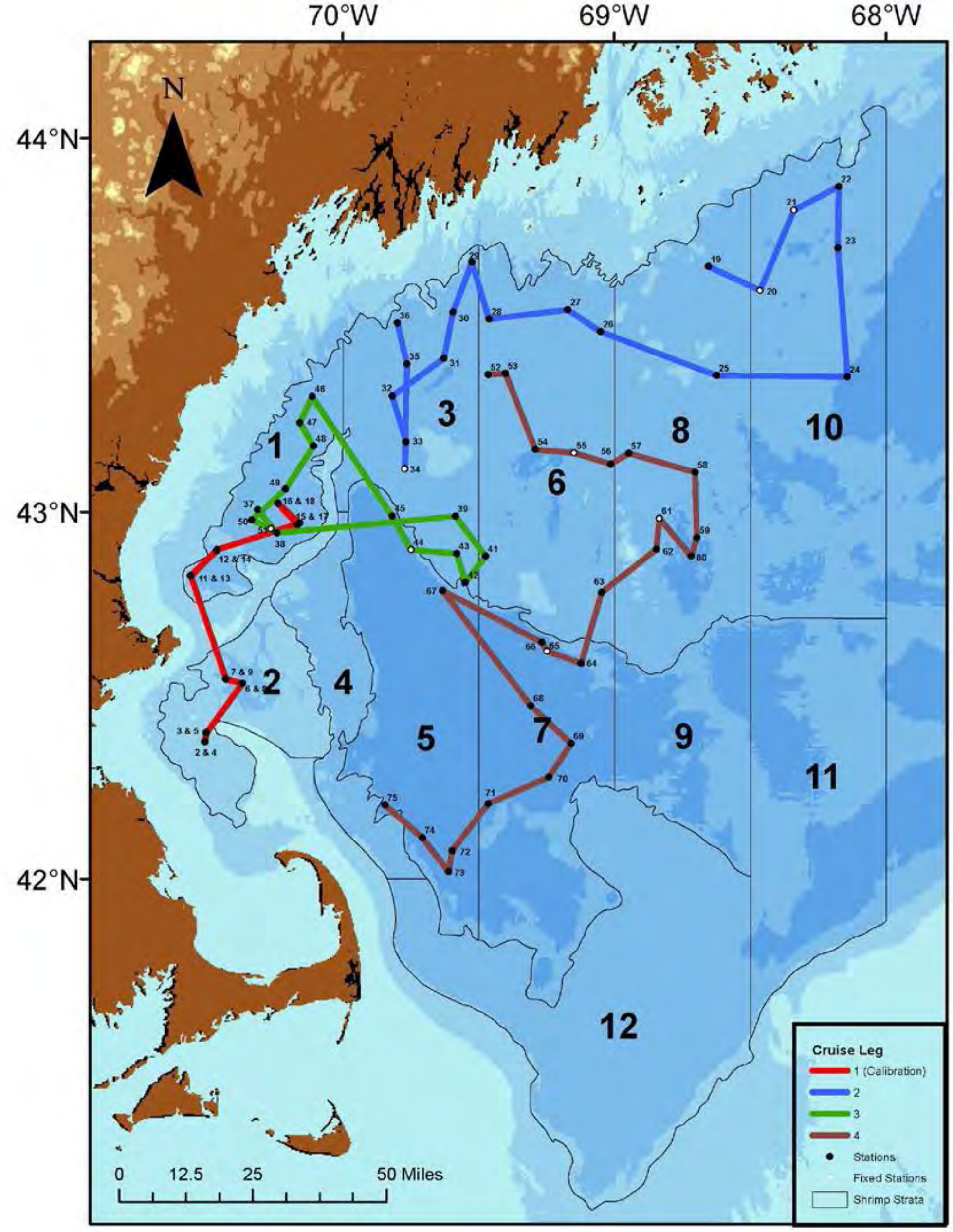


Figure 3. **Trawl hauls made during the 2017 NEFSC/ASMFC northern shrimp survey and trawl door calibration (red track in regions 1 and 2) in the Gulf of Maine aboard FRV *Gloria Michelle*, July-August 2017.**

Atlantic States Marine Fisheries Commission

Addendum to the Northern Shrimp Benchmark Stock Assessment Report

October 2018

Purpose

At the Northern Shrimp Peer Review Workshop, a panel of independent experts reviewed the benchmark stock assessment of northern shrimp, prepared by the ASMFC Northern Shrimp Technical Committee (NSTC) and Stock Assessment Subcommittee. This addendum describes the revision that was made to the base run of the stock assessment as recommended by the peer review panel at the Review Workshop, and presents the results of the new base run of the assessment. To gain a full understanding of the stock assessment, the reader should also examine the original Stock Assessment Report and the Review Panel Report.

Revision and justification

The review panel felt that the choice of size-varying natural mortality with higher values at the smallest and largest sizes ("U-shaped M") for northern shrimp was not justified well enough for management use, and instead recommended the use of the Lorenzen method to calculate M (Lorenzen, 1996). Sensitivity runs exploring the Lorenzen M were not included in the original stock assessment report, but had been conducted and were available to be reviewed by the panel at the Review Workshop.

In addition, based on discussions with the panel about the correlation in some of the length composition residuals, the effective sample size (ESS) of the commercial fleet was reduced and recalculated to reflect the proportion of total trips sampled, rather than the total number of trips. This did not significantly impact the fit or the output of the model, but improved some of the convergence properties for the retrospective analysis and sensitivity runs.

See the Review Panel Report for full justification and discussion.

Results

Lorenzen M

The Lorenzen (1996) method calculates a length-varying natural mortality based on the weight of each length class, with smaller sizes having a higher M than larger sizes. The Lorenzen estimates of M were scaled to account for the lifespan of northern shrimp, so that approximately 1.5% of the unexploited population would be left at age 6. This results in an estimate of M-at-length that is lower than the U-shaped M for the smallest and largest sizes, and higher than the U-shaped M for the majority of the exploited population (Figure A1).

As in the original base model, the length-varying M was scaled by an annual Predation Pressure Index (PPI) so that M was both length- and time-varying (Figure A2).

Goodness of Fit

The model was able to fit the length-composition data relatively well for both the indices (Figures A3 – A5) and the catch (Figures A6 – A9), fitting both the broader size range of the survey length composition and the narrower distribution of the catch composition. As with the original base case, in some years, the predicted peak of the length frequency was in the right place, but was smaller than the observed peak (e.g, 1984, 1988, 1989, 1993; Figure A3). In other years, the model predicted a larger proportion of small shrimp than were observed (e.g., 2006, 2013, 2015, 2017; Figure A3), suggesting either an overestimate of recruitment, or slower growth in subsequent years than calculated by the model. Smaller than expected numbers of small shrimp could also be due to management and/or market limitations on the fishing season in some years to months when small shrimp are less likely to be caught. In both the trap and trawl fleet, the length composition of the research fishery years (2014 – 2017) were fit less well than the other years, reflecting the smaller number of trips that made the length comps more variable (Figure A7 and A8).

The model fit the total annual indices well, with more patterning in the residuals in the NEFSC Fall Trawl survey than in the ASMFC summer survey (Figures A10 and A11). The model still struggled to fit the extremely high value in 2006. Overall, the model fit the total catch well, although it underestimated the peak catches in the late 1990s, prior to a steep decline into the early 2000s (Figures A12). There was some slight patterning in the residuals by fleet, with two or three years of positive residuals followed by two or three years of negative residuals before reversing again (Figure A13).

The retrospective pattern was minimal. The time series of exploitation rates were slightly lower than the run with the 2017 terminal year, (Figure A14; Mohn's rho=0.044) and the time series of SSB and recruitment were slightly higher (Figure A15 and Figure A16; Mohn's rho=0.057 for SSB and -0.04 for recruitment). The terminal year estimates of each time series were not consistently above or below the equivalent 2017 estimate.

Growth matrices and selectivity

The estimated growth transition matrix produced distributions of size-at-age that were consistent with published growth curves (Figure A17). The fleet selectivity curves were shifted further to the right than has been traditionally assumed for the mixed fleet and the open fishery trawl fleet, while the trap fleet reached full selectivity sooner than the other two fleets (Figure A18). Both the trawl and trap fleets had a higher selectivity on smaller shrimp in the research time block (2014 - 2017) than in the open fishery (2000-2013) (Figure A18). The estimated selectivity of the ASMFC summer survey and the NEFSC Fall Trawl were similar for the Bigelow years (2009 – 2017), but the NEFSC Fall Trawl was shifted further to the right than the ASMFC summer survey during the Albatross years (Figure A19).

Spawning stock biomass, F, and recruitment

Spawning stock biomass is at extremely low levels and has been since 2013 (Table A1, Figure A20). SSB in 2017 was estimated at 752 mt, well below the time series mean of 3,600 mt. SSB shows three large peaks over the time series in 1995, 2007, and 2009, ranging from 6,668 – 8,438 mt. There was a decline in SSB after each peak, and after the peaks in 1995 and 2009, the decline continued for 6 or more years afterwards, leading to time series lows.

Fishing mortality has also been at time series lows in recent years (Table A1, Figure A21). Full F for the mixed fleet peaked in 1997 after being relatively stable for 1984-1994; the trawl and trap fleets were more variable from 2000 onward; although the trap F was much lower than the trawl F for the entire time period, both fleets showed a strong peak in 2011-2012. Note that full F is very high for the mixed fleet and the trawl fleet (maxing out at over 7.5 for the trawl fleet); this is due to the selectivity patterns estimated by the model for those fleets that have lower selectivity on most of the size classes that are exploited by the fishery. An average F for the population was calculated to account for differences in selectivity patterns; the numbers-weighted average F on shrimp ≥22 mm carapace length peaked in 2011 and 2012 before dropping to 0.025 in 2017, well below the time series mean of 0.42 (Table A1, Figure A22). This is a function of the fishery closure implemented in 2014.

Recruitment has also been low in recent years, with recruitment in 2017 estimated at 1.13 billion shrimp (Table A1, Figure A23). The median of the time series is 2.63 billion shrimp. The 2015 year class was above average, but the 2011, 2014, 2016, and 2012 year classes were the lowest on record. Variability in recruitment has increased since 2000, with higher highs and lower lows in recruitment deviations than 1984-1999 (Figure A23). The highest year class on record is the 2001 year class at 35.4 billion recruits, more than twice as much as the next highest value (the 2006 year class), but not as extreme as the 2001 value predicted by the original base run of the model.

Comparison with original base run

Using the Lorenzen M did not have a significant effect on the magnitude or trend of the population estimates compared to the original base case. Spawning stock biomass was estimated to be slightly higher at the beginning of the time series and slightly lower at the end of the time series in the original base run, but the differences were negligible (Figure A24). Recruitment estimates were lower across the time-series for the new base run, due to the fact that the Lorenzen estimates of M for the smallest size classes were lower than estimates for the U-shaped M. However, both runs identified the same strong and weak year classes, and both showed the same pattern of increasing variability from the year 2000 onwards. Estimates of average F were generally similar under the new base case across the time-series, with some years slightly higher and some years slightly lower. Both runs showed that average F has been very low in recent years.

Comparison with ASAP and CSA model runs

The base case of the ASAP model was also re-run with the Lorenzen M instead of the U-shaped M for comparison with the new runs of the UME model. The CSA does not use a length-varying M, so the base case for that model remained the same. It’s difficult to make direct comparisons across models, because each model has a different structure and defines quantities such as recruitment, biomass, and fishing mortality slightly differently. However, overall, all three models produce similar results in terms of both trends and magnitude (Figure A25 and A26). The new ASAP run estimated higher fishing mortality across the time series compared to the other two models and to the original ASAP run, but agreed with the other two models that F has been very low since the moratorium (Figure A25). The new ASAP run estimated lower recruitment across the time series than the original base run and the UME model; both ASAP and the UME model estimated higher recruitment than the CSA, which is to be expected because the CSA defines recruits as shrimp that will enter the fishery that year, instead of Age-1 shrimp (ASAP) or 10-12mm shrimp (UME model) (Figure A25). ASAP and the UME model both start December 1st; comparing the winter abundance for these models shows very similar trends, although the UME is generally higher, reflecting the higher recruitment estimates from the UME model (Figure A26). The CSA model starts July 1st; the summer abundance estimates from the UME model (shrimp ≥ 16mm carapace length at the start of season 2) are more comparable to the total abundance estimates from the CSA model, and show very similar trends and magnitudes (Figure A26).

The fact that all three models with different assumptions and model structures show similar results provided more confidence in the results of the UME model.

Sensitivity Runs: M

The base model used a size- and time-varying estimate of M. As a sensitivity analysis, the NSTC looked at the effects of using a length-constant and time-varying estimate of M (M=0.5 and M=0.95, scaled by the PPI), a length-varying and time-constant estimate of M, and a length and time constant estimate of M (M=0.5).

Overall, trends in recruitment, SSB, and average F were similar across the different M parameterizations, but there were differences in scale (Figures A27-A30). Unsurprisingly, length-varying estimates of M resulted in higher estimates of recruitment, since M on smaller, younger shrimp was higher than M on larger shrimp (Figure A27). The predation index used to scale estimates of M in the time-varying scenarios has generally increased over time, and as a result, time-constant M scenarios had higher estimates of recruitment in the early part of the time-series (Figure A27).

Time-constant M scenarios were slightly more optimistic about the level of SSB in the most recent years, showing a recovery to levels around where the stock was in the mid-2000s, while the time-varying M scenarios remained low relative to the rest of the time series and relatively flat (Figure A28). This was true for both the length-constant and length-varying versions of M.

Estimates of average F were more similar across M scenarios, although the estimate of average F from the high M (M=0.95, time-varying) scenario were lower for most of the time-series (Figure A29).

The NSTC chose the length- and time-varying M as the base case because it was more biologically realistic, it improved the fit of the model, and it improved the retrospective pattern (Table A2; Figures A30 and A31). The use of the U-shaped M provided more realistic estimates of selectivity for the mixed fleet and the early part of the trawl fleet, with more smaller shrimp being selected in that scenario than in the length-constant scenarios, where only the largest size classes were strongly selected; the Lorenzen M selectivity pattern was somewhere in between the U-shaped M and the length-constant M in terms of how vulnerable the smaller shrimp were to the fishery (Figure A32).

Sensitivity Runs: Environmental Deviations and Recruitment

The NSTC explored several ways to incorporate environmental drivers into the assessment. The new base run modeled recruitment as deviations from mean recruitment with no environmental information incorporated. For the sensitivity analysis, runs were also done where recruitment was modeled as deviations from a Beverton and Holt curve, with and without fitting to environmental deviations, and where recruitment was modeled as deviations from mean recruitment with recruitment deviations fit to the environmental index. An attempt to fit a Cushing stock-recruitment curve which incorporates environmental data into the stock-recruitment relationship did not converge.

The results of these sensitivity analyses were comparable to the original base case. Overall, the models fit with environmental data identified the same strong and weak year classes as models fit without environmental data; however, the models that incorporated environmental data estimated higher recruitment for strong year classes and lower recruitment for weak year classes than the models without environmental data (Figure A33). There are some small differences between estimates of SSB between models that do and do not incorporate environmental effects, with a slightly more pronounced effect from 2014-2017, where the base model SSB estimate was approximately 10% higher than the other models (Figure A34). Differences in average F were minimal across the different scenarios (Figure A35). Fitting to the environmental deviations made the retrospective patterns slightly worse, particularly for recruitment and SSB (Figures A36 and A37).

For more discussion of these results, see Section 5.2.3 of the original stock assessment report.

Sensitivity Runs: Index Choices

The new base run of the UME model used the ASMFC summer survey and the NEFSC Fall Trawl Survey. The indices of abundance were calculated using a spatio-temporal standardization process to create model-based indices. For the sensitivity analyses, runs were conducted with the traditional design-based indices for the summer survey and the NEFSC Survey, as well as with the ME-NH Inshore Trawl Survey included, and with the summer survey only.

The design-based indices resulted in slightly lower estimates of recruitment for some of the stronger year classes, but otherwise showed similar trends (Figure A38). The design-based indices resulted in slightly higher estimates of SSB at the beginning of the time-series and lower estimates of SSB from 2012-2017 compared to the model-based indices (Figure A39). Estimates of average F were very similar across all scenarios (Figure A40). Adding and removing indices did not have a strong effect on the trends or magnitude of the population estimates, indicating all three indices are providing similar information.

The design-based indices were fit less well than the model-based indices, resulting in a higher log-likelihood (Table A2). The design-based indices also resulted in a slightly worse retrospective pattern compared to the base run, as did the addition of the ME-NH Inshore Survey (Figures A41 and A42).

Sensitivity Runs: Growth Blocks

The new base run of the UME model estimated two growth matrices, one for each season. To look at potential differences in growth from year to year, model runs that fit four sets of growth matrices were conducted, one for each season and growth block combination. Growth blocks were identified in three different ways: warm and cold years, based on seasonal temperature anomalies from the NEFSC trawl surveys; above or below average size-at-age years from the ASMFC summer survey data (see Section 4.3 of the original stock assessment report); and a regime change with a pre- and post-2000 set of seasonal growth matrices.

There were not large differences in recruitment among the different growth models (Figure A43).The parameterization that had the largest effect on estimates of SSB and average F was the regime change, with lower estimates of SSB and higher estimates of F prior to 2000 compared to the other model configurations (Figures A44 and A45). Two growth blocks did reduce the log-likelihood of the model (Table A2), but showed worse retrospective patterns, possibly related to difficulties in estimating multiple growth models (Figures A46 and A47). The model estimated slower growth in cooler years, years after 2000, and years where the size-at-age was above average (Figure A48).

Biological Reference Points and Stock Status

The use of the Lorenzen M in the base case did not change the NSTC's conclusion that model-based or historical reference points that rely on an assumption of equilibrium conditions are inappropriate for the northern shrimp stock at this point. The NSTC recommended adopting a projection-based approach to determine allowable levels of harvest.

A length-based projection model in R was developed to project the population forward under various scenarios about recruitment, M, and F. The projection was repeated 1,000 times with stochastic draws of recruitment, initial abundance-at-size for non-recruits, and fishery selectivity parameters. Recruitment was drawn from a log-normal distribution with a mean equal to recruitment from 2013-2017 (Figure A49). As a sensitivity analysis, a run was also conducted with recruitment drawn from a log-normal distribution with a mean equal to the time-series average of recruitment (Figure A49). The population was projected forward under no F for 50 years to see where the population would stabilize under different conditions. This was done with an M equal to the time-series average, and with an M equal to the average of the last 5 years (Figure A49).

To develop catch recommendations, the population was projected forward 3 years, and the probability that SSB was above 2017 SSB was calculated. The allocation of F between the trap and trawl fisheries was set using the ratio catch for each fleet over the last 3 years of the open fishery (2011-2013); trap catch was 12% of trawl catch over that time period.

The assumptions about M and recruitment had the largest effects on the projection trajectories under no fishing (Figure A50). Projections conducted with M equal to the time series mean and recruitment drawn from the 2011-2017 mean indicated the population would grow under no fishing pressure and SSB would stabilize around 2,915 mt, less than the “stable period” mean (1985-1994) of 3,889 mt, but more than triple the 2017 estimate of 752 mt. Using the time-series mean of recruitment resulted in an estimate of long-term SSB greater than the “stable period” mean, at 6,717 mt. However, under higher natural mortality scenarios, with M equal to the average of the last five years, the population did not recover, stabilizing at around 720 mt, slightly lower than 2017 SSB.

With short term projections, the M and recruitment scenarios had an impact on the effect of different F levels (Figure A51). For the high, recent M scenarios, even low levels of harvest (F=0 or F=status quo) caused a decline in SSB, regardless of the recruitment scenario. For the time-series average M scenarios, higher levels of harvest caused the population to decline from 2018 to 2019, but most harvest scenarios had a greater than 50% chance of being above SSB_{2017} in 2020 (Figure A52). Under the high M scenario with recent levels of recruitment, the chance of being above SSB_{2017} levels in 2020 was only 6% even under no fishing (Table A3, Figure A52).

Overall, the northern shrimp stock in the Gulf of Maine is depleted relative to the stable period mean. Low recruitment and high natural mortality hinder stock recovery. Projections suggest the stock could recover to moderate levels under current recruitment levels, but not if natural mortality remains high. If M continues to increase, the likelihood of recovery is extremely low, even in the absence of fishing, although fishing would hasten the decline.

Table A1. Population estimates from the new base run of the UME model.

Year	Average F (N-Weighted)	Recruitment (Billions of shrimp)	Total Abundance (Billions of shrimp)	Spawning Stock Biomass (mt)	Total Biomass (mt)
1984	0.35	2.14	6,309	4,364	18,028
1985	0.25	3.22	6,554	3,549	21,244
1986	0.33	2.29	5,039	4,437	18,753
1987	0.61	2.20	4,251	4,338	15,036
1988	0.30	5.87	8,039	3,713	16,770
1989	0.36	2.04	5,664	4,928	18,378
1990	0.40	1.65	4,324	2,909	17,476
1991	0.46	2.58	4,282	3,369	13,540
1992	0.52	1.96	3,852	4,067	11,988
1993	0.32	6.37	8,158	3,270	14,860
1994	0.31	3.05	6,869	4,405	18,738
1995	0.37	2.67	6,720	6,668	24,104
1996	0.63	1.77	4,412	5,226	18,341
1997	0.91	2.88	4,618	4,018	13,454
1998	0.70	2.03	4,325	3,445	12,494
1999	0.30	1.95	3,986	3,148	12,373
2000	0.83	7.40	8,765	3,031	14,025
2001	0.81	1.65	3,946	1,980	10,398
2002	0.09	35.44	36,826	3,514	34,795
2003	0.52	1.91	6,182	2,080	16,419
2004	0.30	3.77	5,322	1,210	12,048
2005	0.36	12.26	14,723	4,208	21,345
2006	0.22	14.94	21,790	5,606	37,993
2007	0.40	4.38	12,353	8,438	39,626
2008	0.25	8.74	13,370	4,609	35,319
2009	0.16	10.08	13,887	7,201	29,510
2010	0.61	13.91	18,436	5,722	33,641
2011	1.41	2.59	5,811	3,251	17,076
2012	0.91	0.83	1,906	1,495	6,803
2013	0.23	1.30	1,636	790	3,171
2014	0.000	2.92	3,414	986	4,576
2015	0.004	0.98	1,738	858	3,942
2016	0.006	5.84	6,378	814	7,486
2017	0.025	1.13	1,695	752	3,290
Median	0.35	2.63	5,737	3,531	16,595
Mean	**0.42**	**5.14**	**7,811**	**3,600**	**17,560**

Table A2. Likelihood comparisons of sensitivity runs

Model Scenario		**BASE**	**B**	**C**	**D**	**E**	**F**	**G**
Natural mortality assumption	Length-varying	Lorenzen	Lorenzen		Lorenzen		U	
	Time-varying (PPI)	X		X	PPI & temp		X	X
	Base M	0.5	0.5	0.5	0.5	0.5	0.5	0.95
Other adjustment to inputs from BASE		NA	NA	NA	NA	NA	NA	NA
objective function and components	objective function	13,879.10	13,959.30	13,865.70	13,875.60	13,959.10	13,916.50	13,881.20
	catch total	-96.16	-76.13	-94.19	-88.85	-75.05	-95.64	-99.53
	index fit total	58.58	109.81	72.19	31.60	108.92	57.08	55.54
	catch length comp	7,121.30	7,143.90	7,122.06	7,118.41	7,140.13	7,122.87	7,120.09
	index length comp	6,646.53	6,634.86	6,637.35	6,654.44	6,636.32	6,648.44	6,658.39
	recruit deviations	148.88	146.87	128.32	160.04	148.76	183.78	146.74
RMSE	Mixed fleet catch	0.60	2.36	1.06	1.14	2.54	0.47	0.35
	Trawl catch	0.95	1.64	0.77	1.28	1.60	1.12	0.78
	Trap catch	0.02	0.01	0.01	0.04	0.01	0.02	0.03
	Index - Summer Suvey	6.34	8.37	6.89	4.94	8.31	6.10	6.45
	Index - NEFSC	3.36	4.54	3.67	3.12	4.56	3.51	3.02
Terminal year (2017) estimates	SSB (mt)	752.4	2,167.2	1,064.3	673.1	2,156.7	666.3	667.0
	Jan 1 biomass (mt)	3,289.6	6,820.6	2,583.7	3,430.5	4,351.0	3,720.9	4,421.6
	Expl. biomass (mt)	541.5	1,734.5	795.6	411.2	1,781.1	510.9	252.3
	Total stock (millions)	1,694.5	2,839.2	749.2	1,861.9	1,073.7	2,629.0	2,197.1
	Recruits (millions)	1,128.2	1,653.0	297.2	1,272.4	374.2	2,117.7	1,263.5
	F ave N-weighted	0.03	0.01	0.02	0.03	0.01	0.03	0.02
Retrospective Mohn's rho, 5-yr peel to 2013	rho SSB	0.06	0.06	0.04	0.02	0.10	0.06	0.02
	rho recruits	-0.04	0.15	0.04	-0.03	0.17	-0.05	-0.04
	rho F ave N-weighted	0.04	-0.07	-0.03	0.03	-0.08	0.05	0.09

Table A2 (cont.). Likelihood comparisons of sensitivity runs

Model Scenario		**BASE**	**H**	**I**	**J**	**K**
Natural mortality assumption	Length-varying	Lorenzen	Lorenzen	Lorenzen	Lorenzen	Lorenzen
	Time-varying (PPI)	X	X	X	X	X
	Base M	0.5	0.5	0.5	0.5	0.5
Other adjustment to inputs from BASE		NA	Design-based indices	Summer index only	Catch scaled up 25% prior to 2001	Catch CV = 0.05 (CSA)
objective function and components	objective function	13,879.10	14,006.10	11,076.20	13,884.60	13,852.50
	catch total	-96.16	-94.68	-97.97	-93.96	-148.87
	index fit total	58.58	159.53	46.06	65.44	68.60
	catch length comp	7,121.30	7,121.95	7,120.17	7,125.54	7,130.18
	index length comp	6,646.53	6,649.56	3,871.54	6,644.97	6,647.17
	recruit deviations	148.88	169.78	136.41	142.61	155.45
RMSE	Mixed fleet catch	0.60	0.71	0.62	0.88	0.20
	Trawl catch	0.95	1.00	0.72	0.95	0.26
	Trap catch	0.02	0.04	0.02	0.02	0.01
	index - Summer Suvey	6.34	12.77	6.48	6.48	6.67
	index - NEFSC	3.36	2.88		3.65	3.65
Terminal year (2017) estimates	SSB (mt)	752.4	577.1	763.8	831.8	790.5
	Jan 1 biomass (mt)	3,289.6	2,741.0	3,232.4	3,625.6	3,438.3
	Expl. biomass (mt)	541.5	349.3	608.9	601.6	563.9
	Total stock (millions)	1,694.5	1,345.7	1,669.0	1,864.6	1,760.7
	Recruits (millions)	1,128.2	835.5	1,121.6	1,241.0	1,169.7
	F ave N-weighted	0.03	0.03	0.02	0.02	0.02
Retrospective Mohn's rho, 5-yr peel to 2013	rho SSB	0.06	0.07	0.06	0.05	0.03
	rho Recruitment	-0.04	-0.04	-0.07	-0.04	-0.05
	rho F ave N-weighted	0.04	0.04	0.08	0.05	0.04

Table A2 (cont.). Likelihood comparisons of sensitivity runs

Model Scenario		**BASE**	**L**	**M**	**N**	**O**	**P**	**Q**
Natural mortality assumption	Length-varying	Lorenzen	Lorenzen	Lorenzen	Lorenzen	Lorenzen	Lorenzen	Lorenzen
	Time-varying (PPI)	X	X	X	X	X	X	X
	Base M	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Other adjustment to inputs from BASE		NA	2 Growth Regimes, pre/post-2000	2 Growth Regimes, temp based	2 Growth Regimes, size based	Deviations from B-H S-R curve	Env data as recr dev index (mean R)	Env data as recr dev index (B-H R)
objective function and components	objective function	13,879.10	13,851.50	13,863.10	13,860.20	13,874.00	13,678.80	13,677.80
	catch total	-96.16	-95.81	-94.83	-96.39	-96.44	-99.32	-99.22
	index fit total	58.58	54.86	57.40	56.67	51.77	24.63	23.97
	catch length comp	7,121.30	7,123.23	7,116.89	7,108.53	7,125.08	7,120.48	7,120.98
	index length comp	6,646.53	6,618.51	6,629.93	6,637.99	6,643.32	6,609.30	6,608.81
	recruit deviations	148.88	150.77	153.69	153.37	150.27	0.00	0.00
RMSE	Mixed fleet catch	0.60	0.77	0.61	0.52	0.61	0.64	0.65
	Trawl catch	0.95	0.83	1.08	0.99	0.91	0.57	0.58
	Trap catch	0.02	0.03	0.03	0.02	0.02	0.01	0.01
	index - Summer Suvey	6.34	6.35	6.26	6.23	6.08	4.66	4.64
	index - NEFSC	3.36	3.09	3.37	3.35	3.18	2.94	2.92
Terminal year (2017) estimates	SSB (mt)	752.4	738.4	756.6	780.4	665.2	541.3	533.6
	Jan 1 biomass (mt)	3,289.6	3,248.9	3,206.5	3,360.0	2,685.4	2,075.3	2,021.8
	Expl. biomass (mt)	541.5	460.0	554.8	532.7	488.6	422.2	419.0
	Total stock (millions)	1,694.5	1,648.4	1,614.9	1,690.9	1,262.5	588.9	557.6
	Recruits (millions)	1,128.2	1,096.9	1,069.2	1,122.4	781.6	81.2	59.9
	F ave N-weighted	0.03	0.03	0.03	0.02	0.03	0.04	0.04
Retrospective Mohn's rho, 5-yr peel to 2013	rho SSB	0.06	0.07	0.08	0.06	0.06	0.07	0.08
	rho Recruitment	-0.04	-0.01	-0.02	-0.02	0.00	-0.12	-0.10
	rho F ave N-weighted	0.04	0.01	0.03	0.04	0.00	0.06	0.07

Table A3. The TAC and probability of SSB being above SSB$_{2017}$ under different F, M, and recruitment scenarios.

Model	Year	Trawl F	Trap F	Trawl TAC	Trap TAC	p(SSB > SSB 2017)
M=Time series mean, R=Recent	2018	F = 0	F = 0	0 mt (0 lbs)	0 mt (0 lbs)	0%
	2019			0 mt (0 lbs)	0 mt (0 lbs)	100%
	2020			0 mt (0 lbs)	0 mt (0 lbs)	100%
	2018	F = 0.02	F = 0	14.1 mt (31,137 lbs)	1.3 mt (2,867 lbs)	0%
	2019			17.3 mt (38,214 lbs)	1.6 mt (3,564 lbs)	100%
	2020			23.8 mt (52,393 lbs)	2 mt (4,465 lbs)	100%
	2018	F = 0.11	F = 0.01	68.1 mt (150,110 lbs)	6.2 mt (13,766 lbs)	0%
	2019			79 mt (174,266 lbs)	7.3 mt (16,004 lbs)	72%
	2020			107.1 mt (236,197 lbs)	8.9 mt (19,607 lbs)	99%
	2018	F = 0.14	F = 0.02	81.1 mt (178,845 lbs)	7.4 mt (16,262 lbs)	0%
	2019			92.3 mt (203,416 lbs)	8.4 mt (18,511 lbs)	56%
	2020			124.3 mt (273,949 lbs)	10.3 mt (22,703 lbs)	99%
	2018	F = 0.34	F = 0.04	188.3 mt (415,112 lbs)	16.9 mt (37,322 lbs)	0%
	2019			191.2 mt (421,625 lbs)	16.6 mt (36,641 lbs)	1%
	2020			256.8 mt (566,198 lbs)	19 mt (41,919 lbs)	65%
	2018	F = 0.4	F = 0.05	213.5 mt (470,794 lbs)	19.1 mt (42,197 lbs)	0%
	2019			211.5 mt (466,238 lbs)	18.1 mt (39,933 lbs)	0%
	2020			281.4 mt (620,353 lbs)	20.9 mt (46,072 lbs)	52%
M & R =Recent	2018	F = 0	F = 0	0 mt (0 lbs)	0 mt (0 lbs)	0%
	2019			0 mt (0 lbs)	0 mt (0 lbs)	0%
	2020			0 mt (0 lbs)	0 mt (0 lbs)	6%
	2018	F = 0.02	F = 0	13.3 mt (29,390 lbs)	1.2 mt (2,685 lbs)	0%
	2019			12.4 mt (27,264 lbs)	1.2 mt (2,588 lbs)	0%
	2020			12.2 mt (26,823 lbs)	1.1 mt (2,378 lbs)	4%
	2018	F = 0.11	F = 0.01	64.8 mt (142,815 lbs)	5.9 mt (13,041 lbs)	0%
	2019			56.5 mt (124,558 lbs)	5.2 mt (11,542 lbs)	0%
	2020			53.2 mt (117,214 lbs)	4.6 mt (10,188 lbs)	2%
	2018	F = 0.14	F = 0.02	77.4 mt (170,591 lbs)	7 mt (15,400 lbs)	0%
	2019			66.1 mt (145,718 lbs)	6.1 mt (13,523 lbs)	0%
	2020			61.6 mt (135,880 lbs)	5.4 mt (11,985 lbs)	1%
	2018	F = 0.34	F = 0.04	176.9 mt (389,952 lbs)	16.3 mt (36,014 lbs)	0%
	2019			134.7 mt (297,025 lbs)	12.1 mt (26,676 lbs)	0%
	2020			125.1 mt (275,877 lbs)	9.8 mt (21,626 lbs)	0%
	2018	F = 0.4	F = 0.05	204 mt (449,762 lbs)	18.2 mt (40,137 lbs)	0%
	2019			148.6 mt (327,616 lbs)	13.3 mt (29,382 lbs)	0%
	2020			135 mt (297,568 lbs)	10.8 mt (23,743 lbs)	0%

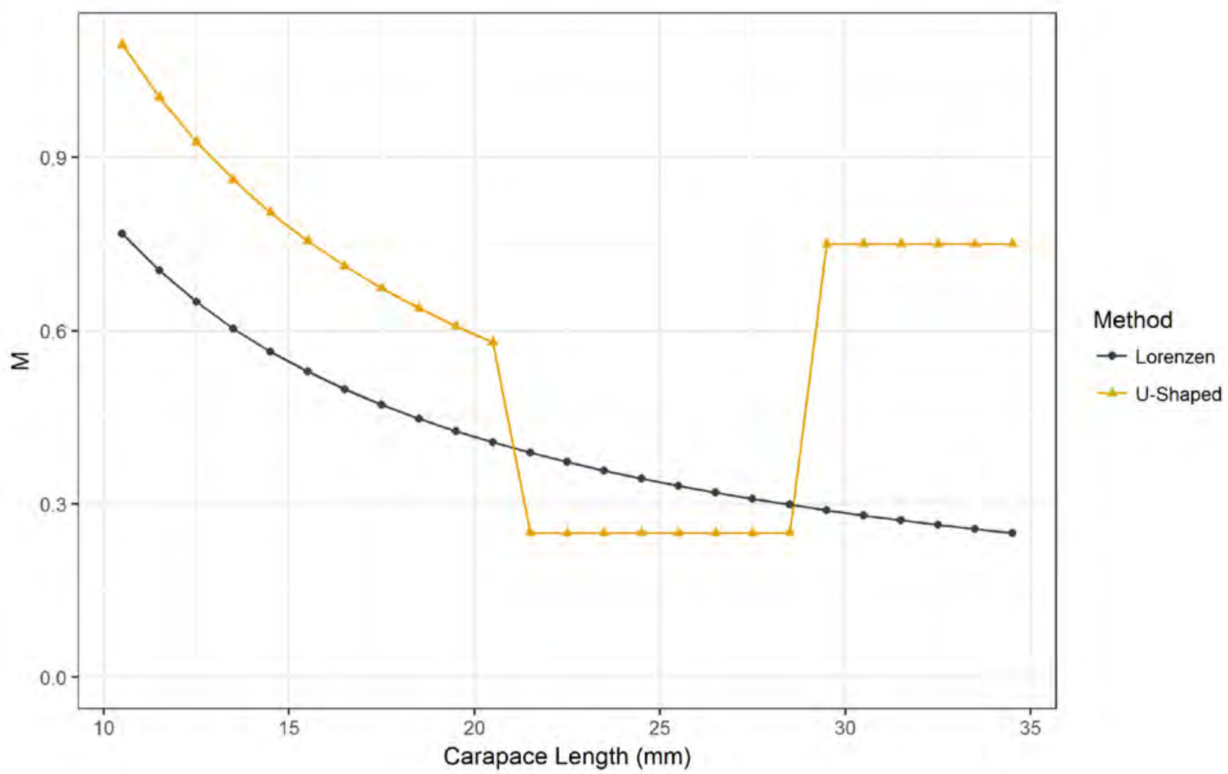


Figure A1. Comparison of U-shaped and Lorenzen estimates of M-at-length (unscaled by PPI).

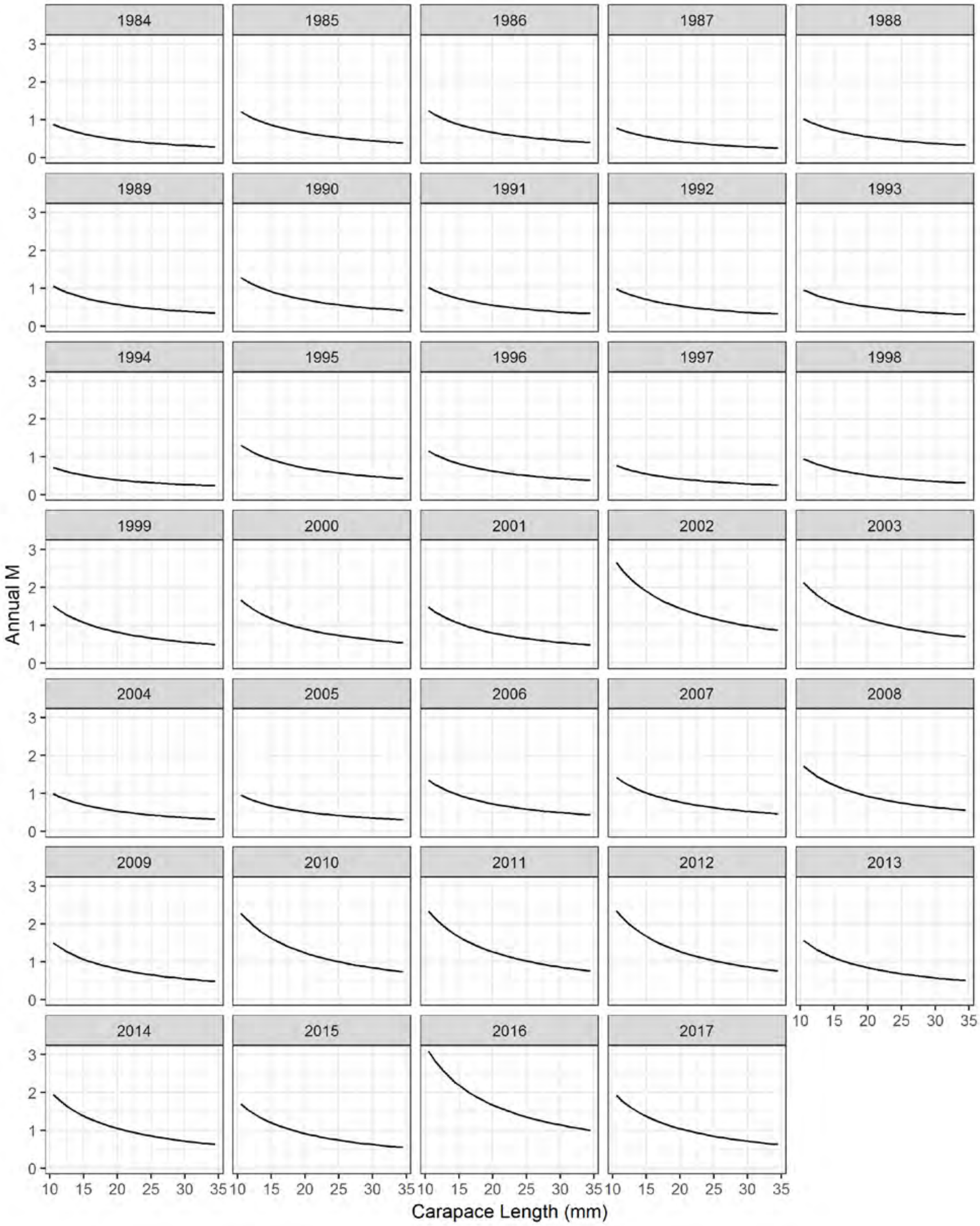


Figure A2. Annual Lorenzen estimates of M-at-length, scaled by the PPI, used in the new base case.

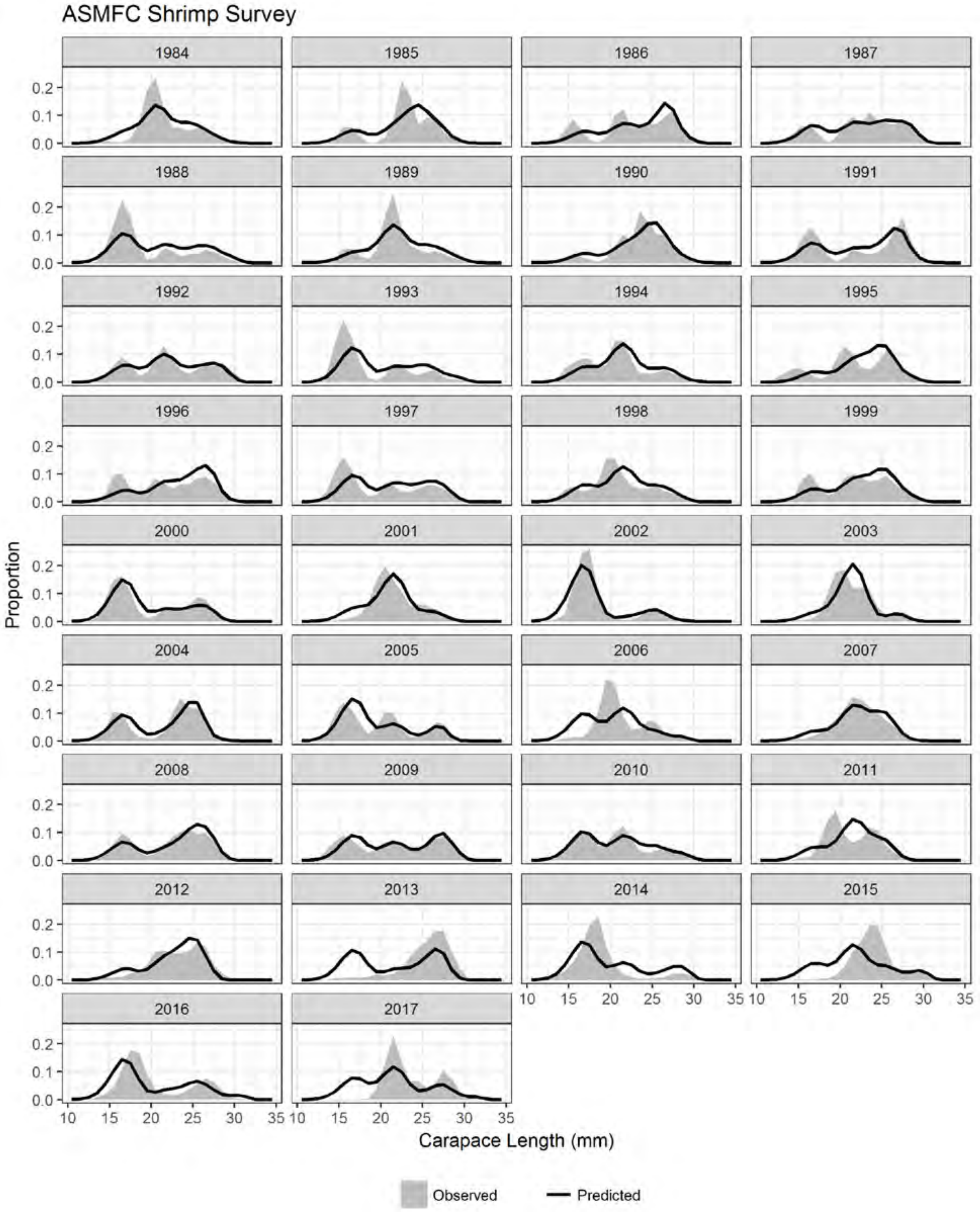


Figure A3. Observed and predicted length composition from the ASMFC Shrimp Survey.

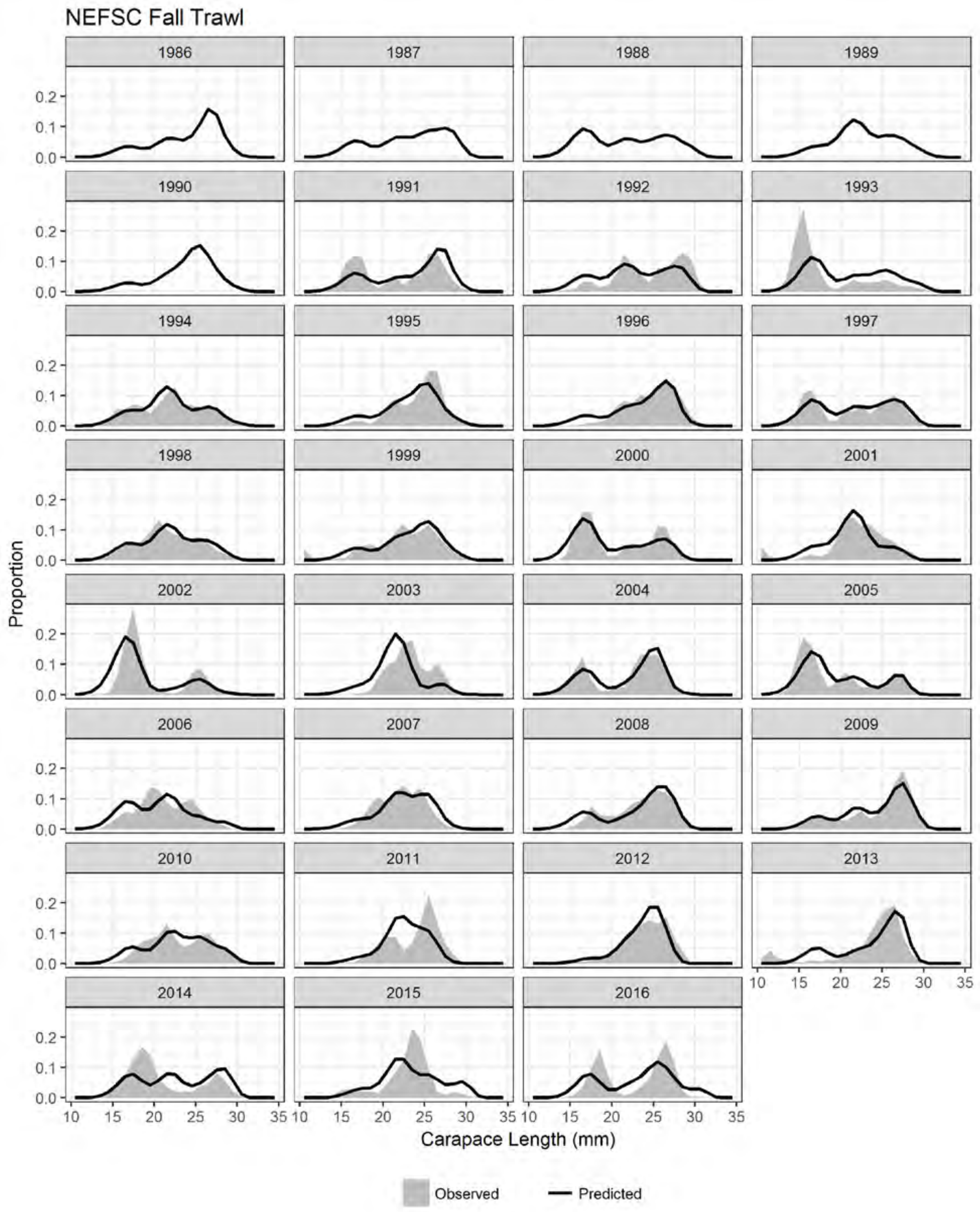


Figure A4. Observed and predicted length composition from the NEFSC Fall Trawl Survey.

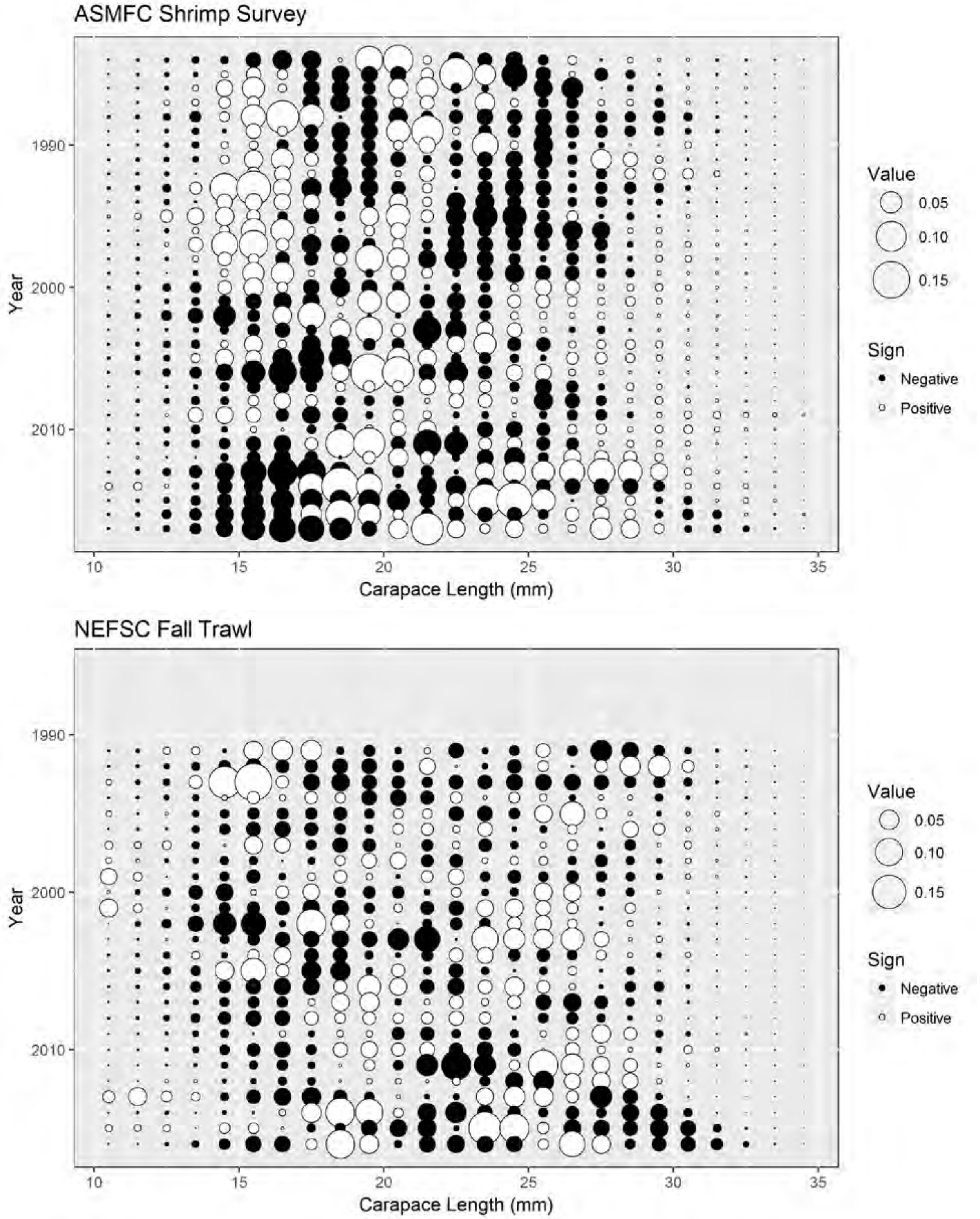


Figure A5. Length composition residuals (observed – predicted) for the ASMFC Shrimp Survey (top) and the NEFSC Fall Trawl Survey (bottom).

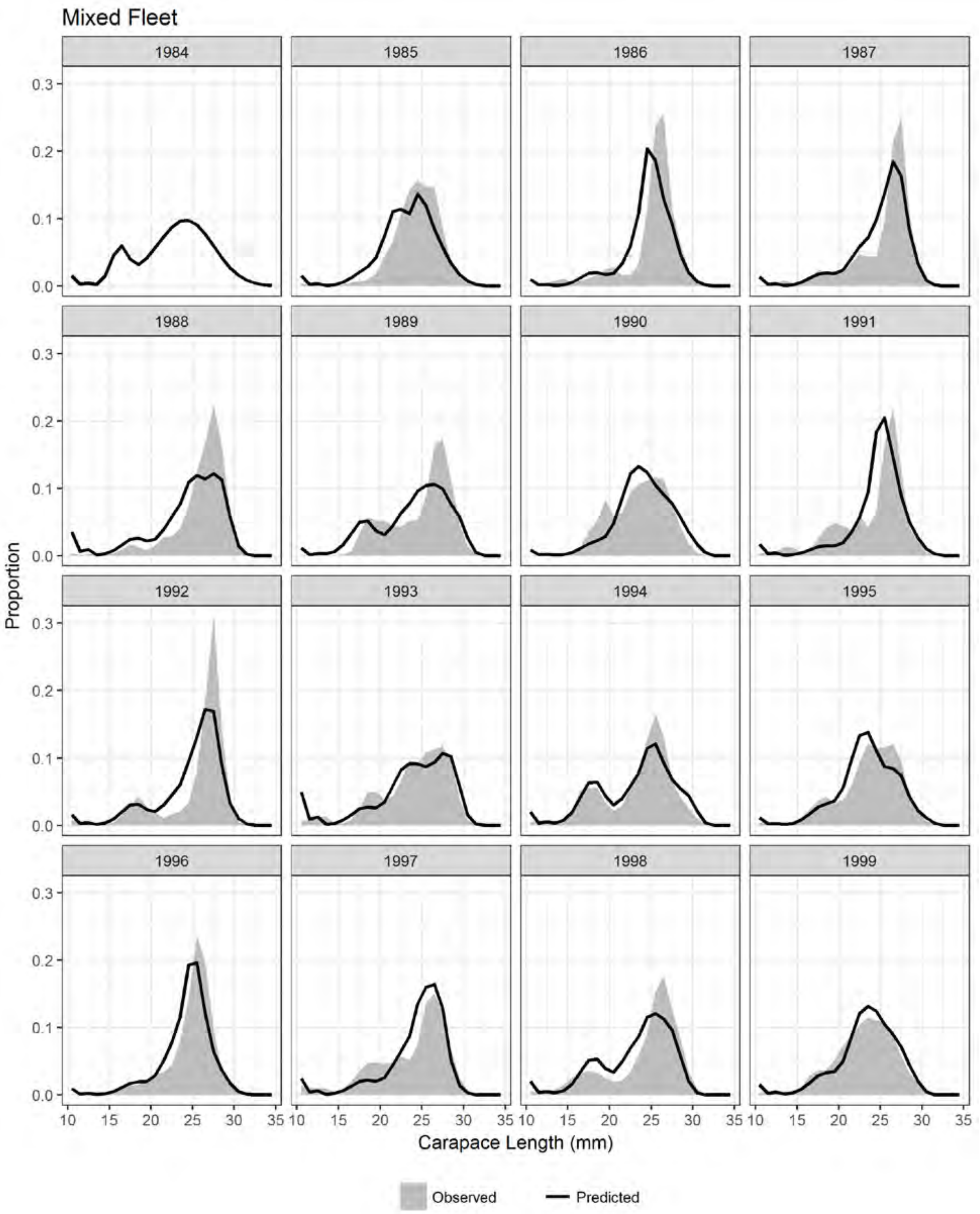


Figure A6. Observed and predicted length composition from the mixed fleet.

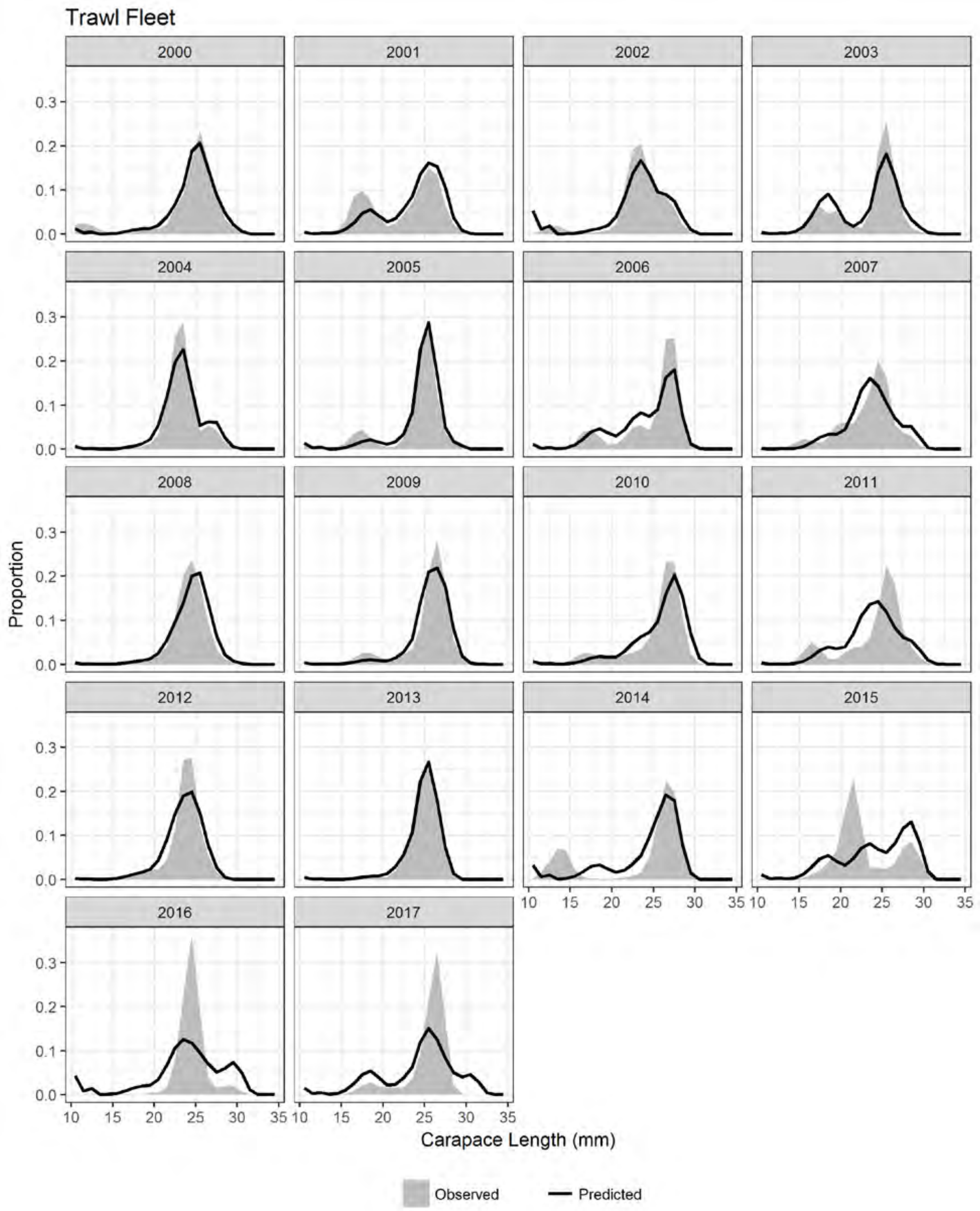


Figure A7. Observed and predicted length composition from the trawl fleet.

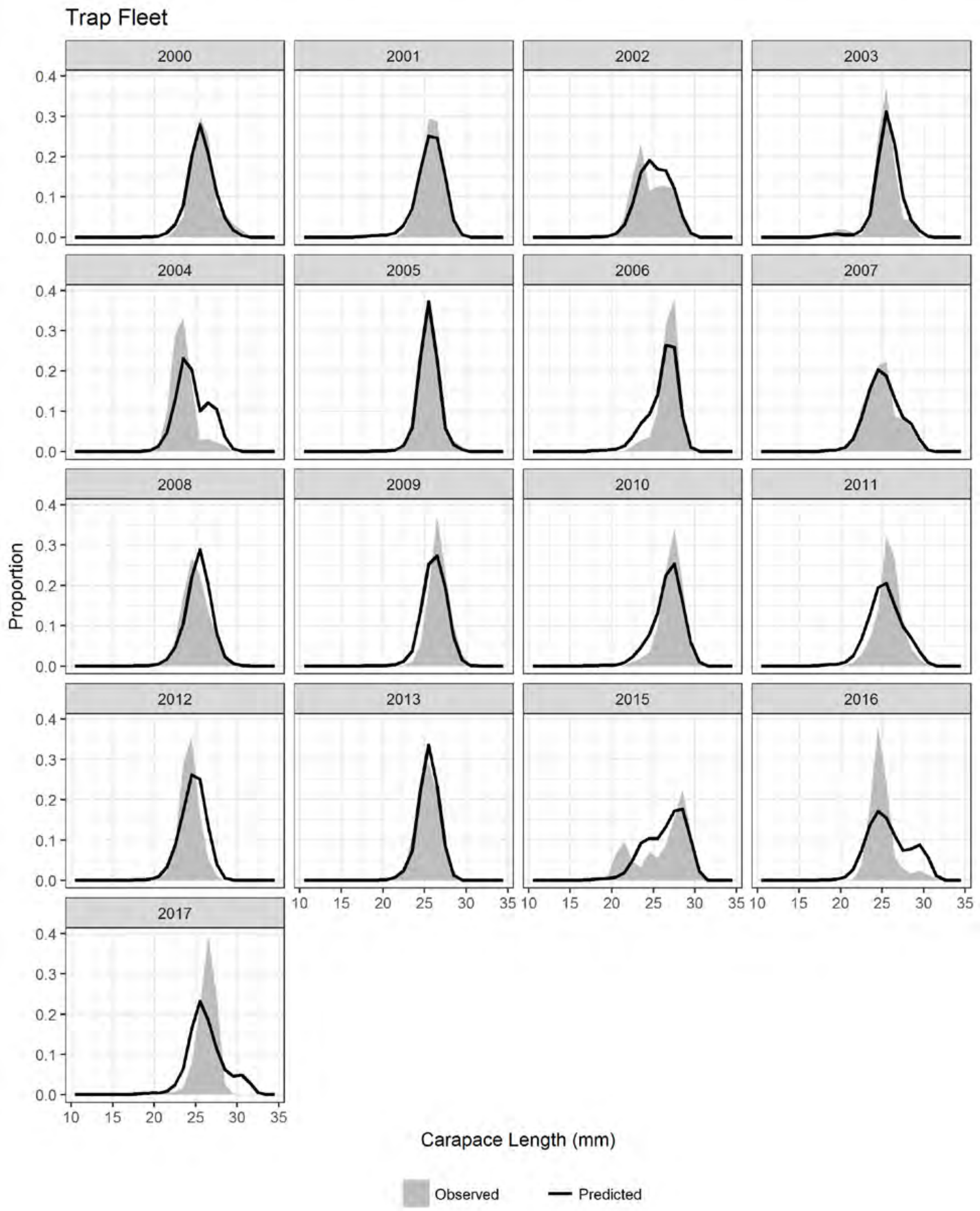


Figure A8. Observed and predicted length composition from the trap fleet.

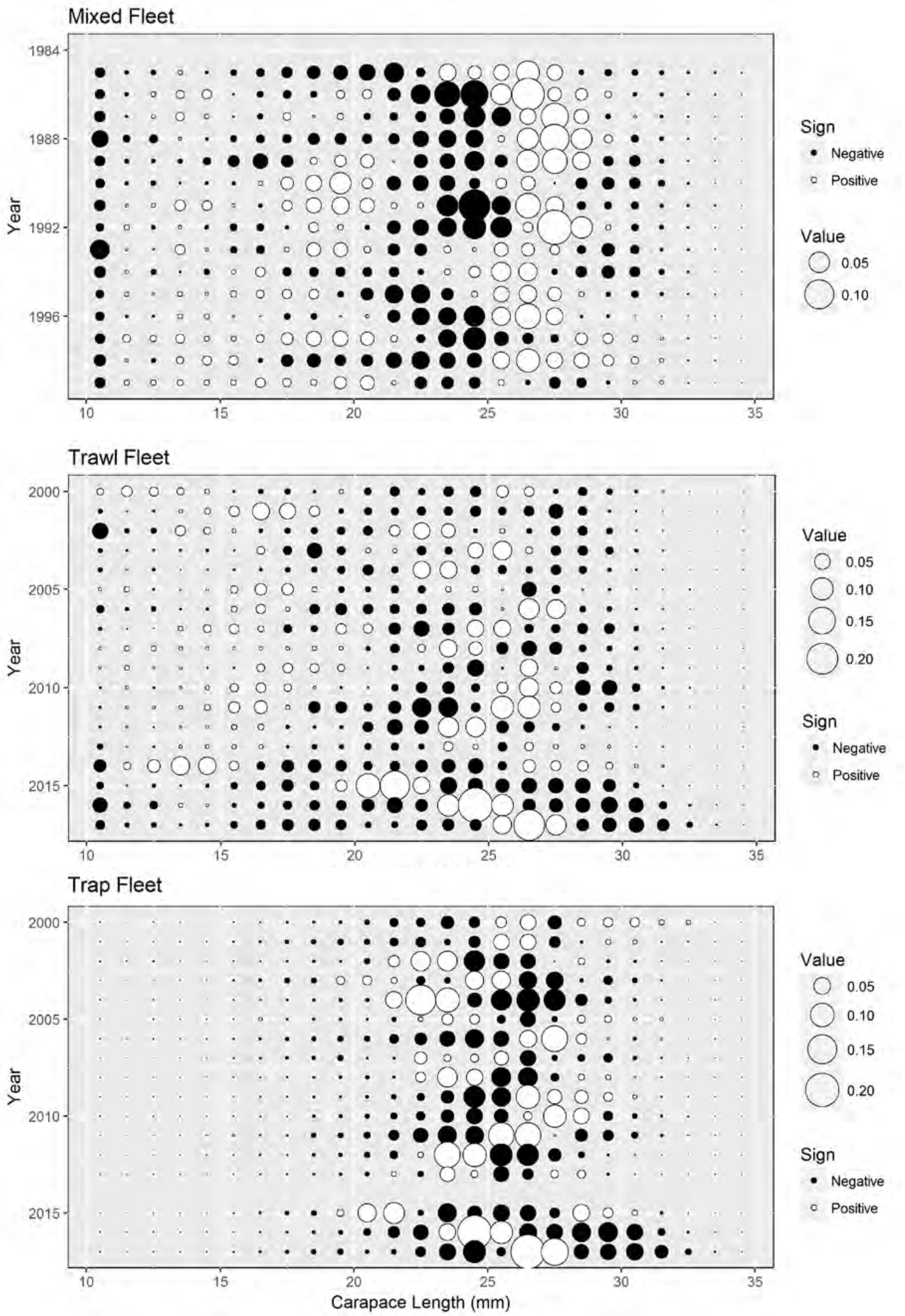


Figure A9. Length comp. residuals for the mixed (top), trawl (middle) and trap (bottom) fleets.

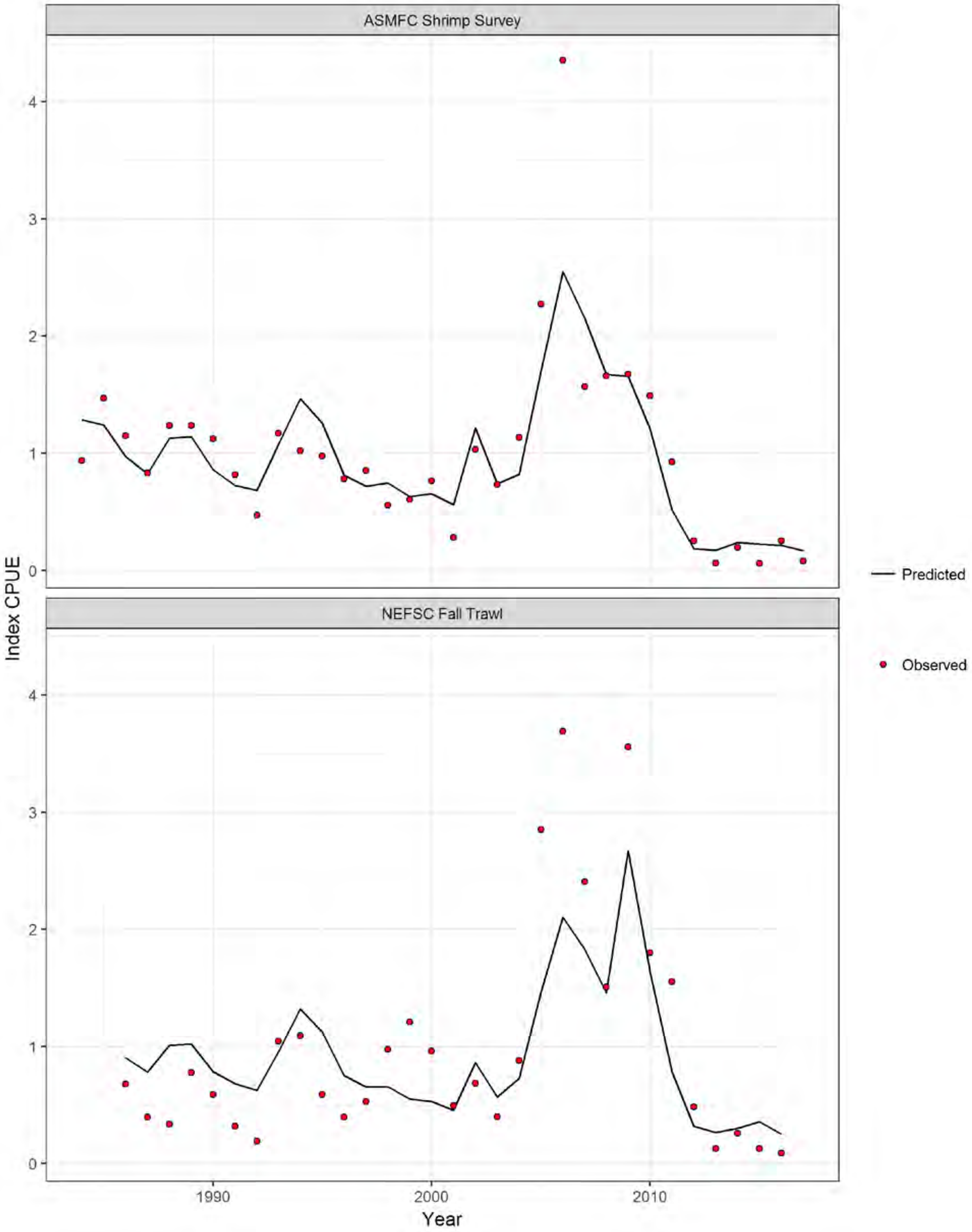


Figure A10. Observed and predicted index values for the ASMFC shrimp survey (top) and the NEFSC Fall Trawl Survey (bottom).

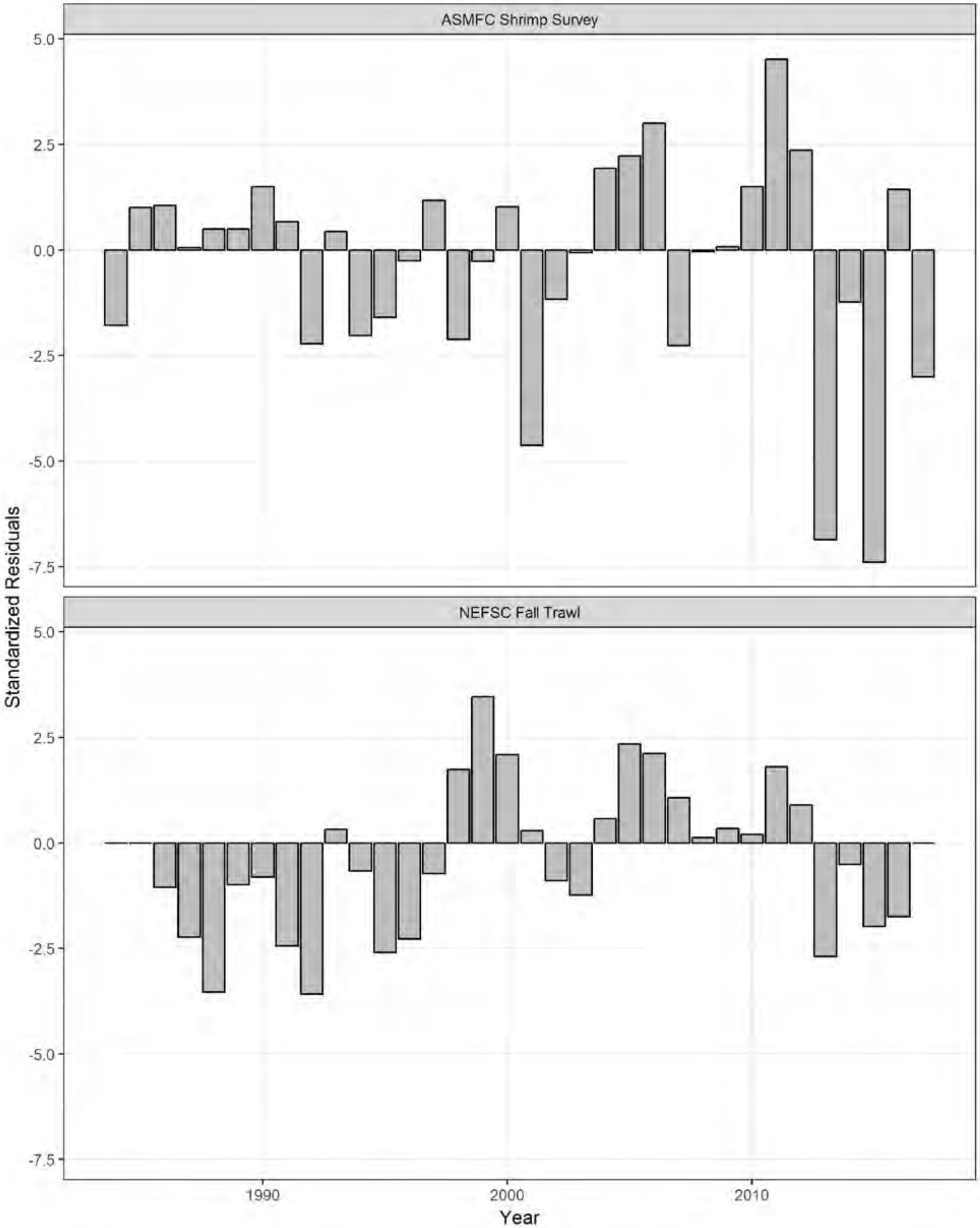


Figure A11. Standardized residuals for the ASMFC Shrimp Survey (top) and NEFSC Fall Trawl Survey (bottom).

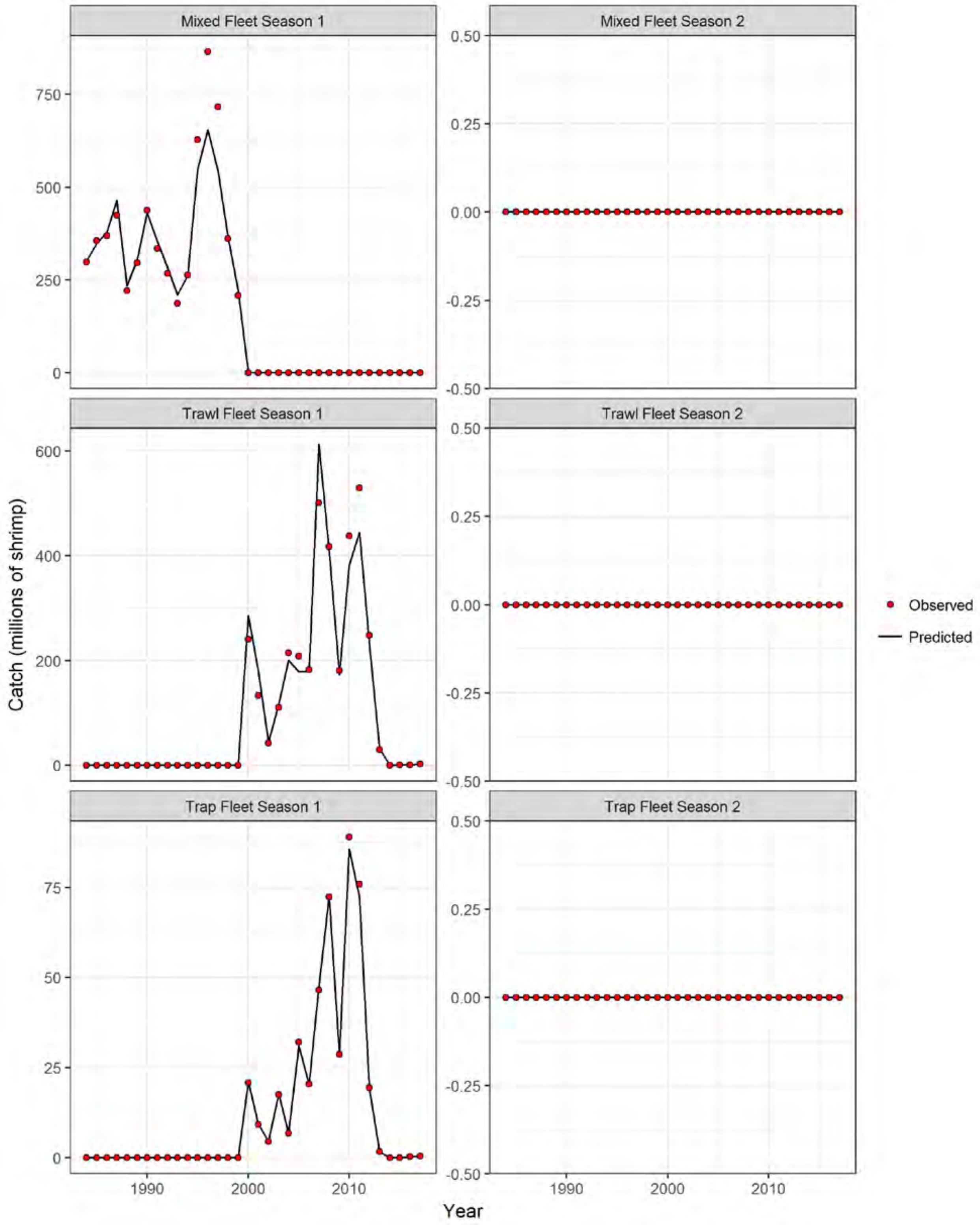


Figure A12. Observed and predicted total catch by fleet and season.

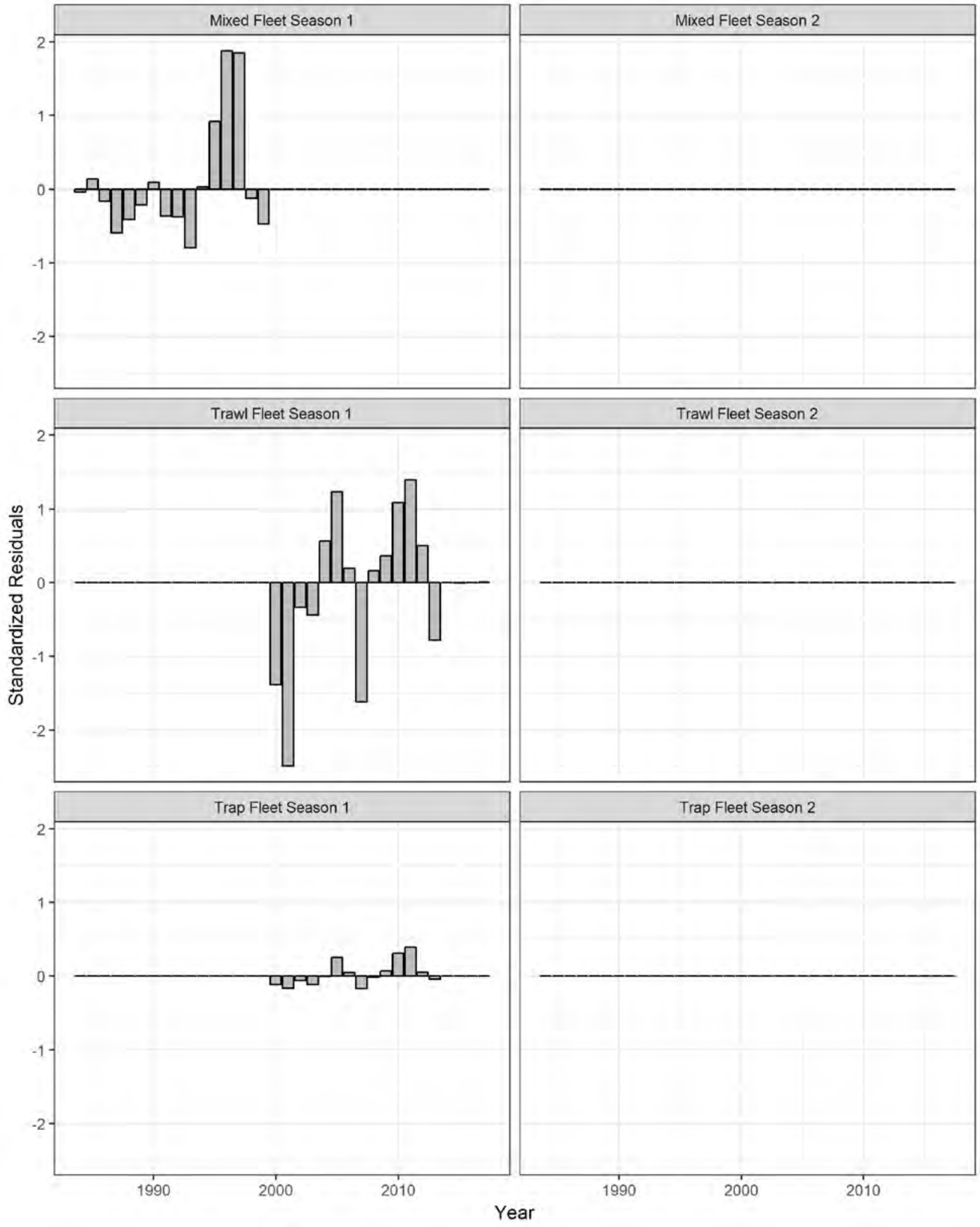


Figure A13. Standardized residuals for total catch by fleet and season.

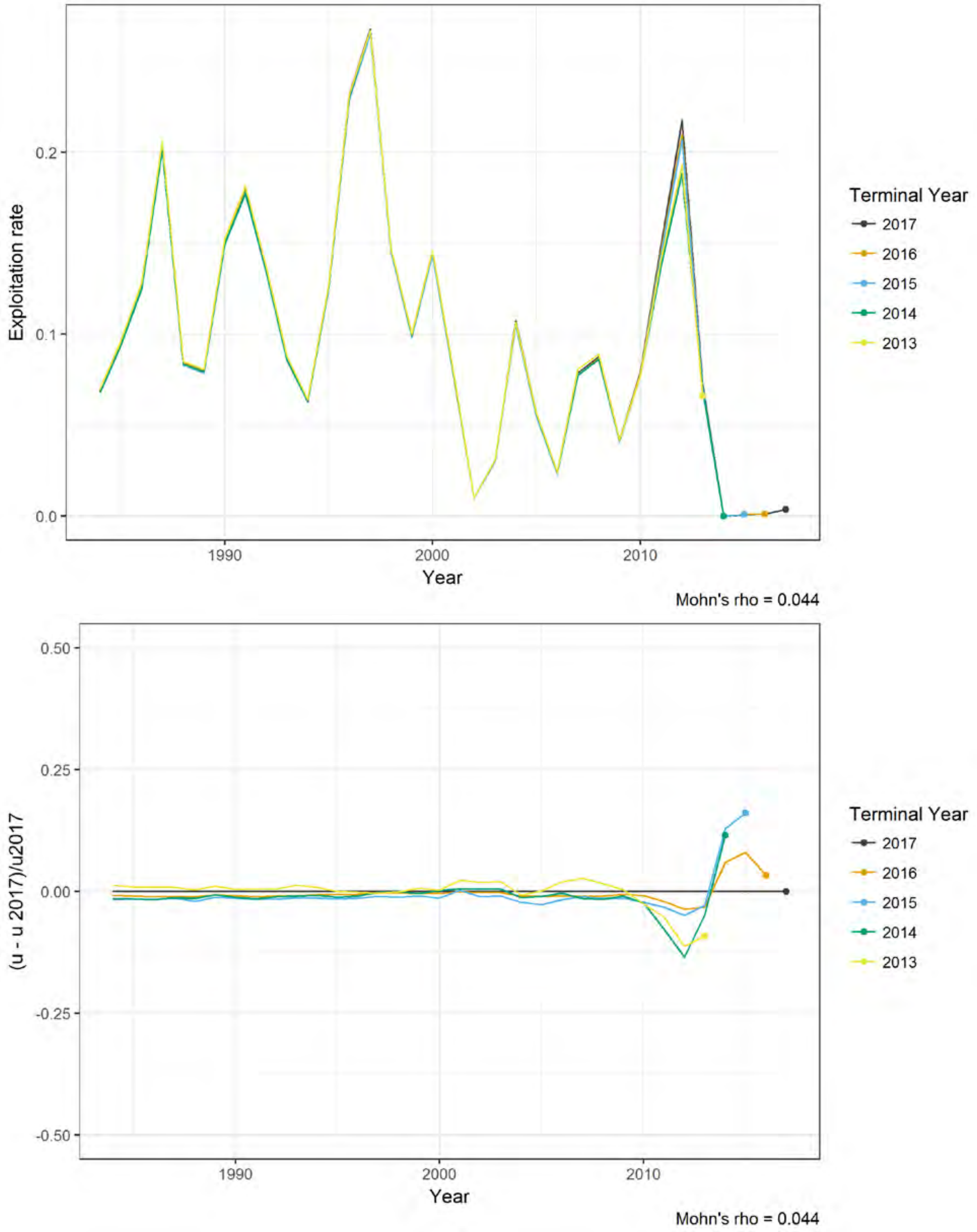


Figure A14. Retrospective pattern for exploitation rate on the absolute (top) and relative (bottom) scale.

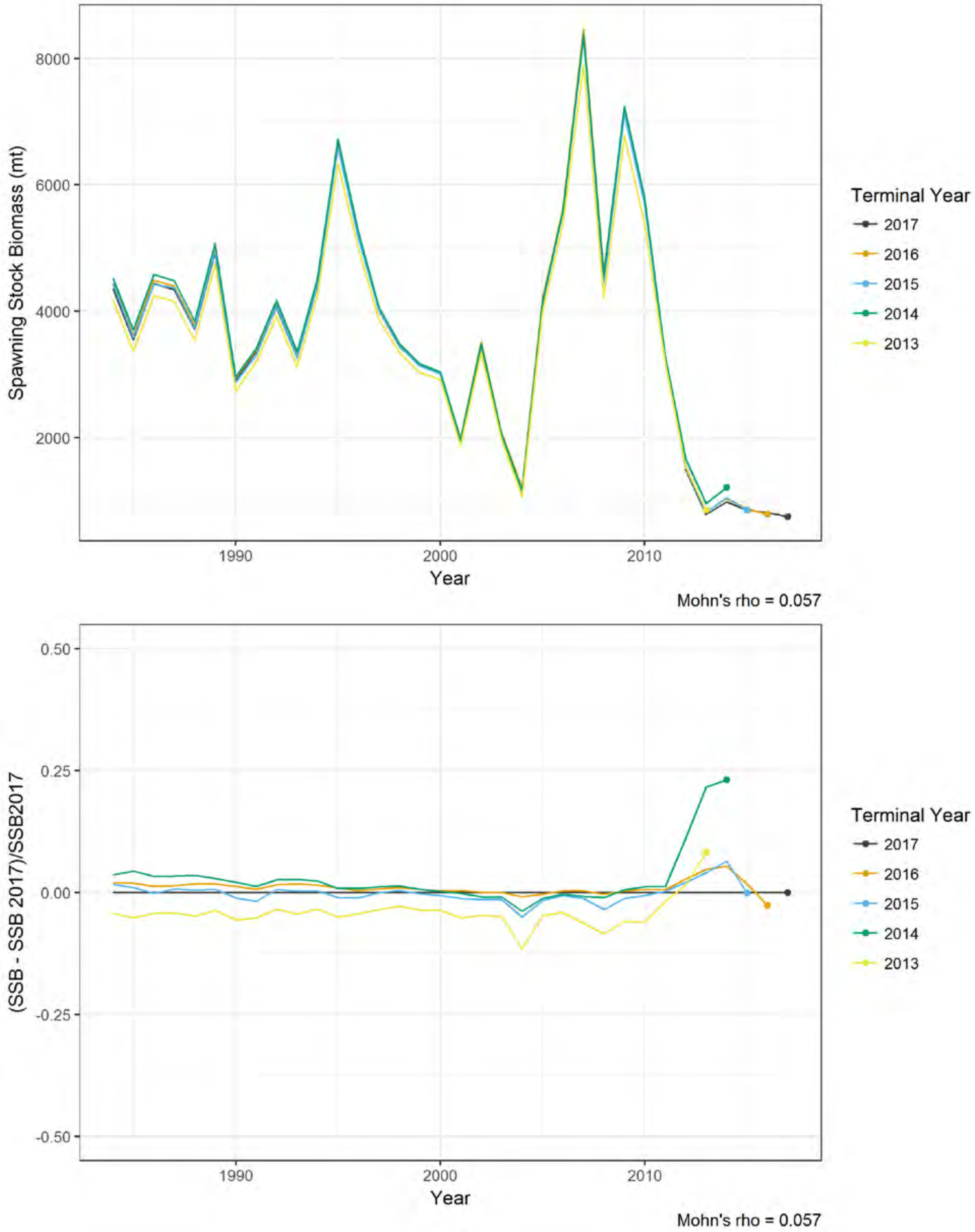


Figure A15. Retrospective pattern for spawning stock biomass on the absolute (top) and relative (bottom) scale.

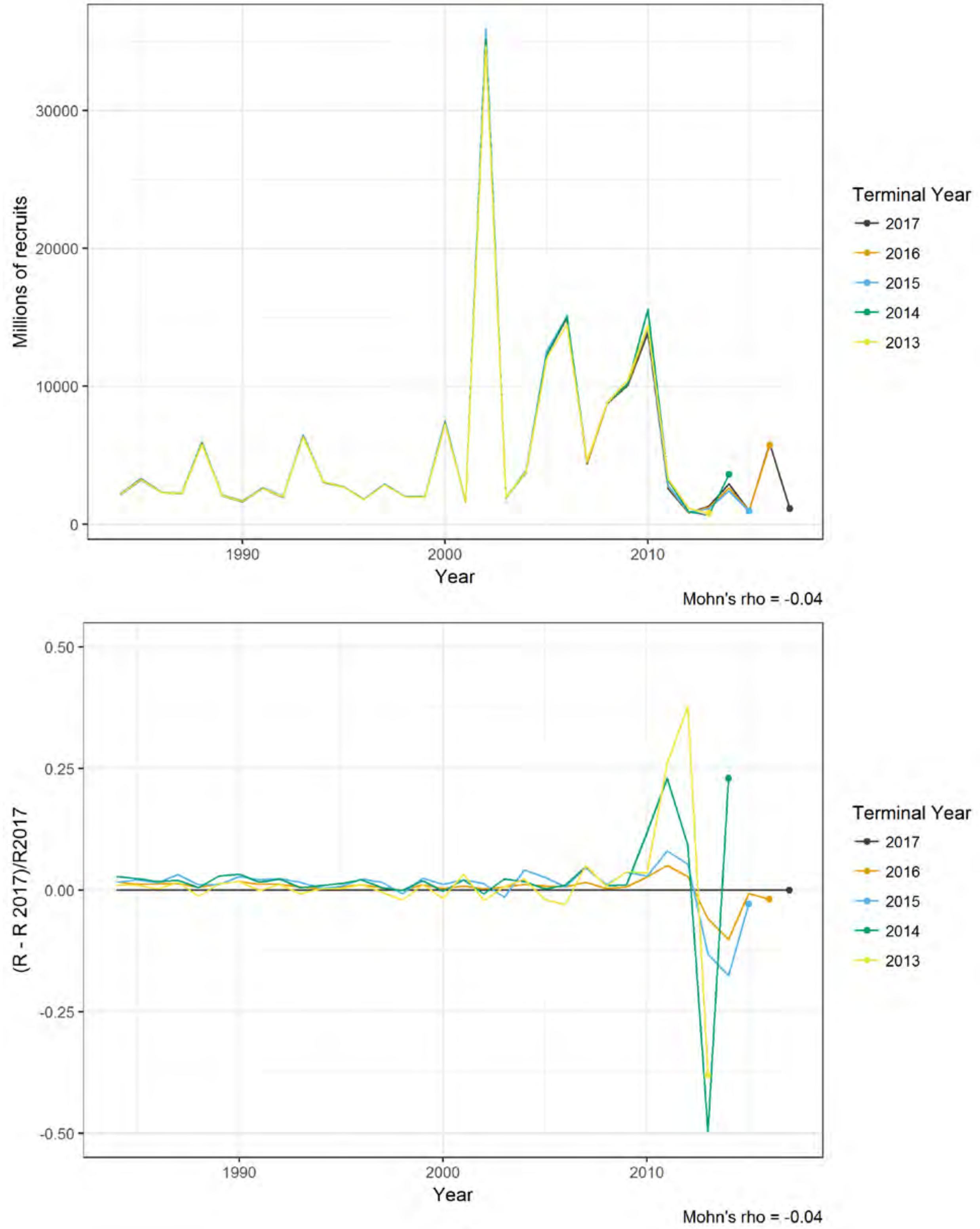


Figure A16. Retrospective pattern for recruitment on the absolute (top) and relative (bottom) scale.

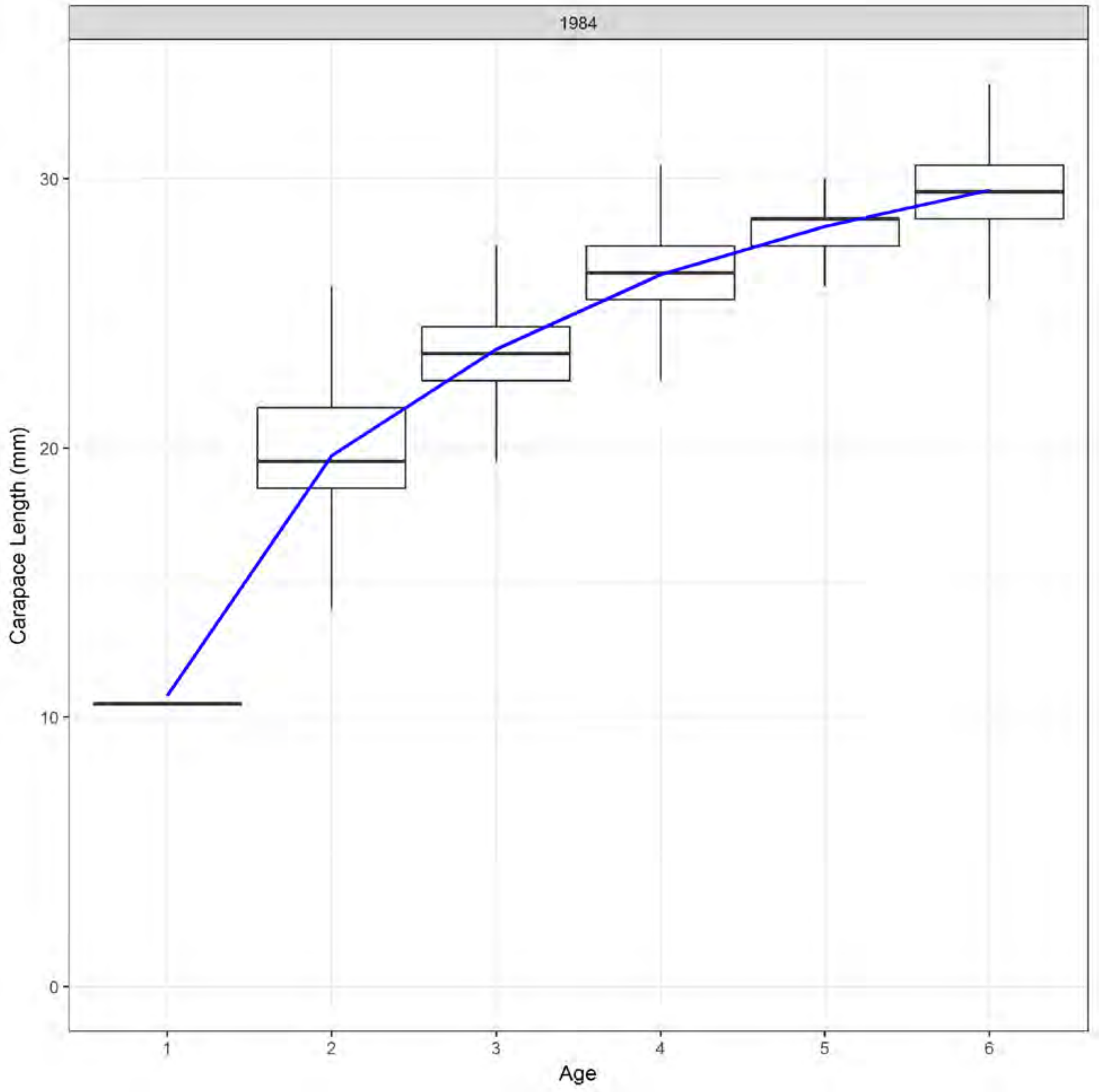


Figure A17. Predicted growth curve of northern shrimp based on the seasonal growth-transition matrices estimated by the UME model.

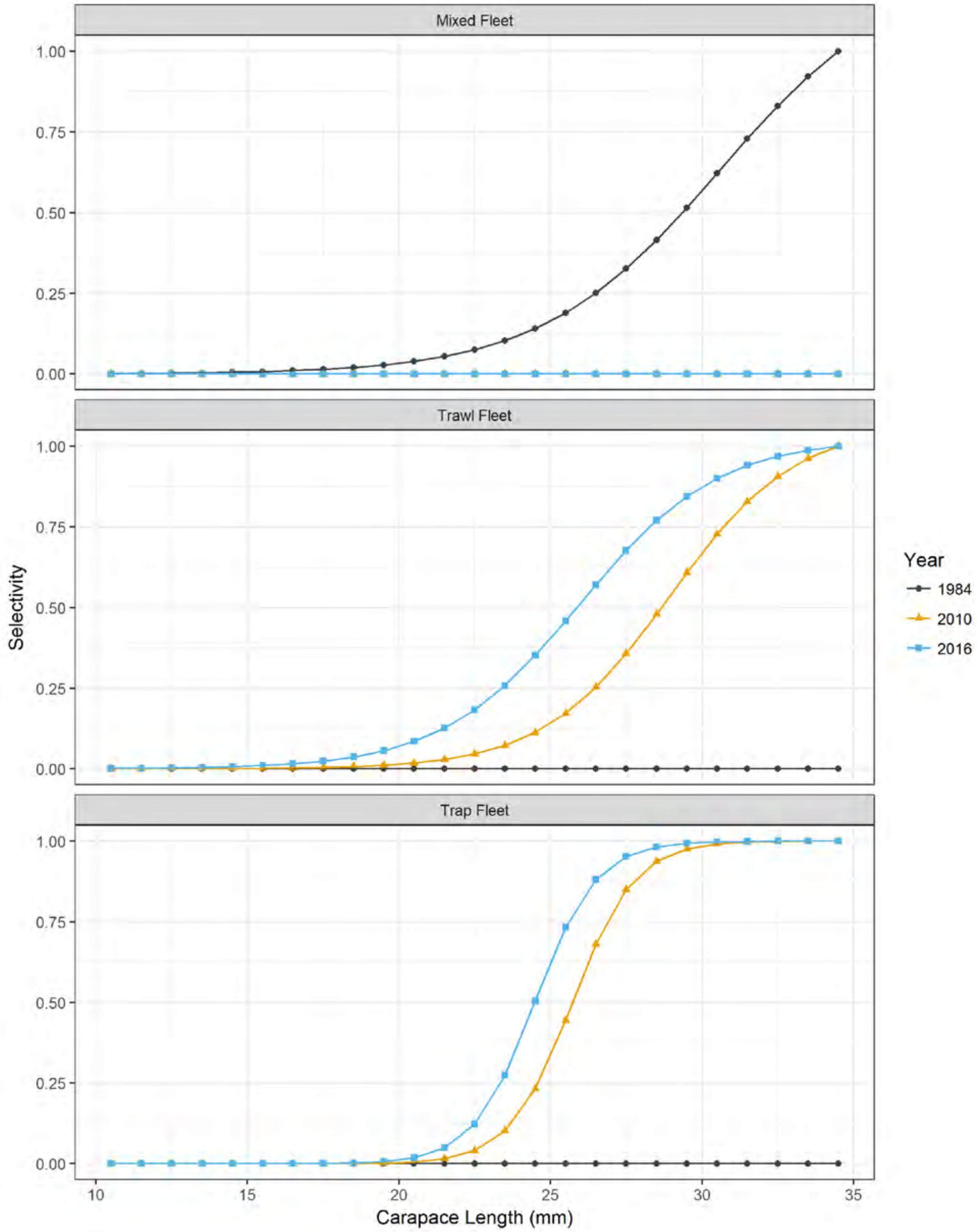


Figure A18. Estimated selectivity patterns for each fleet and selectivity block.

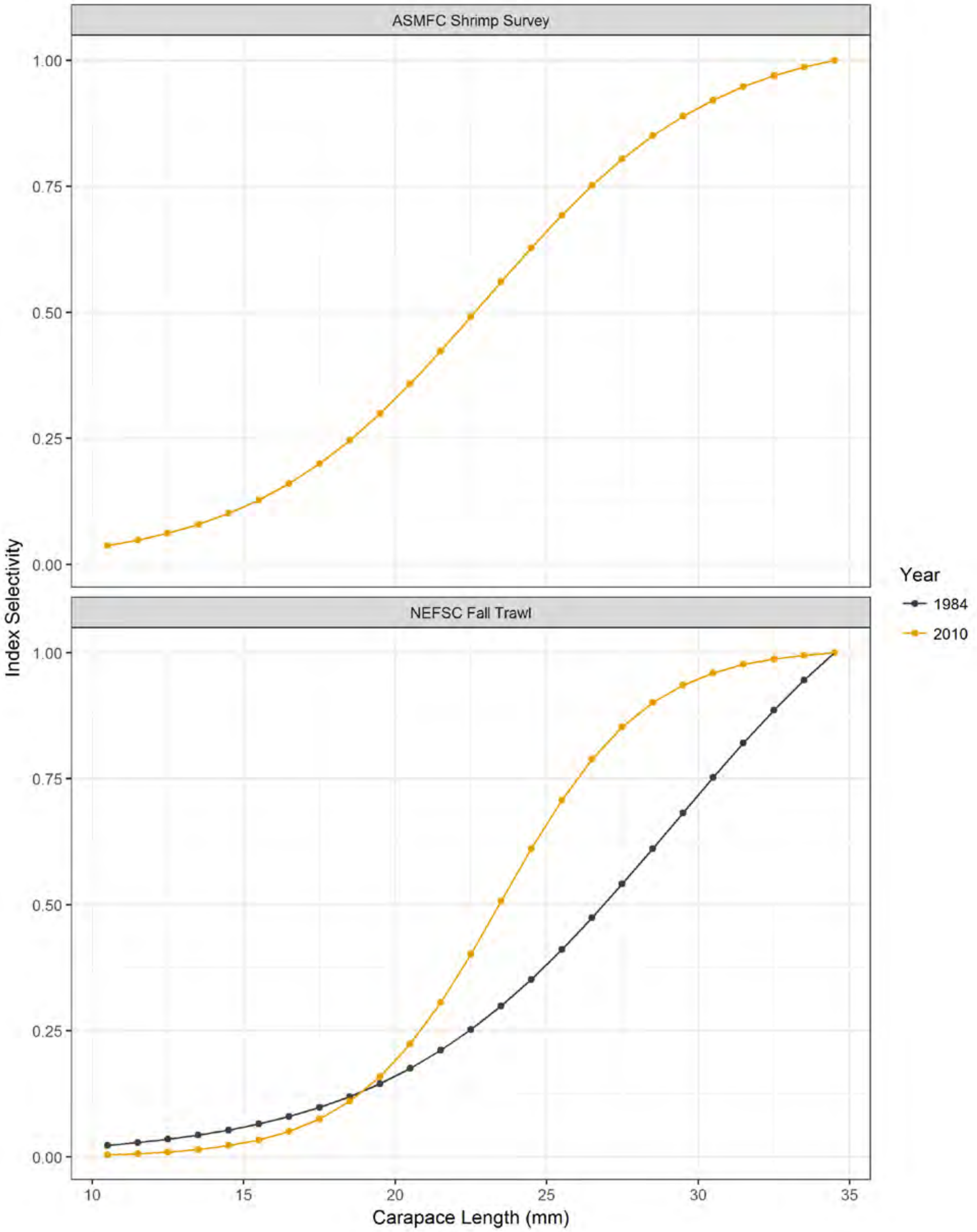


Figure A19. Estimated selectivity patterns for each index and selectivity block.

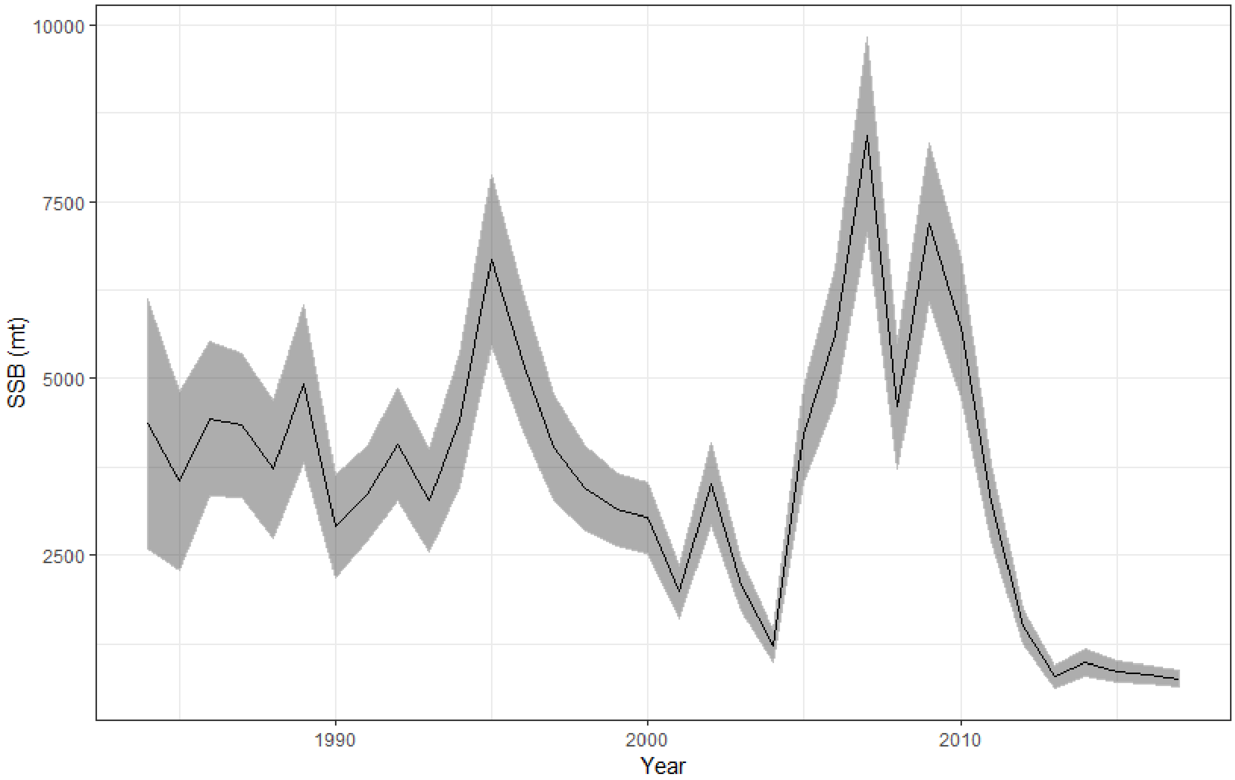


Figure A20. Spawning stock biomass estimates from the new base run of the UME model; shaded area indicates 95% confidence intervals.

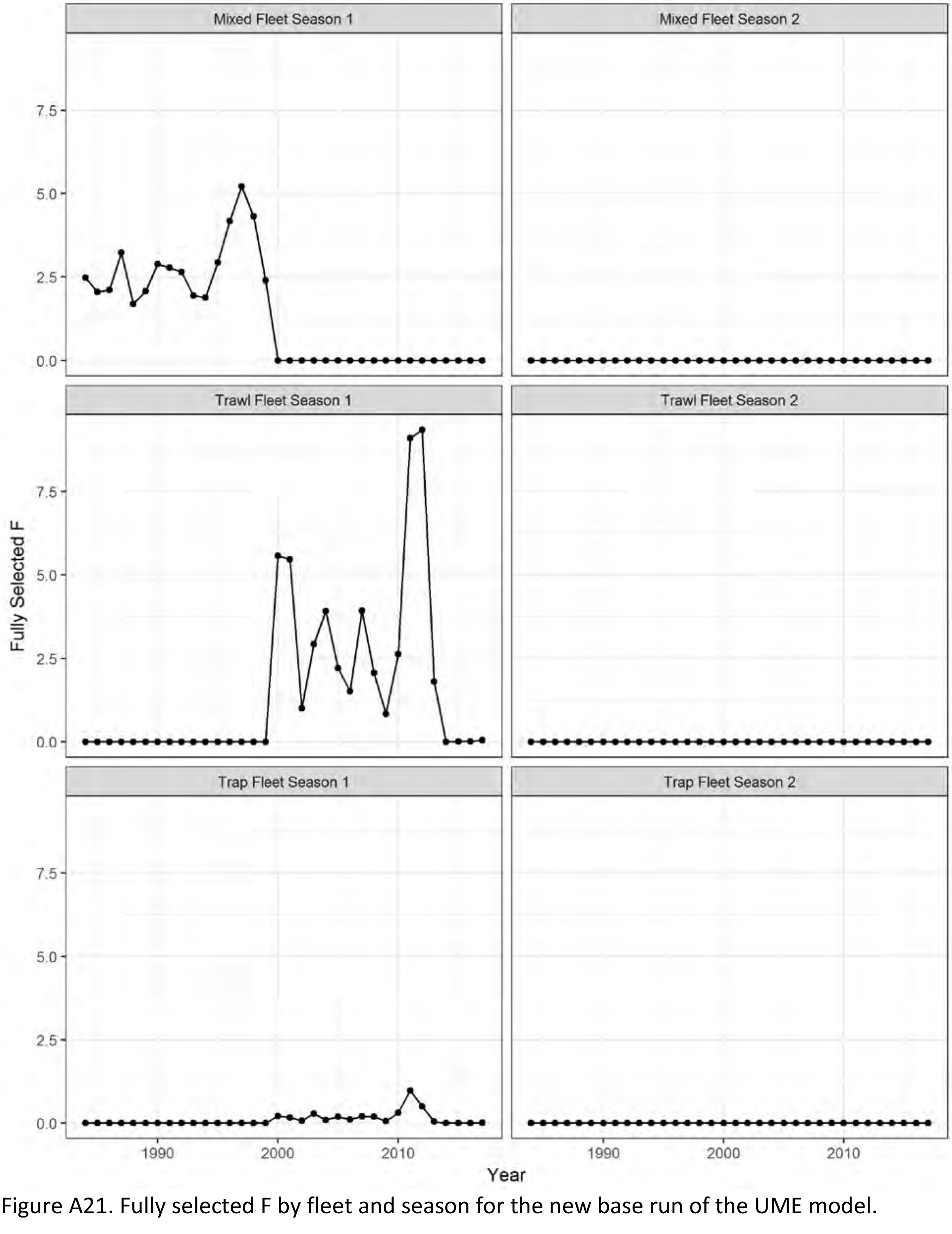


Figure A21. Fully selected F by fleet and season for the new base run of the UME model.

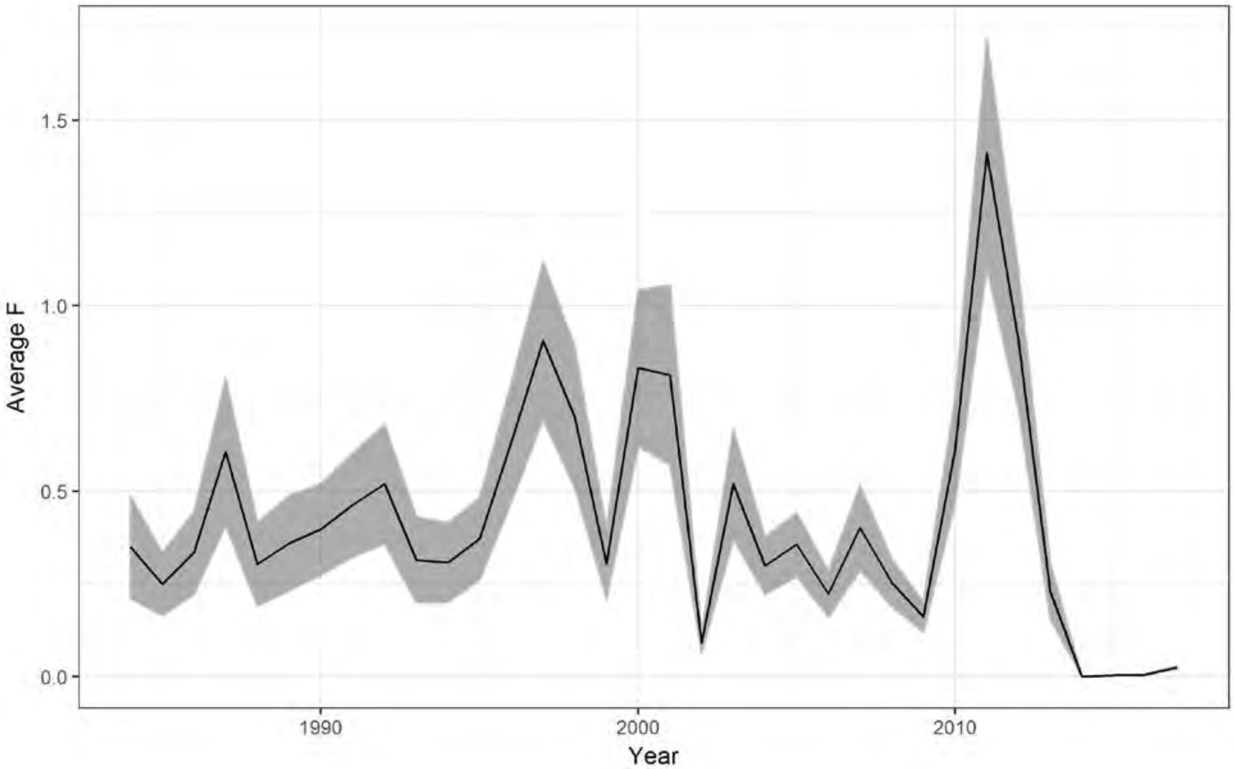


Figure A22. Abundance-weighted average fishing mortality for shrimp ≥ 22mm carapace length from the new base run of the UME model; shaded area indicates 95% confidence intervals.

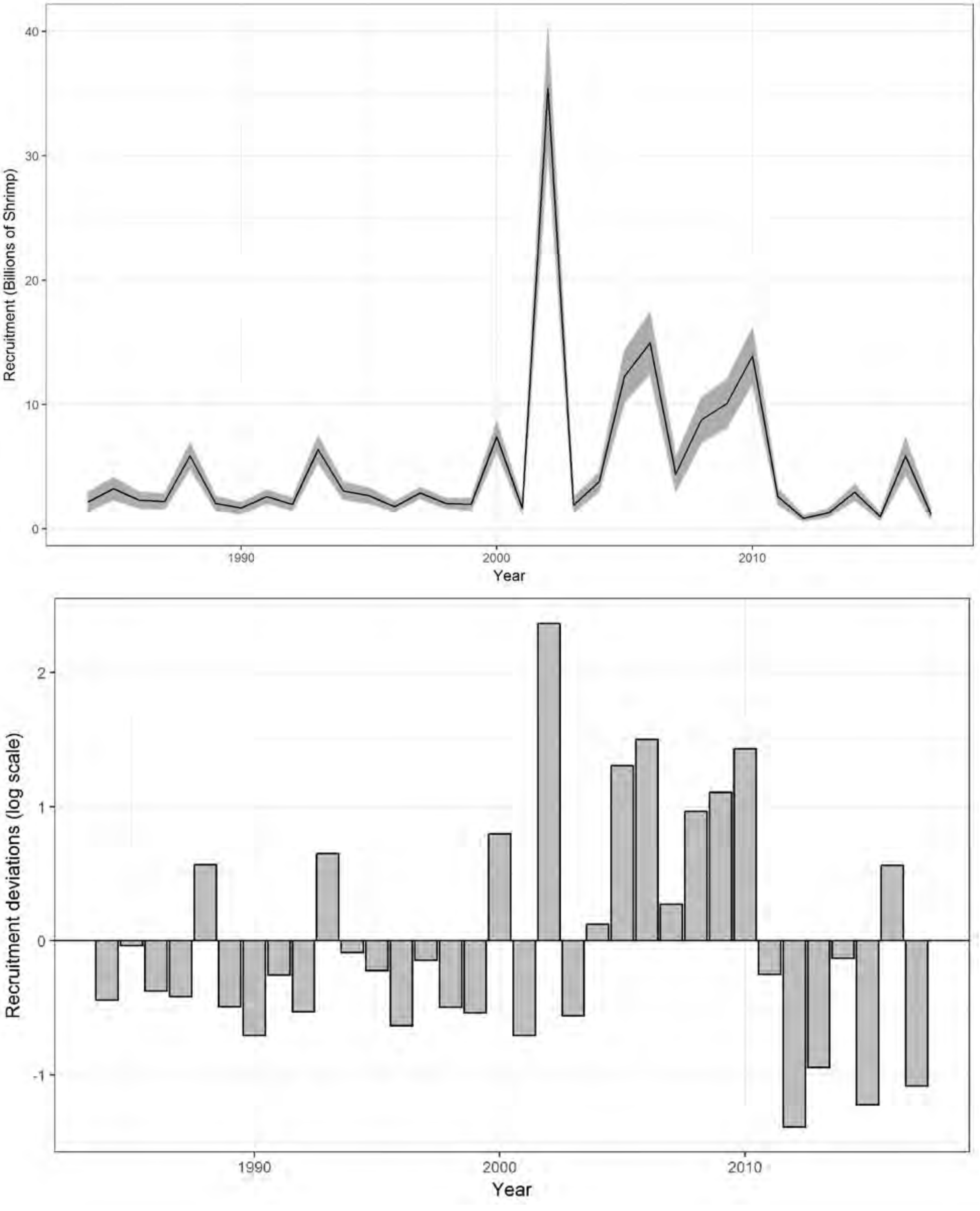


Figure A23. Estimated total recruitment with 95% confidence intervals in billions of 10-12mm shrimp (top) and annual log-scale deviations from mean recruitment (bottom) from the new base runs of the UME model.

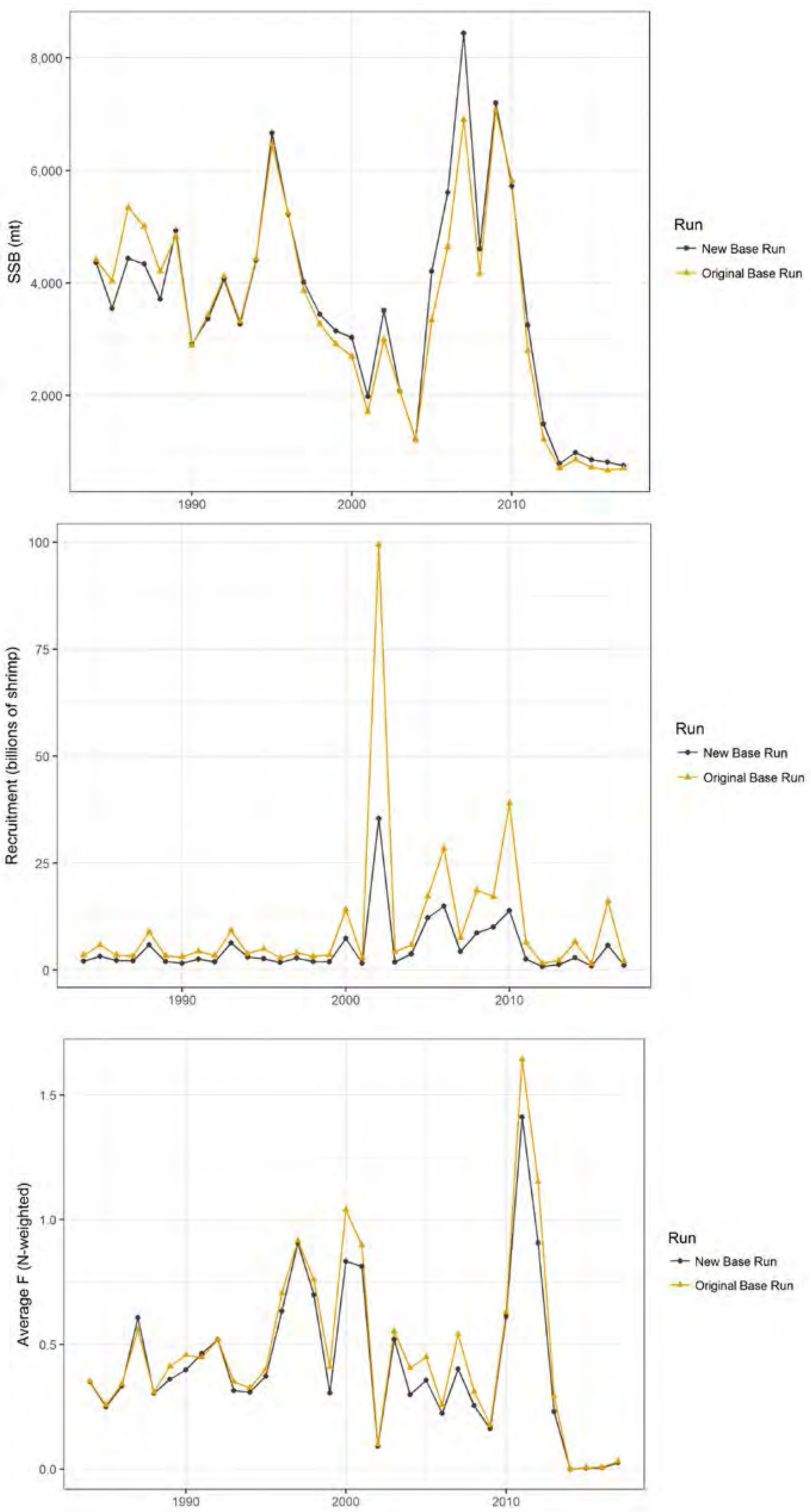
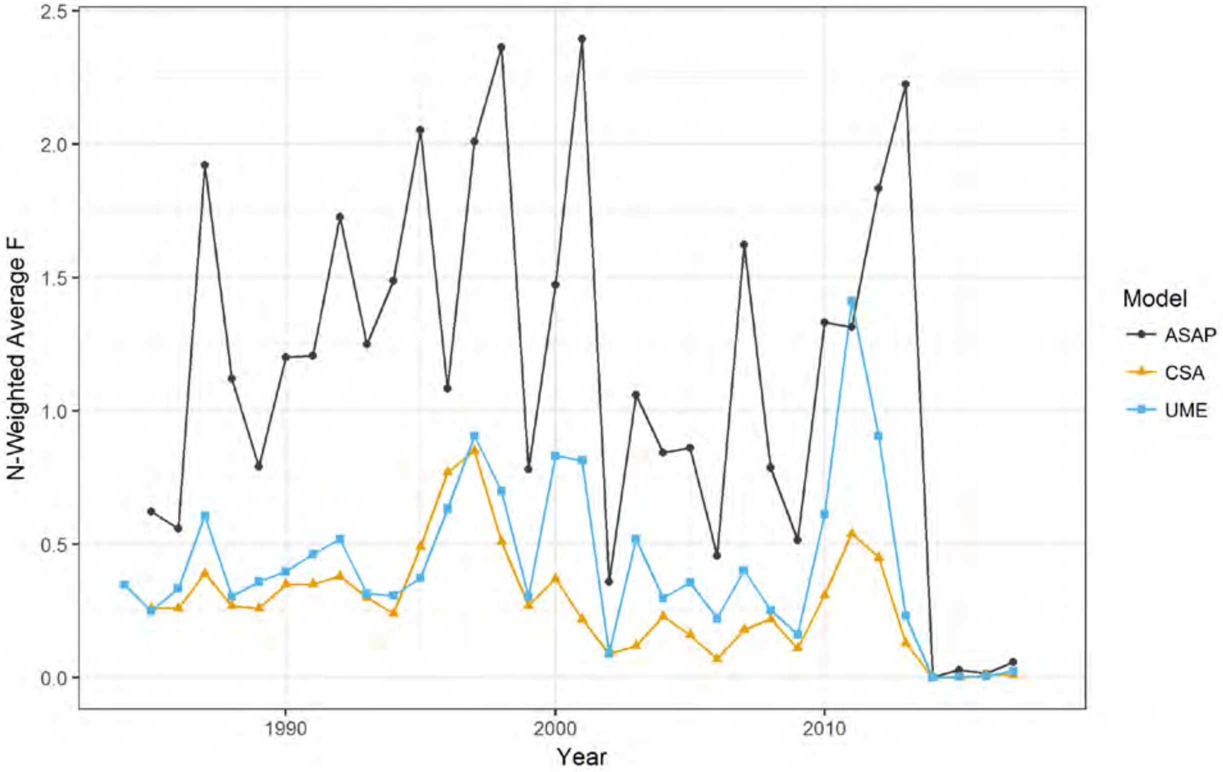


Figure A24. Comparison of SSB (top), recruitment (middle) and average F (bottom) estimates from the new base run and the original base run.



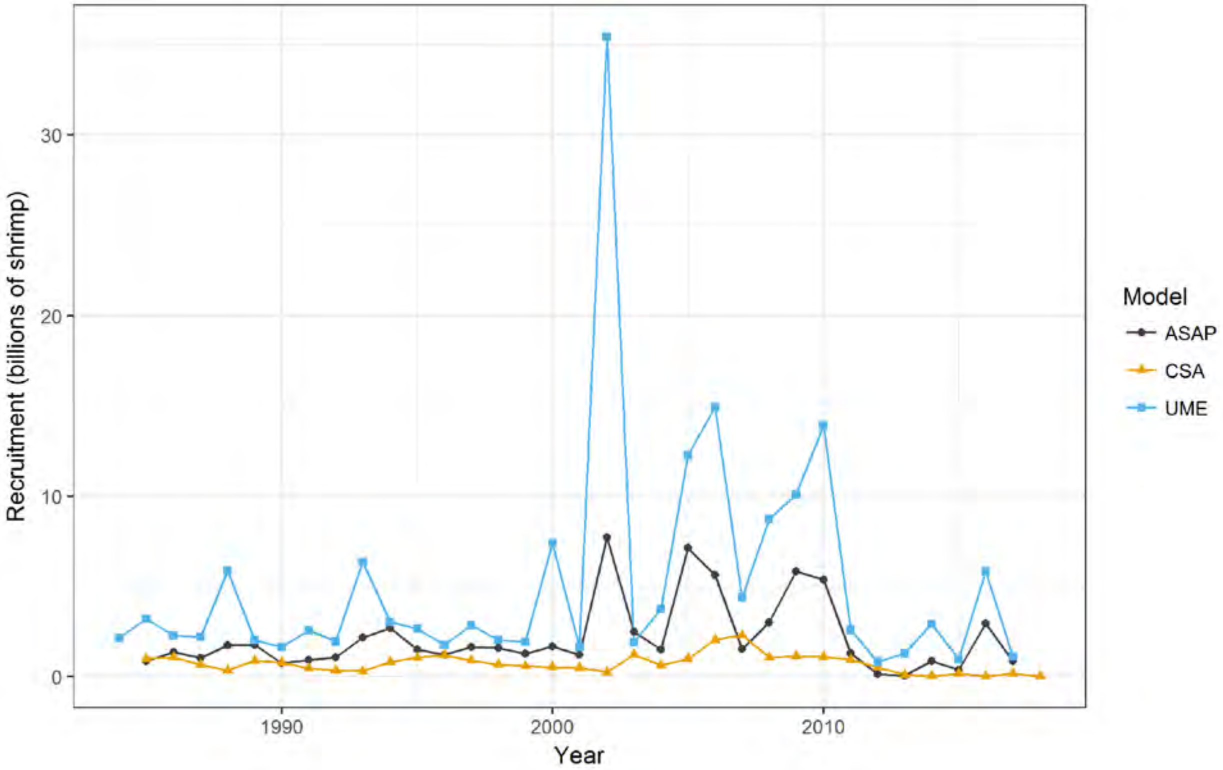


Figure A25. Comparison of fishing mortality (top) and recruitment estimates (bottom) from the new base run, the new ASAP run, and the original CSA run.

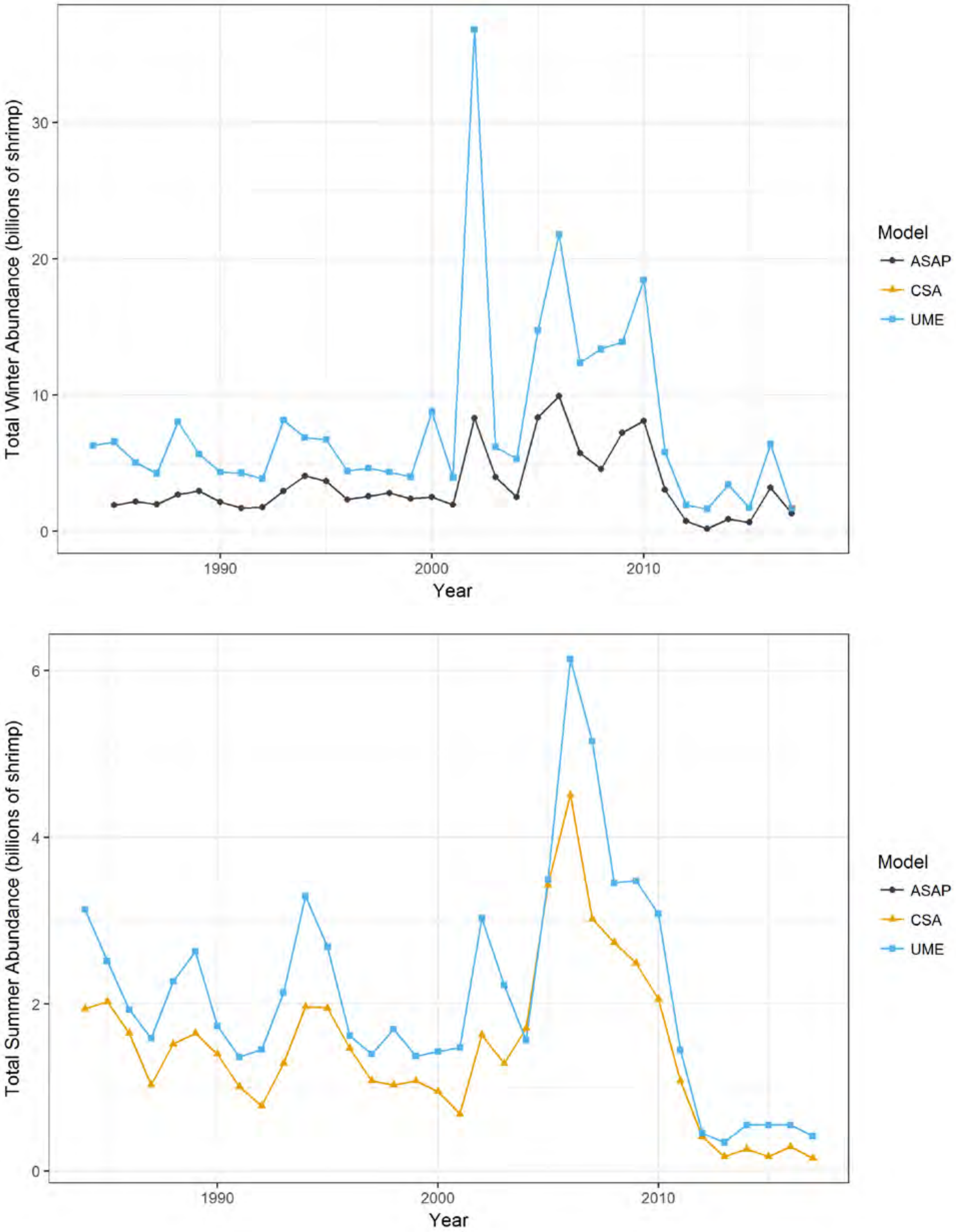


Figure A26. Comparison of total abundance estimates from the new base run of the UME, the new ASAP run, and the original CSA model.

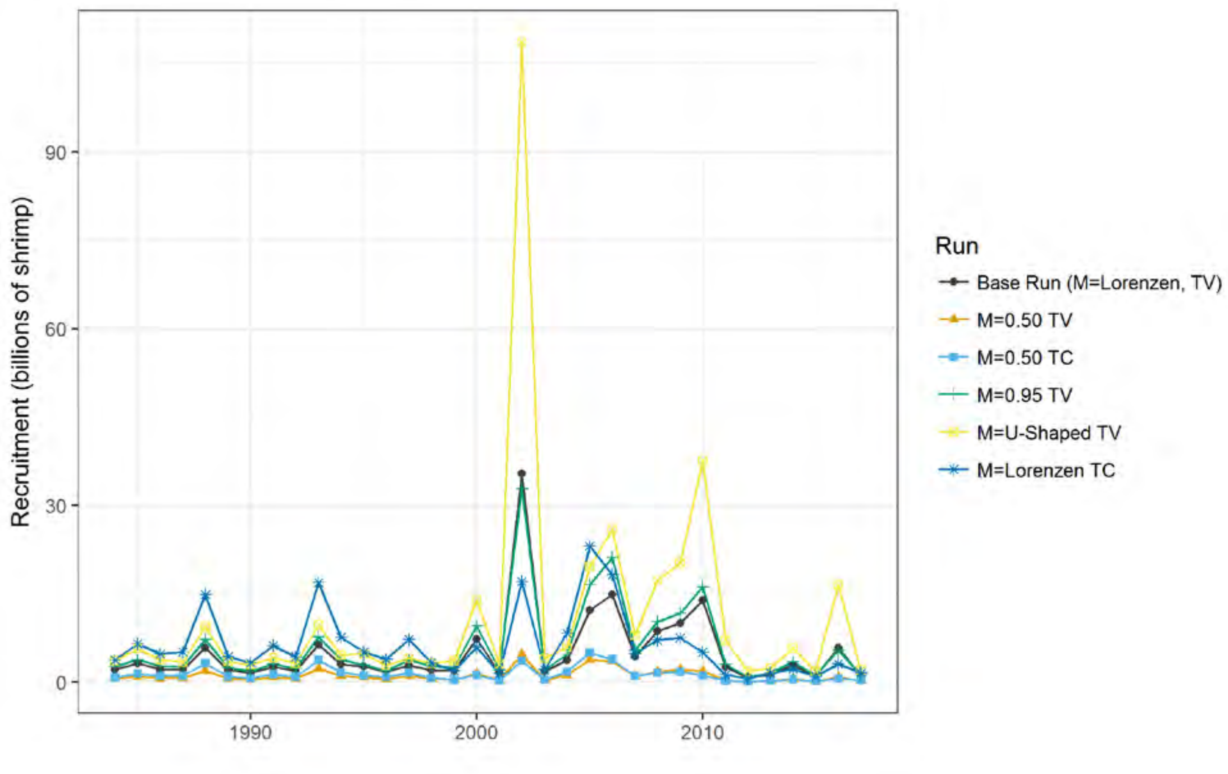


Figure A27. Recruitment estimates from the new base run of the UME model under different M scenarios.

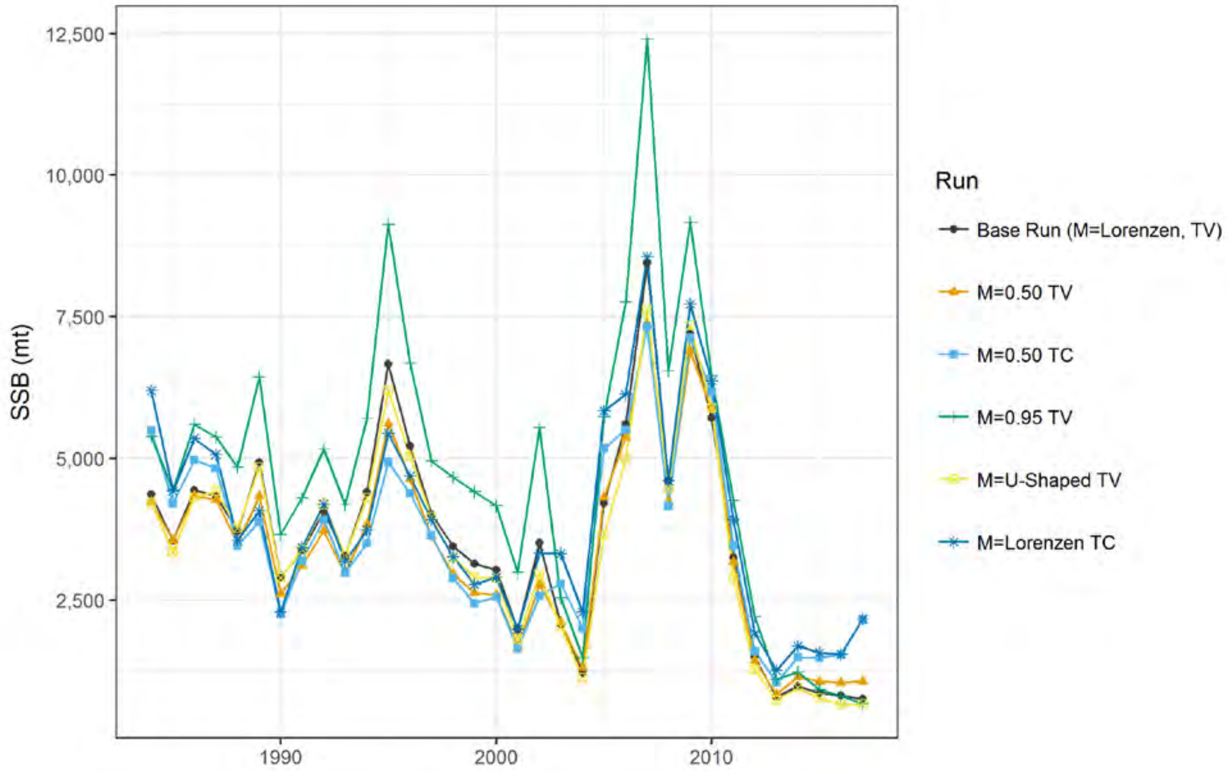


Figure A28. SSB estimates from the new base run of the UME model under different M scenarios.

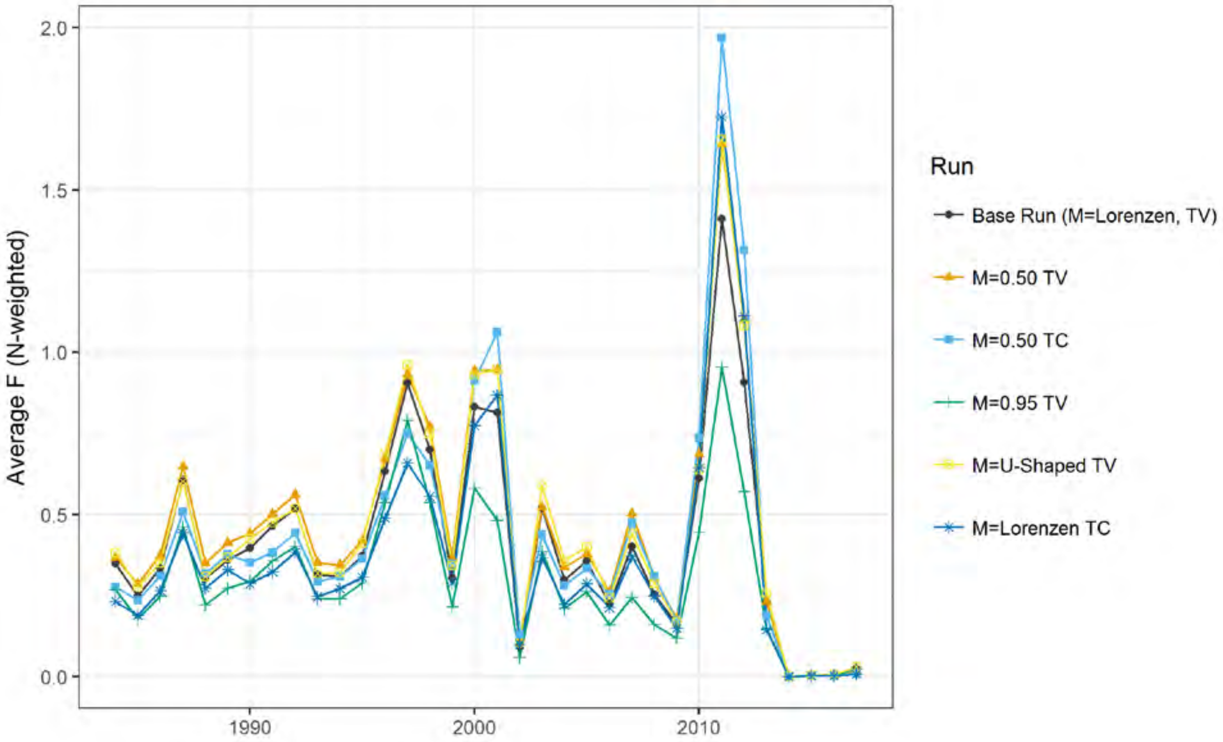


Figure A29. Average F estimates from the new base run of the UME model under different M scenarios.

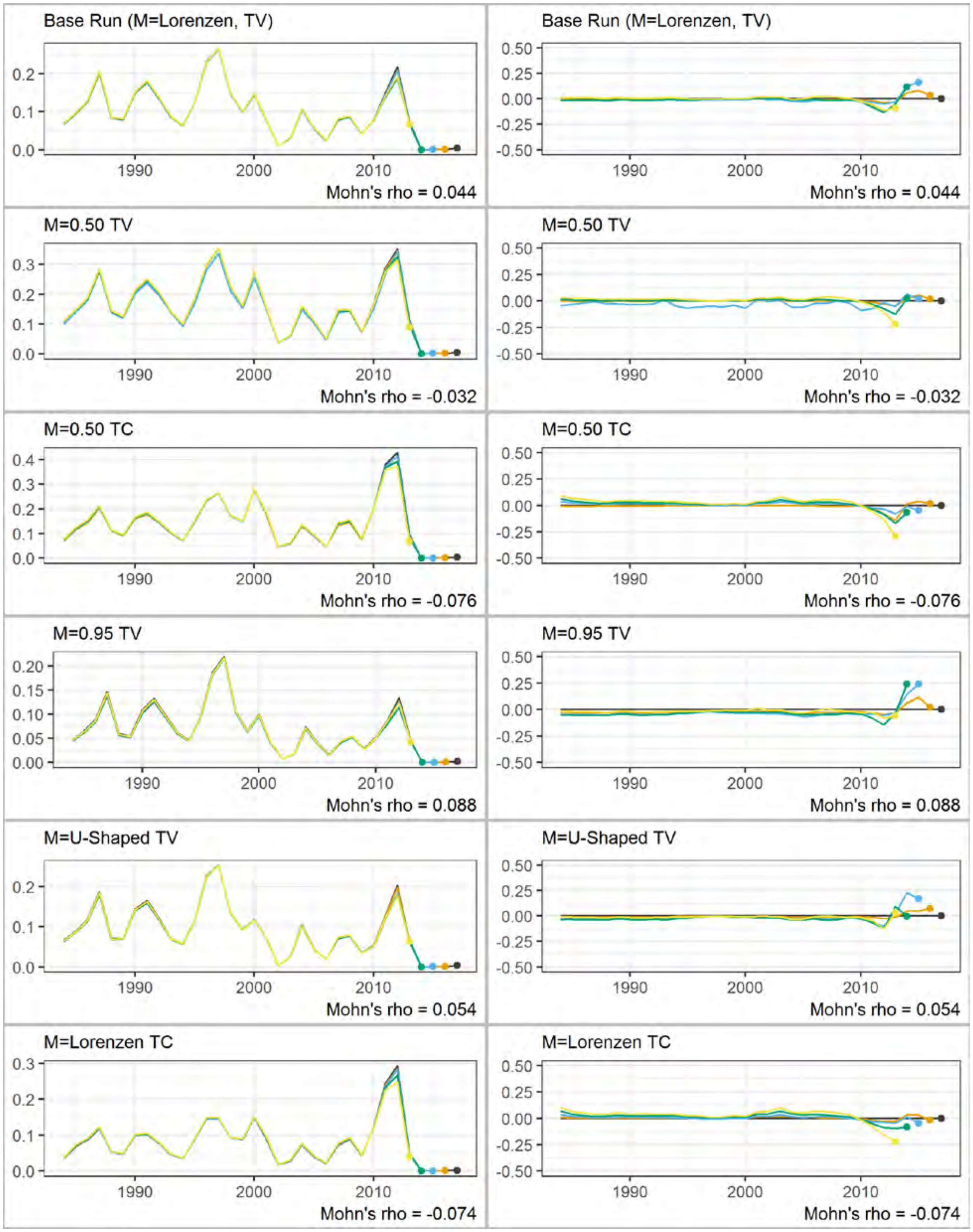


Figure A30. Retrospective patterns in SSB from the new base run of the UME model under different M scenarios.

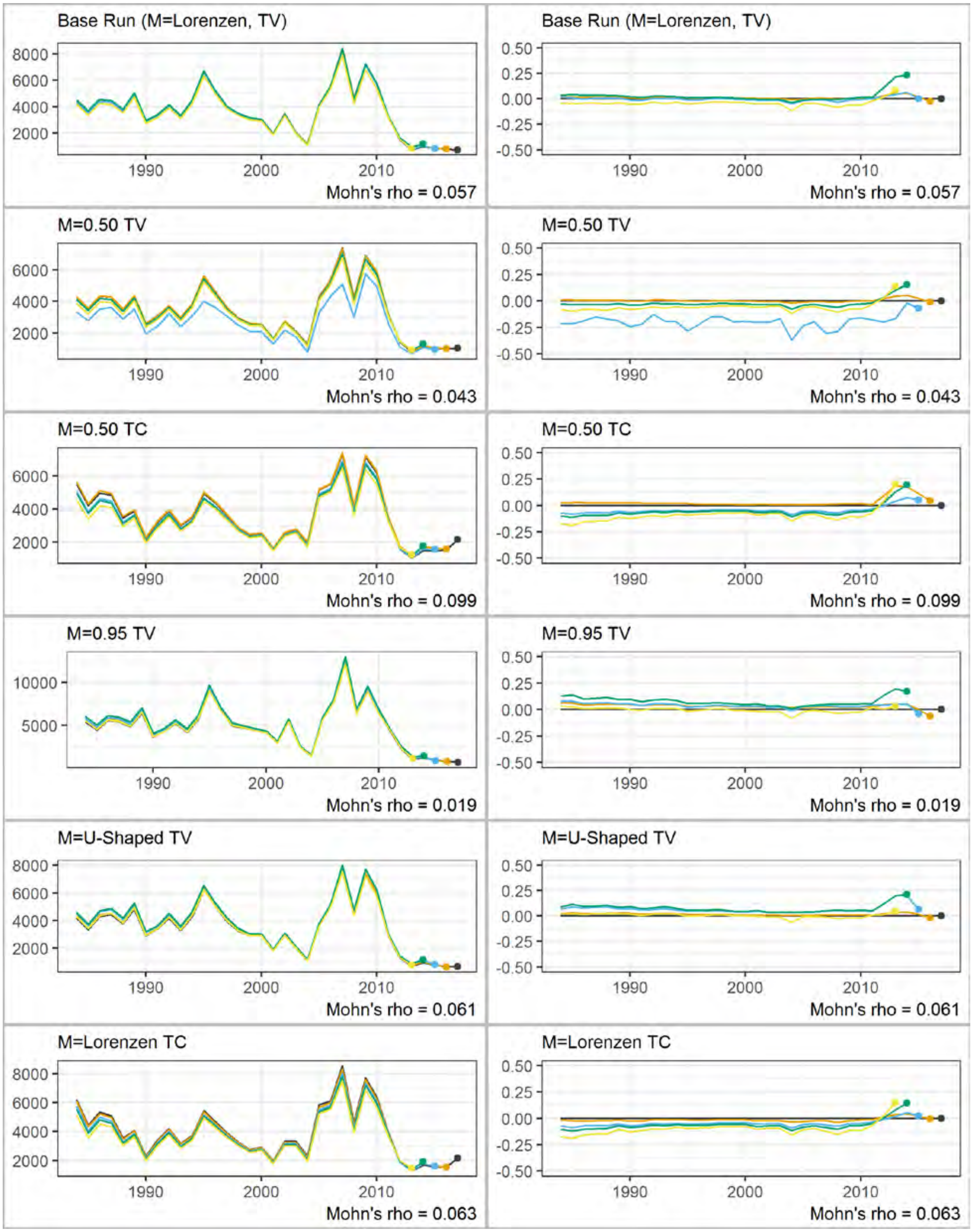


Figure A31. Retrospective patterns in exploitation rate from the new base run of the UME model under different M scenarios.

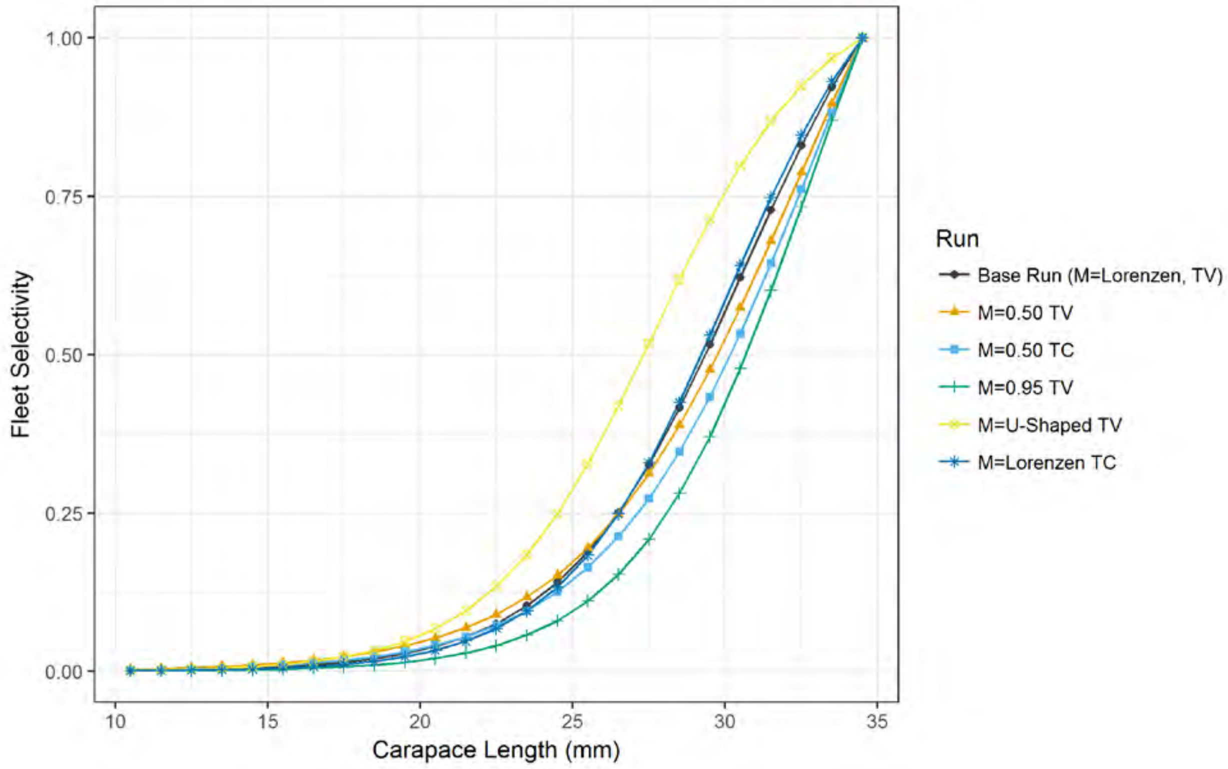


Figure A32. Mixed fleet selectivity patterns for the new base run of the UME model under different M scenarios.

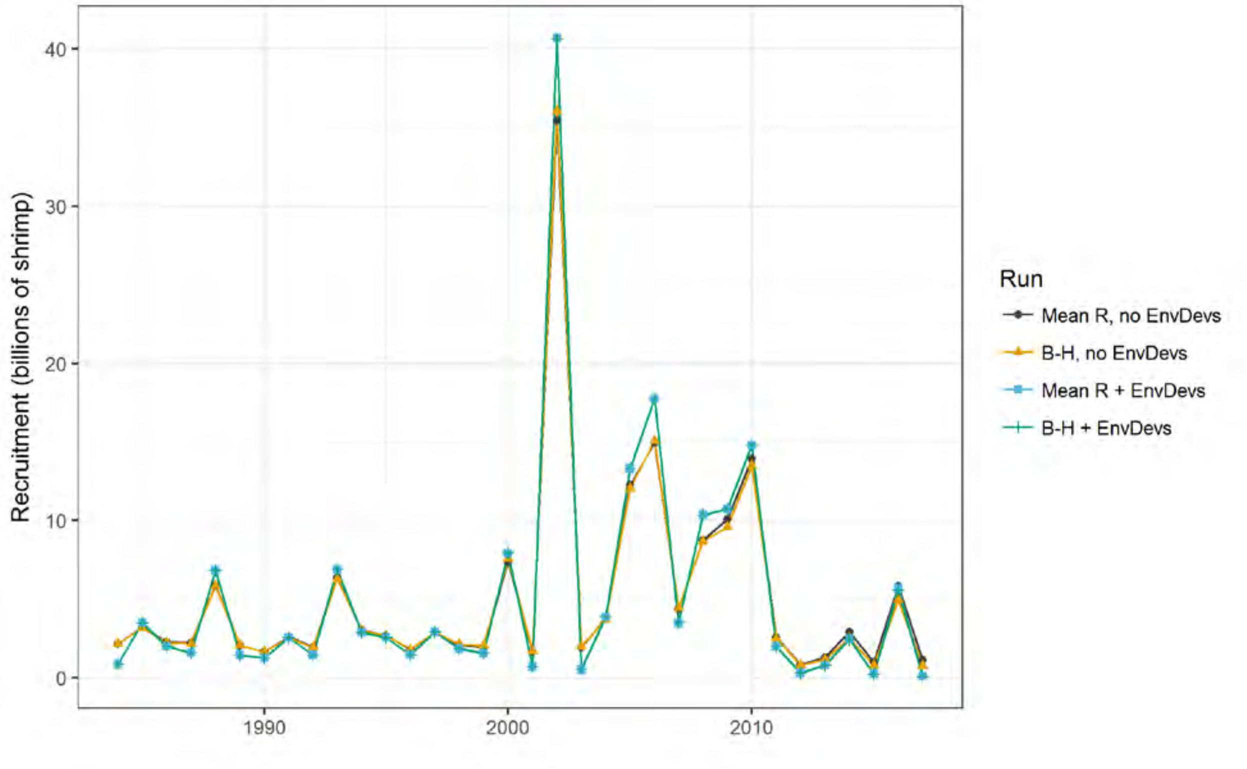


Figure A33. Estimates of recruitment from the new base run of the UME model fit with and without an environmental index of recruitment deviations.

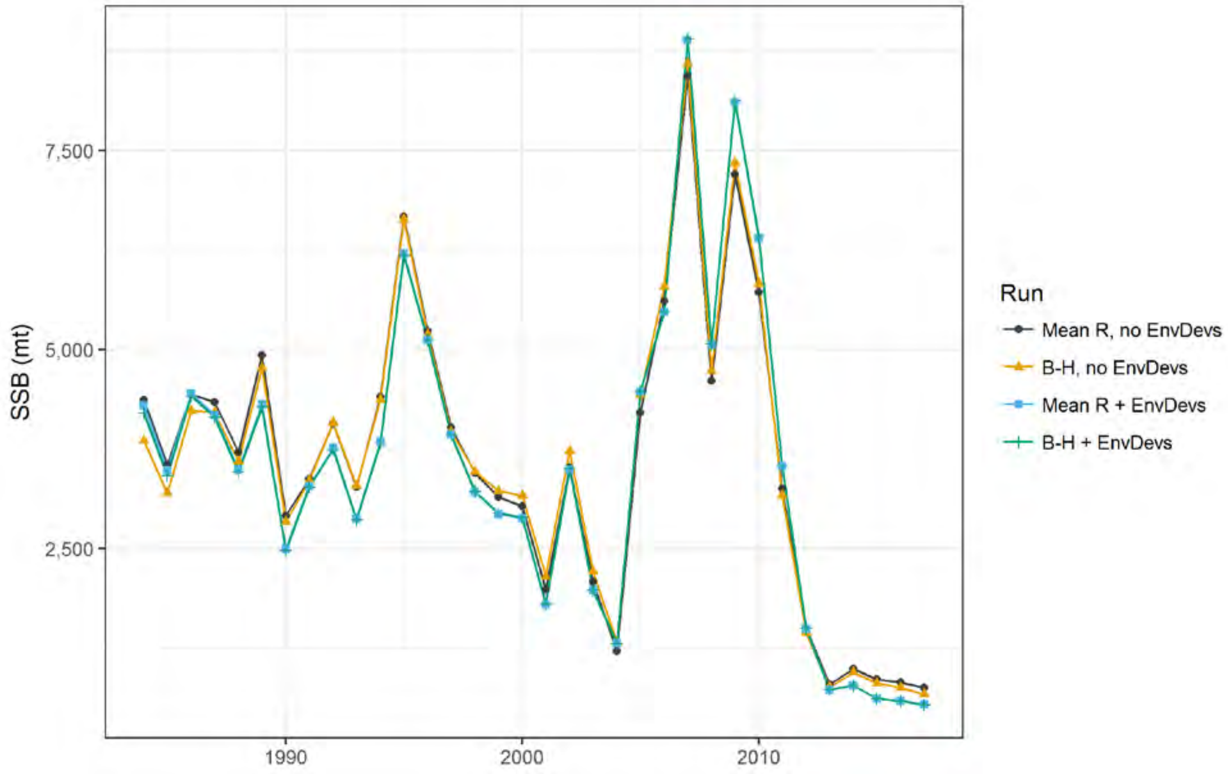


Figure A34. Estimates of SSB from the new base run of the UME model fit with and without an environmental index of recruitment deviations.

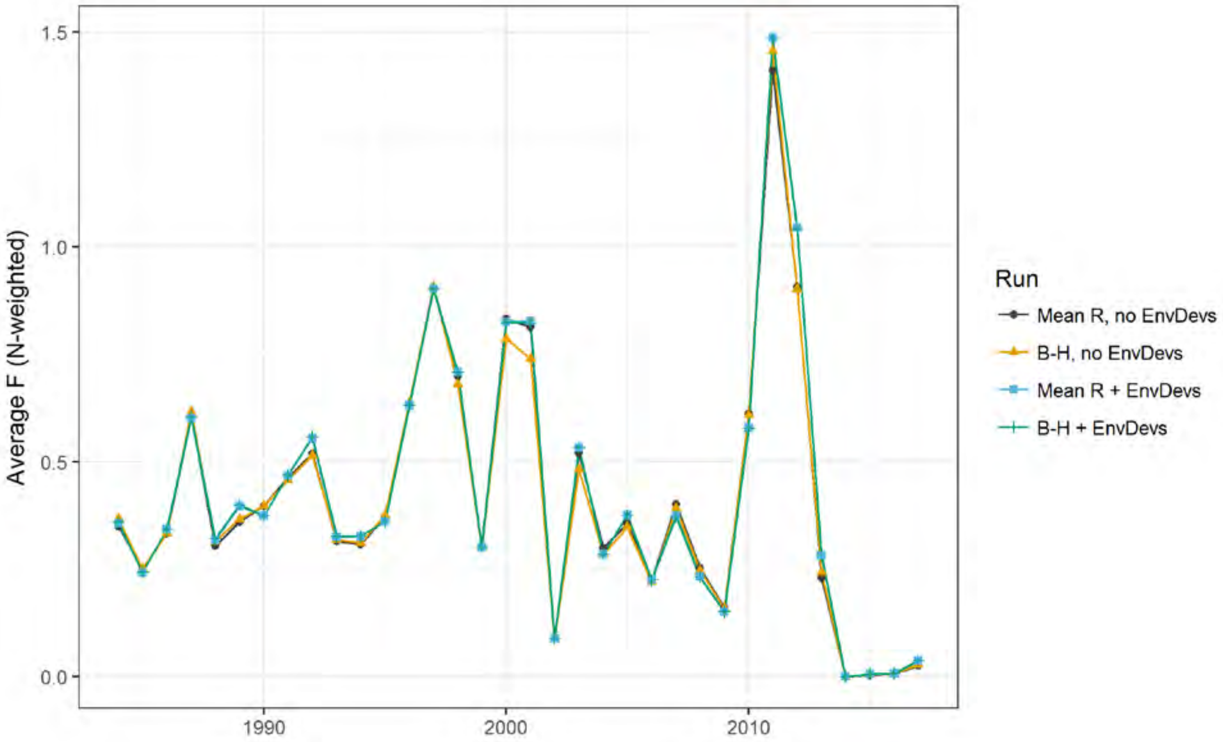


Figure A35. Estimates of average F from the new base run of the UME model fit with and without an environmental index of recruitment deviations.

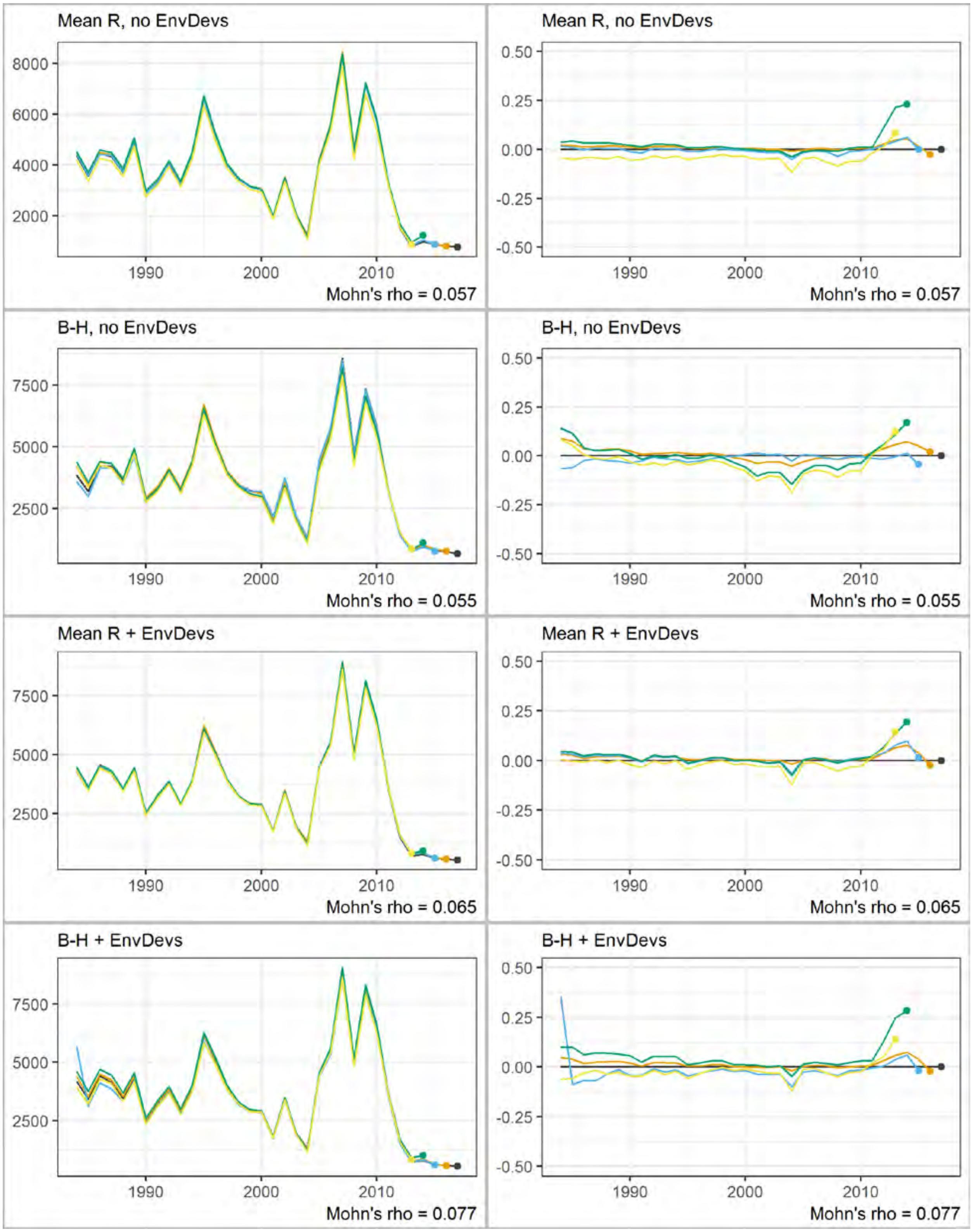


Figure A36. SSB retrospective patterns from the new base run of the UME model fit with and without an environmental index of recruitment deviations.

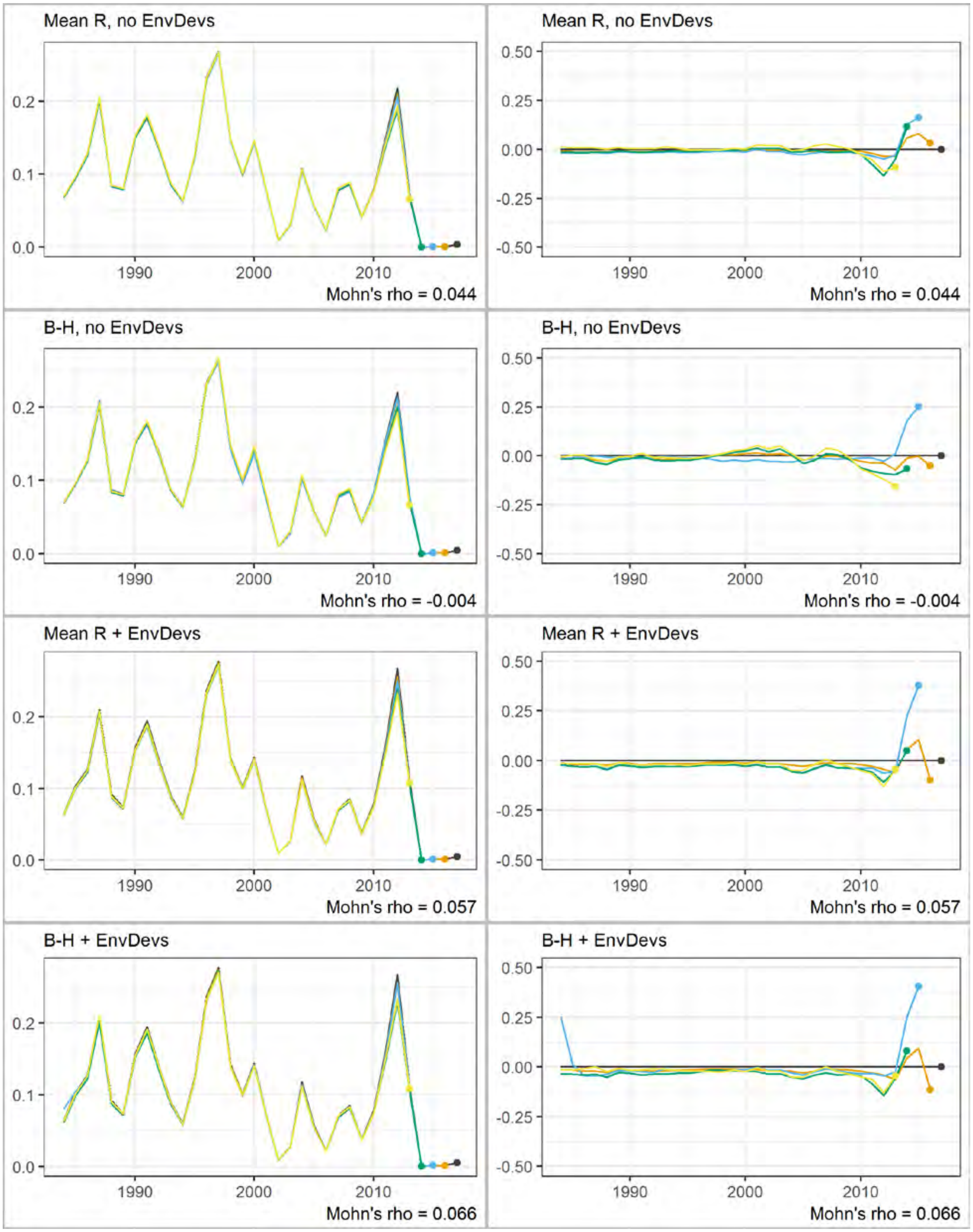


Figure A37. Exploitation rate retrospective patterns from the new base run of the UME model fit with and without an environmental index of recruitment deviations.

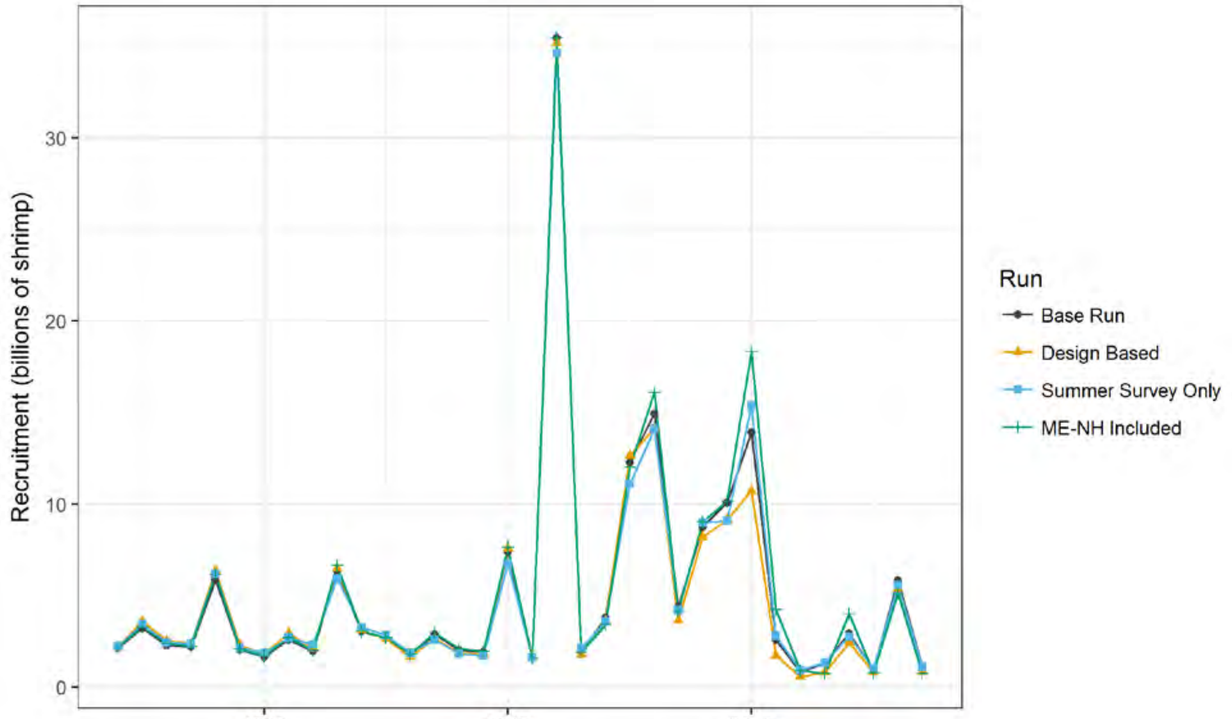


Figure A38. Estimates of recruitment from the new base run of the UME model under different index scenarios.

Figure A39. Estimates of SSB from the new base run of the UME model under different index scenarios.

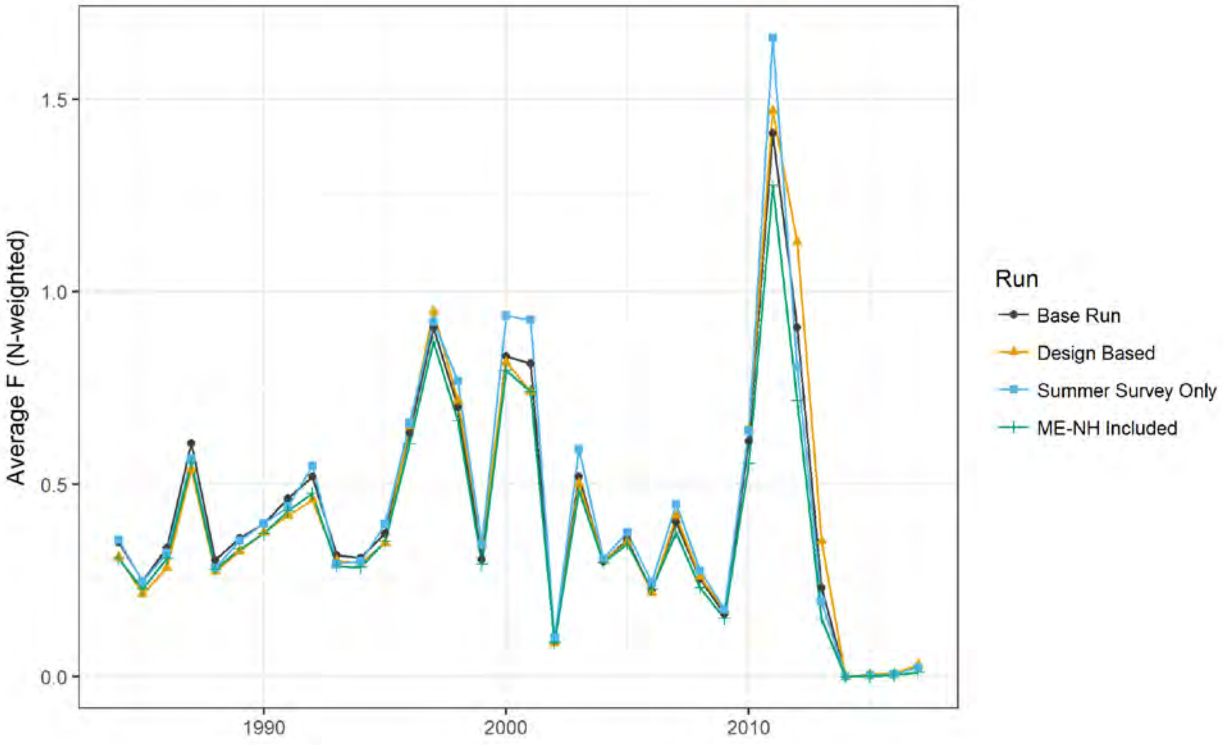


Figure A40. Estimates of average F from the new base run of the UME model under different index scenarios.

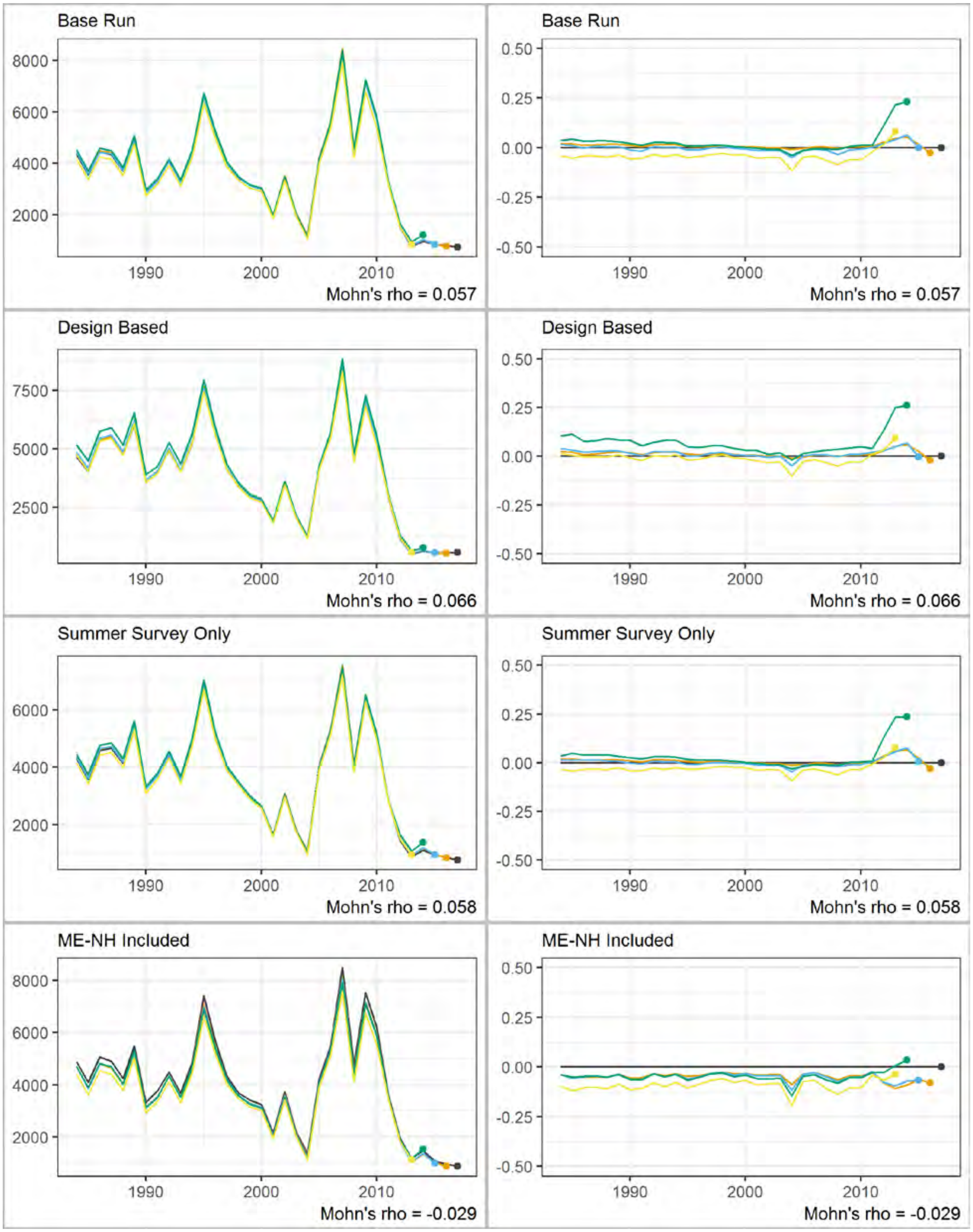


Figure A41.Retrospective patterns in SSB from the new base run of the UME model under different index scenarios.

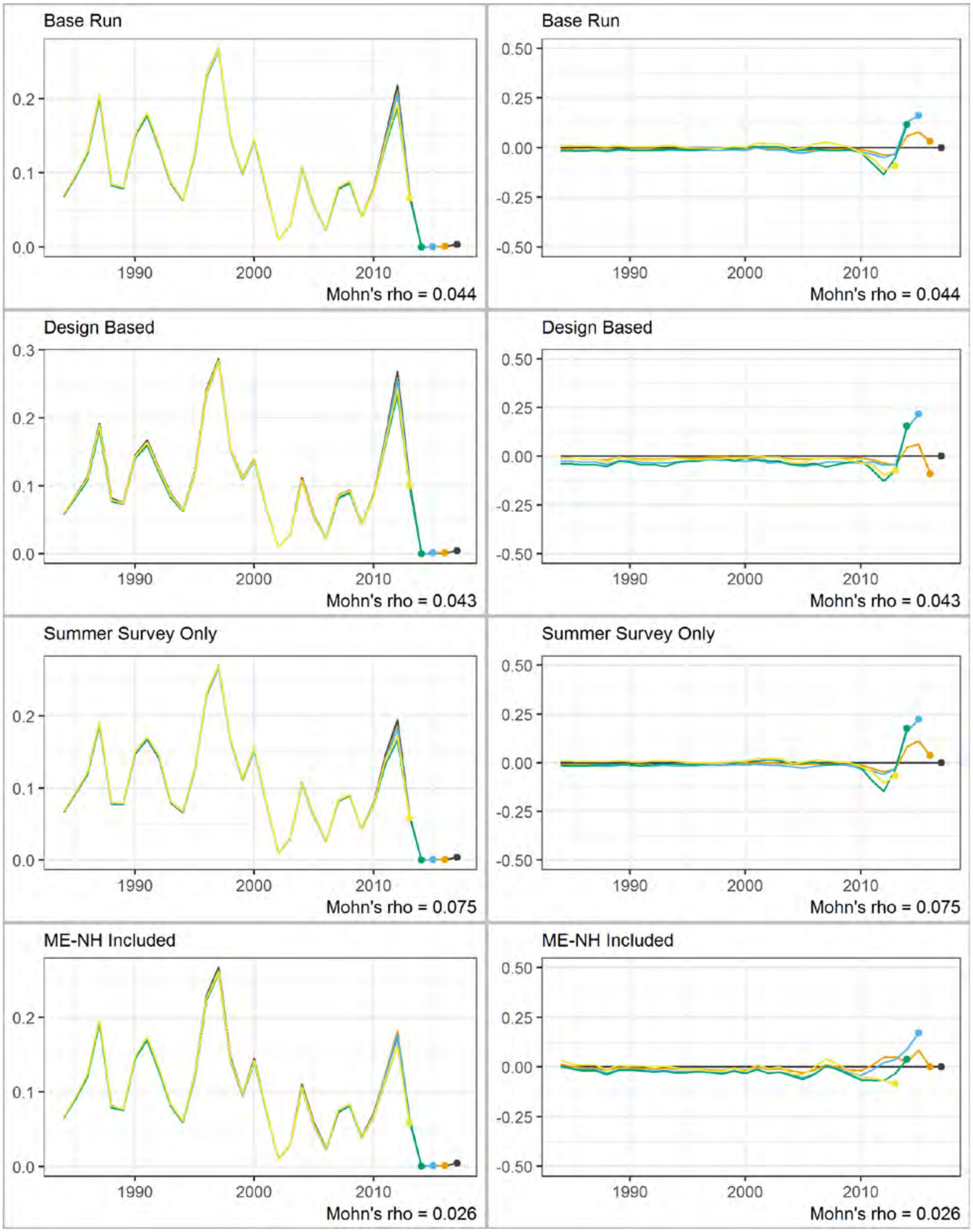


Figure A42.Retrospective patterns in exploitation rate from the new base run of the UME model under different index scenarios.

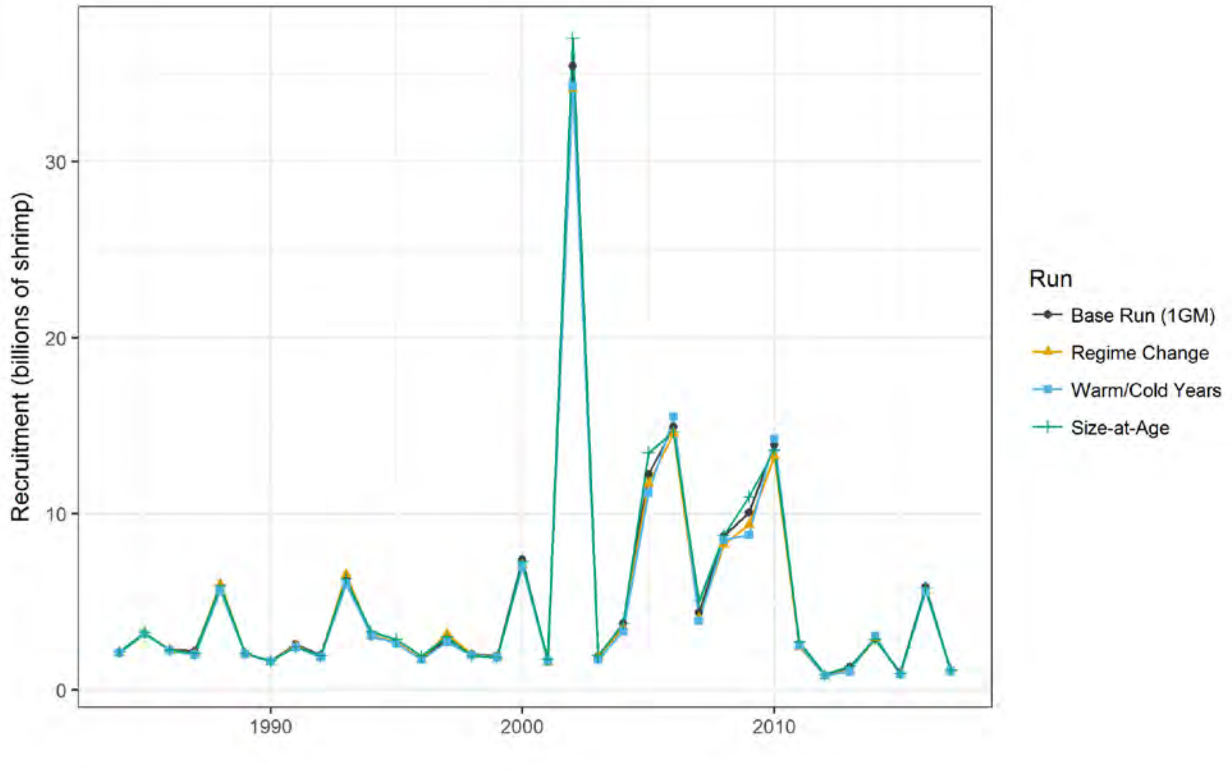


Figure A43. Estimates of recruitment from the new base run of the UME model under different growth block scenarios.

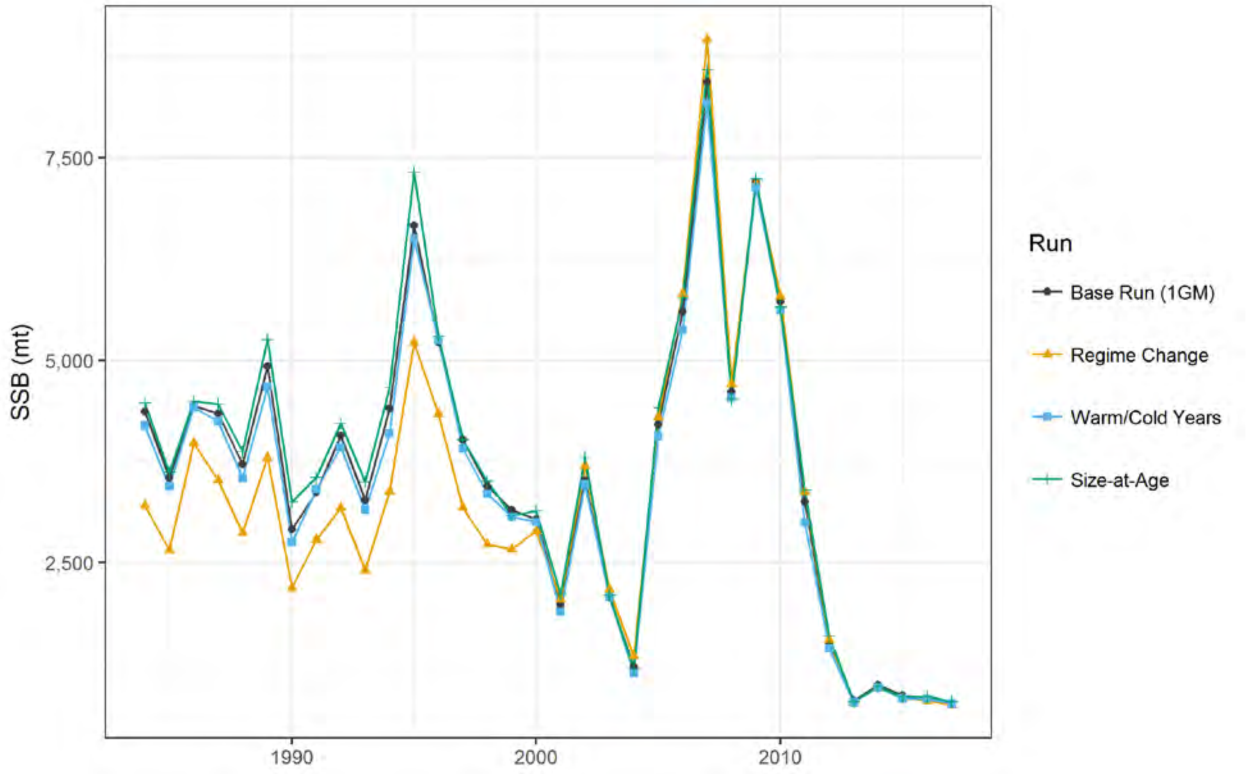


Figure A44. Estimates of SSB from the new base run of the UME model under different growth block scenarios.

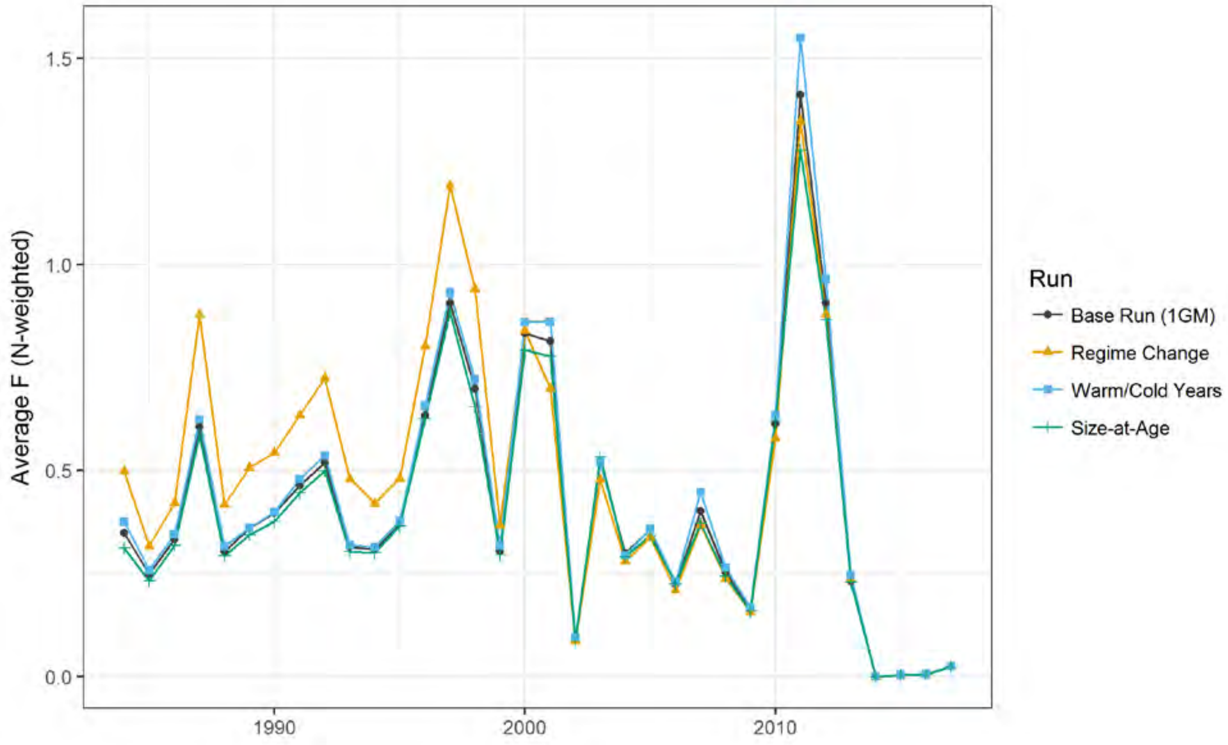


Figure A45. Estimates of average F from the new base run of the UME model under different growth block scenarios.

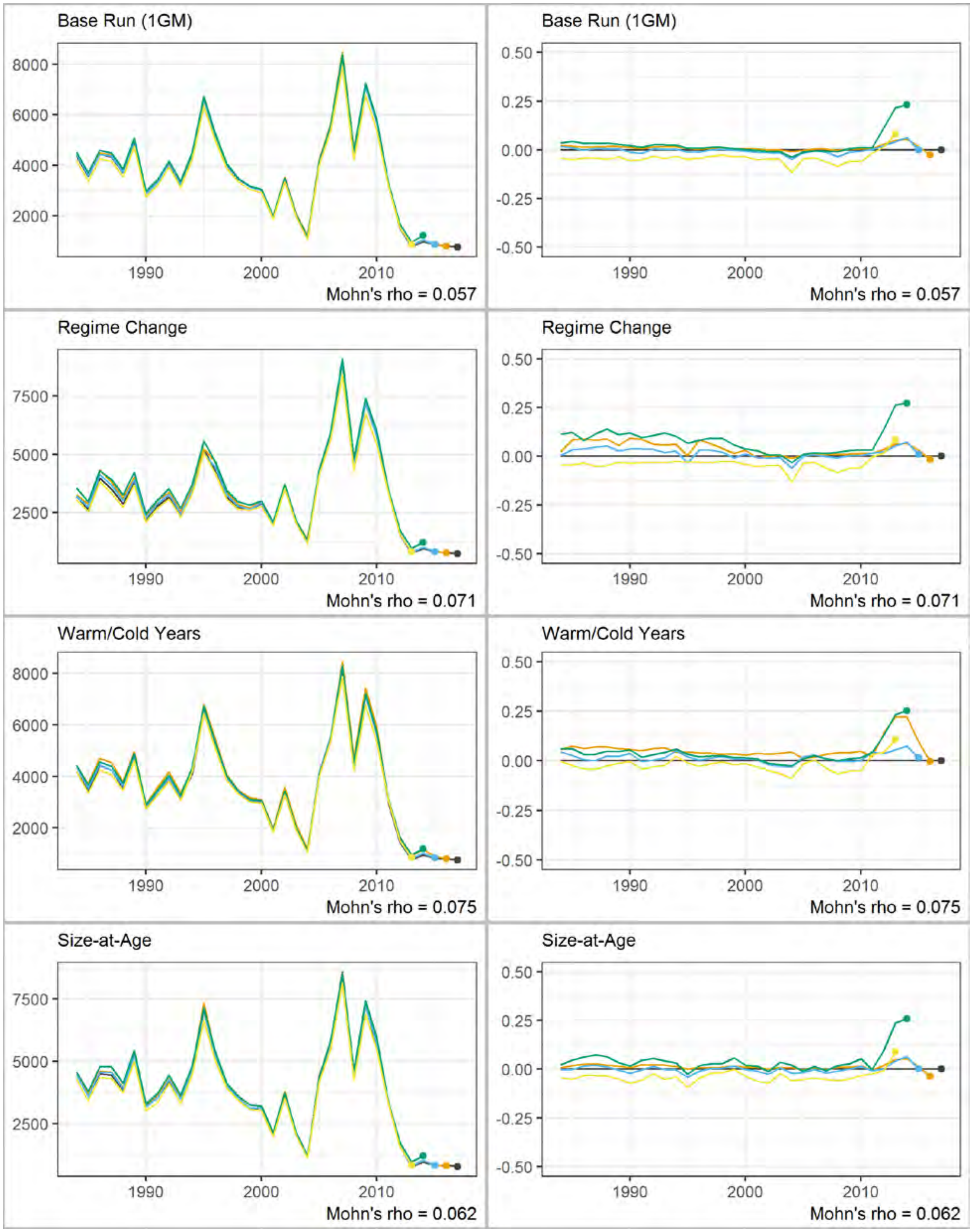


Figure A46. Retrospective patterns in SSB from the new base run of the UME model under different growth block scenarios.

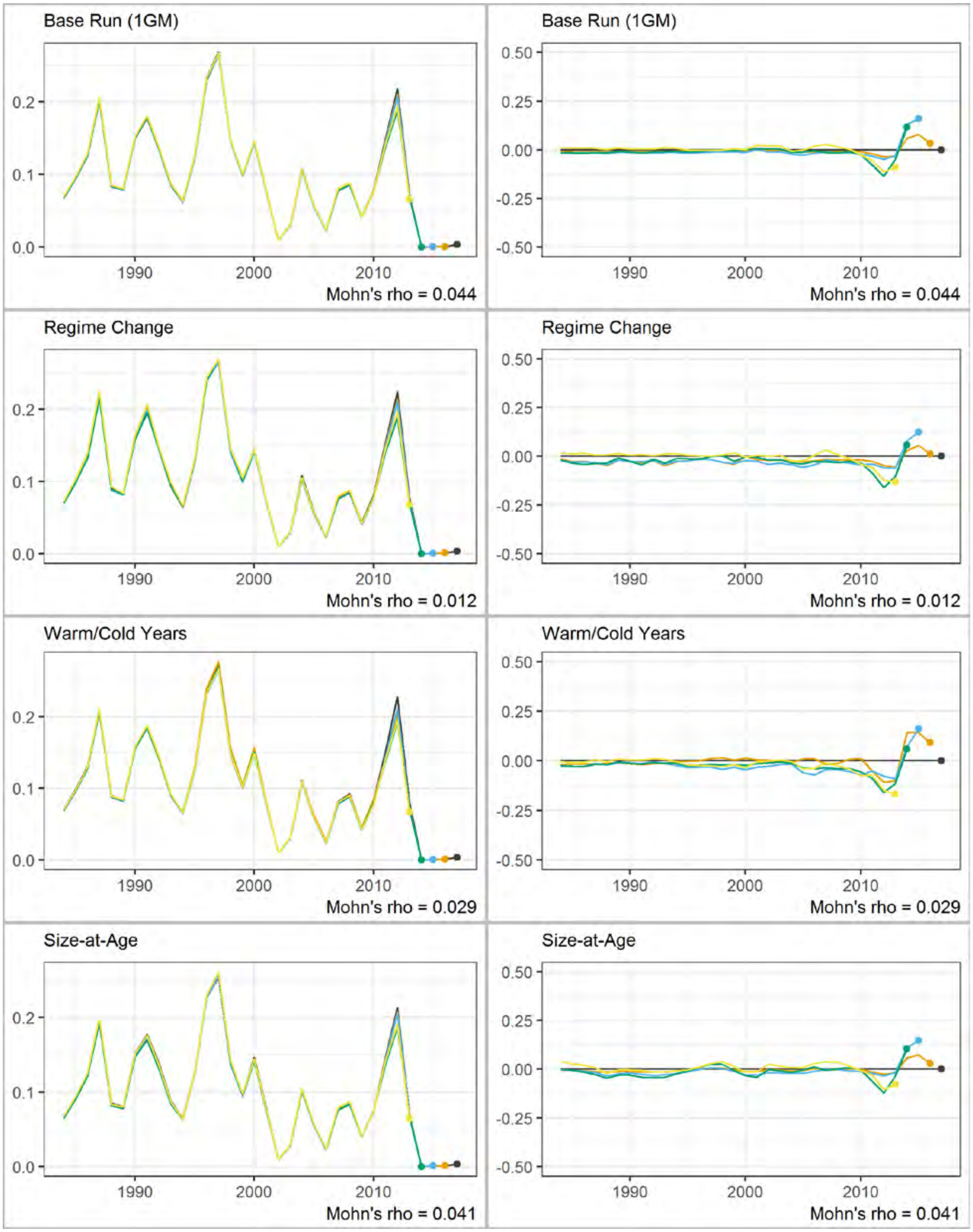


Figure A47.Retrospective patterns in exploitation rate from the new base run of the UME model under different growth block scenarios.

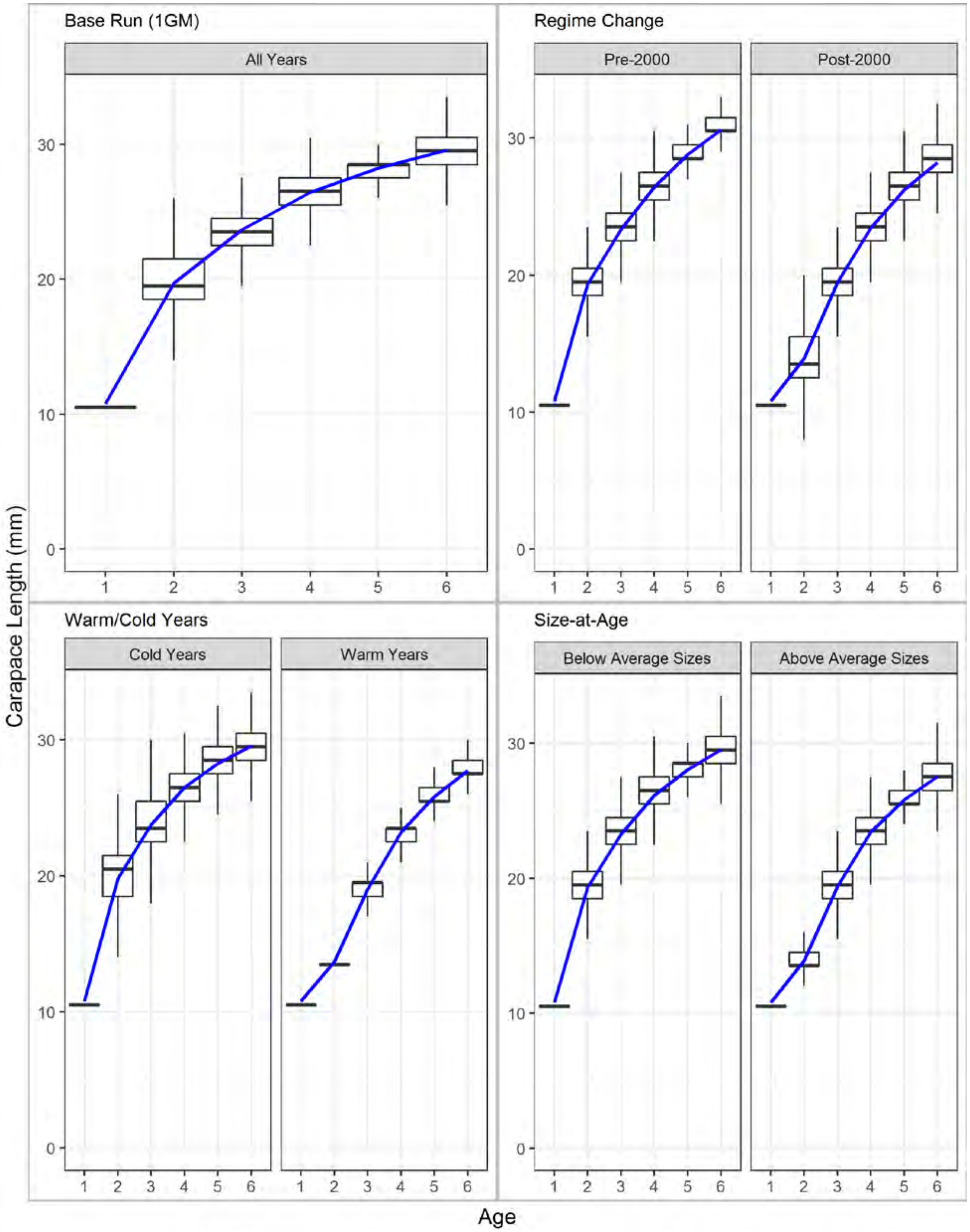


Figure A48. Growth patterns estimated the UME model under different growth block scenarios.

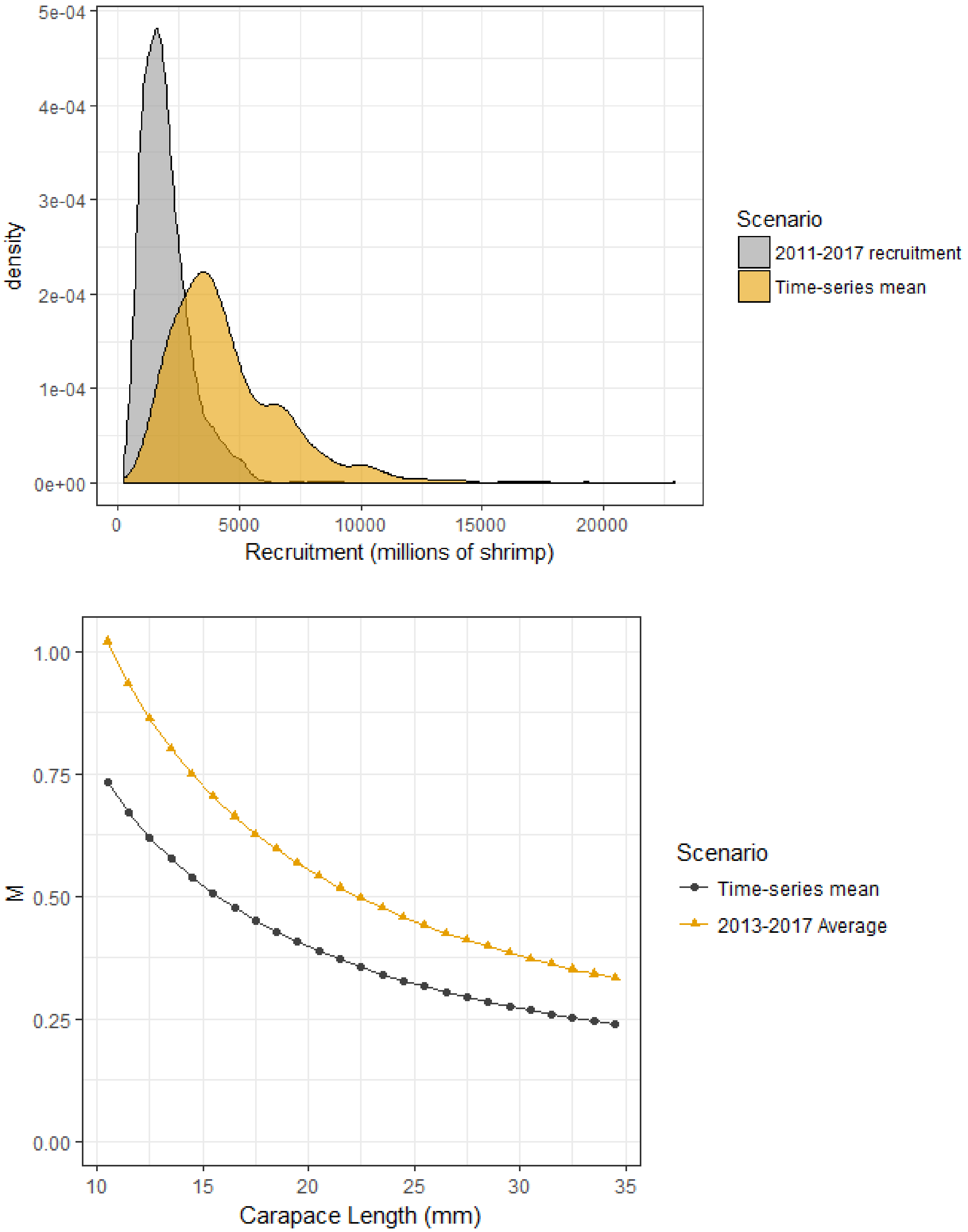


Figure A49. Distributions of recruitment (top) and estimates of natural mortality at length (bottom) used in projections for the new base run of the UME model.

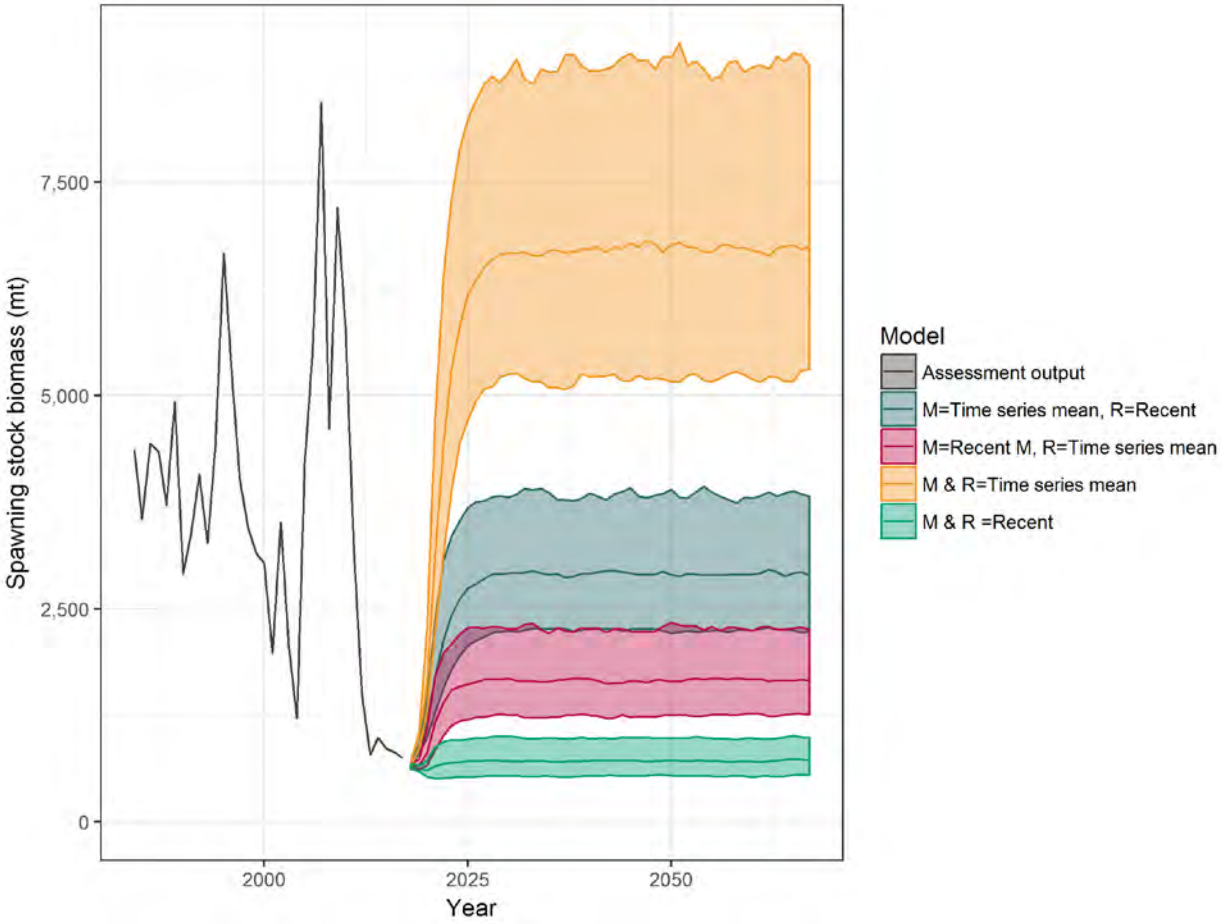


Figure A50. SSB trajectories under no fishing pressure for different M and recruitment scenarios for the new base run of the UME model.

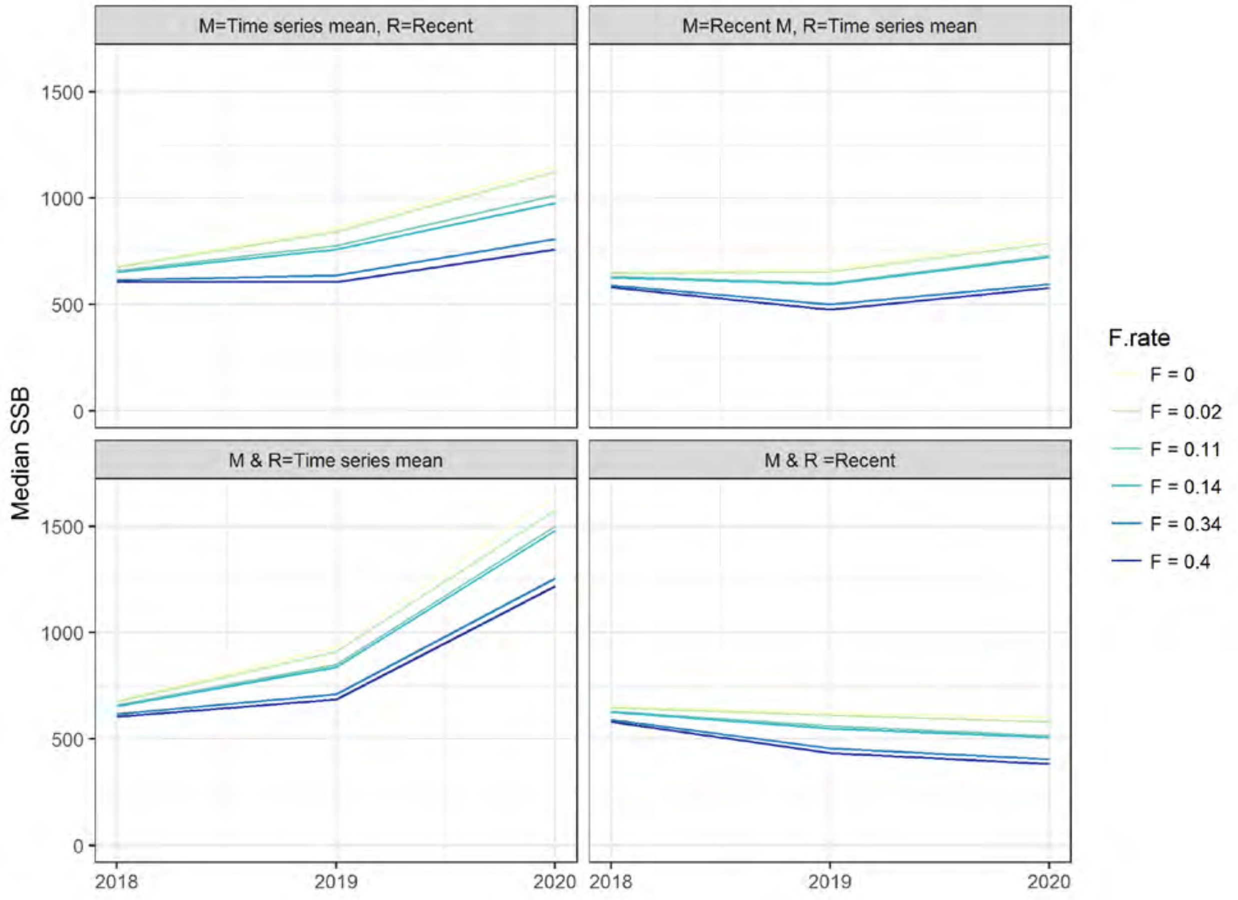


Figure A51. Trajectories of median SSB under different F rates for different M and recruitment scenarios for the new base run of the UME model.

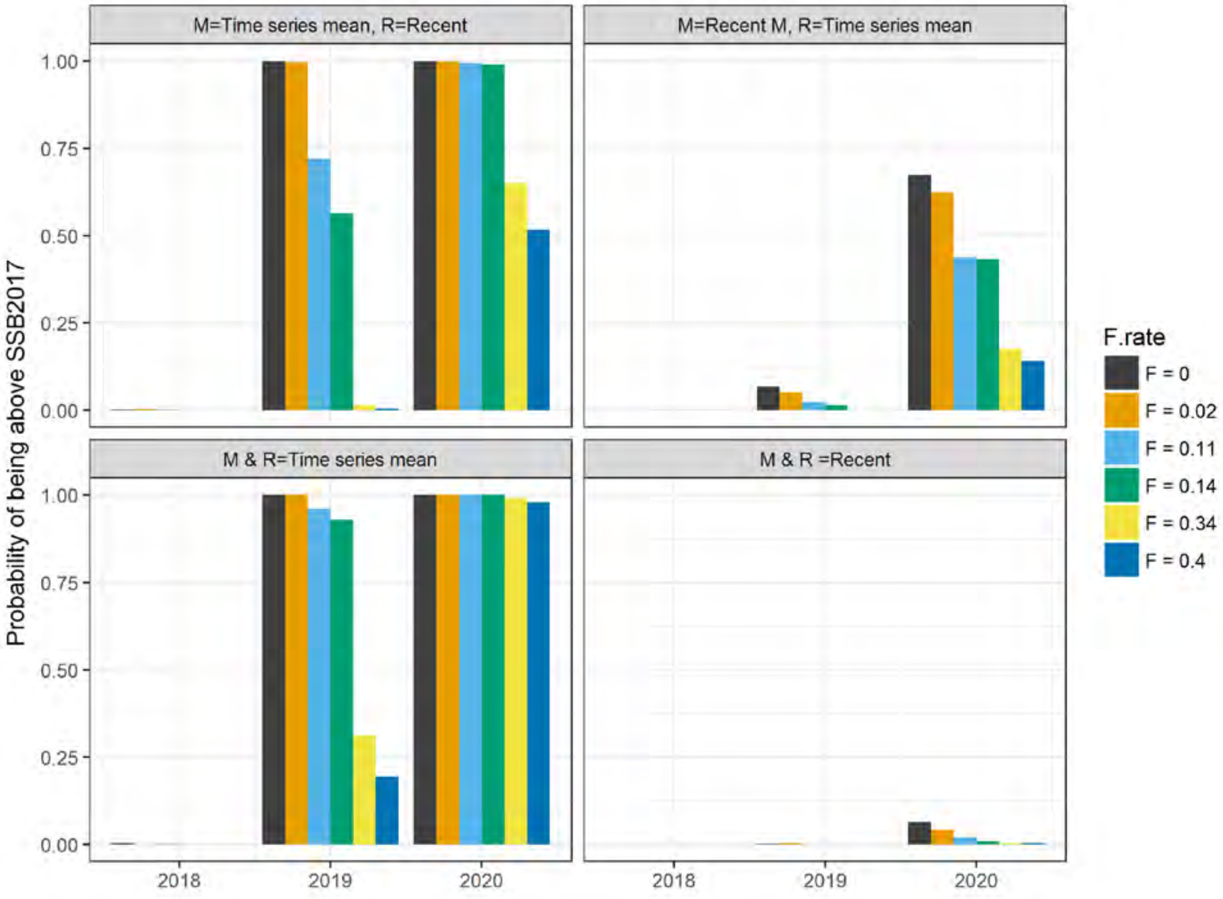


Figure A52. Probability of SSB being above SSB_{2017} under different F, M, and recruitment scenarios for the base run of the new UME model.