# G D A R

GULF DATA, ASSESSMENT, AND REVIEW

# GDAR 02
# Gulf Menhaden Stock Assessment

## 2016 Update

October 2016

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**GSMFC Number 254**

Gulf Data, Assessment, and Review
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# Gulf States Marine Fisheries Commission

## GDAR 02 - Gulf Menhaden Stock Assessment Update

**Submitted to the**
**Gulf States Marine Fisheries Commission**
**October 2016**

**Prepared by the**
**GSMFC State-Federal Fisheries Management Committee's**
**Menhaden Advisory Committee**

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A publication of the Gulf States Marine Fisheries Commission pursuant to National Oceanic and Atmospheric Administration Award Number NA10NMF4070006. This publication is funded by a grant from the National Oceanic and Atmospheric Administration. The views expressed herein are those of the author(s) and do not necessarily reflect the views of NOAA or any of its sub-agencies.

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## 2 Executive Summary

This assessment provides an update to the 2013 Gulf menhaden (*Brevoortia patronus*) benchmark for the Gulf of Mexico. The assessment was updated with recent data from 2012-2015. No changes in structure or parameterization were made to the base model run. Corrections made to data inputs were minor and are described in the body of this report.

The assessment period was 1977-2015. Updated data included commercial reduction, commercial bait, and recreational landings; age compositions from the commercial reduction landings; the coastwide juvenile abundance index based on seine surveys; the adult abundance index based on a gillnet survey; and the biological parameters for the assessment such as mean weight at age and natural mortality.

The primary model, updated here, was the Beaufort Assessment Model (BAM), a statistical catch-age formulation. Additional sensitivity analyses and Monte Carlo bootstraps (MCBs) were also conducted. Stock status was evaluated by measuring the 2015 spawning stock biomass (measured as fecundity) and the 2015 fishing mortality rate against the respective threshold benchmarks of $SSB_{30\%}$ and $F_{30\%}$.

For the base run configuration of BAM, the fishing mortality rate decreased during the 1990s and has remained at a low level since. Additionally, spawning stock biomass (measured as fecundity) has increased steadily since the 1990s and has remained at a high level since. **The base run configuration of BAM indicates that the Gulf of Mexico Gulf menhaden stock is not experiencing overfishing and is not overfished.** The sensitivity runs and MCBs indicate that the stock status is highly likely to be as indicated by the base run.

The stock status for the updated assessment remained the same as the stock status from the benchmark assessment completed during SEDAR 32A. The update assessment has a greater increase in population biomass and spawning stock biomass than the benchmark assessment did; however, this is likely due to increasing indices for both the juvenile abundance index and the adult gillnet index. In addition, the estimate of $R_0$ increased with the additional years of data; however, the parameter was well estimated based on a likelihood profile.

The Menhaden Advisory Committee (MAC) recommends that the next benchmark assessment occur in two years (2018), that new data be further explored and considered, and that data currently being used be re-evaluated.

## 3 Data Review and Updates

In the SEDAR 32A benchmark, the assessment period was 1977–2011. In this update, the terminal year was extended to 2015; making the assessment period 1977-2015. Many of the data sources for the stock assessment remained static, while others were simply updated with the additional four years of data. Bait landings were modified slightly, as described below.

In this update assessment, the Beaufort Assessment Model (BAM) was fitted to the same data sources as in SEDAR 32A:

- Landings: commercial reduction, commercial bait, and recreational
- Indices of abundance: juvenile abundance index based on seine surveys and adult abundance index based on a gillnet survey
- Age compositions of landings: commercial reduction
- Length compositions of indices: gillnet adult survey

### 3.1 Life History

Some life history inputs from SEDAR 32A remained the same in this assessment including the length-length conversions, the ageing error matrix, the age-length key, and the maturity vector. Other life history inputs were updated to include samples from additional years of data.

The overall weight-length relationship and von Bertalanffy growth relationship were updated to include new biological data from 2012 to 2015. These relationships were determined using the same methods as the benchmark assessment with the overall differences in the relationships being small. Changes to these relationships impacted the overall mean weight at age during spawning, the mean weight at age during the middle of the fishing year, the mean fecundity at age, and the natural mortality at age. The mean weight at age during spawning changed less than 1% per age, while the mean weight at age during the middle of the fishing year also changed less than 1% per age. Mean fecundity at age changed 3% or less by age. Finally, natural mortality was updated using the overall mean weights at age using the same methods as used in the last benchmark assessment (Table 1).

### 3.2 Landings

Estimates of landings were updated with 2012-2015 data using the methods outlined in SEDAR 32A (Table 2). Commercial reduction landings and recreational landings were strictly updated using the same methods as during the benchmark assessment. Commercial bait landings were also updated with 2012-2015 data; however, a decision made during the benchmark assessment was reversed. As a consequence, the entire bait landings time series was adjusted. In the previous assessment, gear codes 100 and 125 from the Accumulated Landings System (ALS) database were censored as those landings were thought to be part of the reduction landings time series because the gears indicate purse seine gears. However, a bait boat is currently operating in the Gulf of Mexico and unloading their catches as bait, which are being recorded under those two censored gear codes. Therefore, the MAC made the decision to keep codes 100 and 125 as bait landings. The resultant coastwide catches increased only slightly (less than 2% annually).

### 3.3 Indices of abundance

Both the juvenile abundance index based on seine surveys from LA, AL, and MS, and the adult abundance index based on a gillnet survey from LA were updated with data from 2012-2015. Each index was standardized using the methods from the benchmark assessment.

The terminal year of the seine index in the last benchmark assessment was 2010, because the state of LA had made changes to their survey at the end of 2010. It was unclear to the MAC how the survey changes would impact standardization of the abundance index. So the MAC decided to censor the data point. For this update assessment, the index was updated to include 2011 to 2015. The state of LA has made several changes to sampling over that time period as summarized here:

- Prior to October of 2010 all sites were sampled monthly from January to August and twice monthly from September to December;
- In October of 2010, Louisiana Department of Wildlife and Fisheries (LDWF) expanded the number of survey sites and began sampling all sites monthly;
- In January of 2011, all seine sites began being sampled quarterly (using standard quarters beginning in January, April, July, and October) with all samples due by the end of each quarter;
- Beginning in February of 2013, seine samples were conducted quarterly, during the first month of LDWF selected quarters only (sampling occurred in February, May, August, and November); and
- In July of 2014, seine sampling went to a monthly schedule with all sites sampled monthly.

The MAC discussed these changes over the past five years. The MAC requested seeing the index with and without LA (Figure 1) to see the impact the inclusion of LA would have on the overall trend of the index. Based on these versions of the index, the MAC determined that the state of LA was adequately sampling for index determination, regardless of the survey changes. The addition of LA resulted in the same trend over time but seemed to diminish the variability associated with the index given the larger sample sizes for each year. Thus, the index was updated to include all years through the terminal year of 2015 (Table 3).

The gillnet survey for the adult abundance index has also experienced some changes over the past few years. Prior to October of 2010, all historic gillnet sites (fixed stations) were sampled monthly from October through March and twice monthly from April through September. In October of 2010, additional fixed sampling sites were added to increase the spatial coverage of the survey in all basins. All historic and new sites were sampled on the same schedule as described above. In April of 2013, the survey design was modified to be a random draw of a set number of fixed stations (including both old and new) within each basin each month. The number of samples taken from each basin each month was based on a statistical review and analysis completed by LDWF. Random stations are sampled at the same frequency as described above. During months with two rounds of sampling, random stations are drawn with replacement during each round.

In addition to the survey changes in the state of LA, station identification numbers changed in the state database for each survey since the last assessment. Because of that, data for station codes used in the last assessment needed to be matched up to station codes from the current database using a key provided by the state of LA. This led to slightly different sample sizes for the length compositions associated with the gillnet index and to slightly different data from the state of LA for the seine index. However, the overall indices did not change in trend and the various versions of the index were contained within the confidence intervals of each other (Figures 1 and 2; Table 3).

### 3.4 Length Composition

Length compositions were developed from the gillnet survey. Sample sizes for the gillnet length compositions increased slightly compared to the benchmark assessment due to the matching of station codes between the new and old databases (see section above for a description; Figure 3; Table 4; Table 6). However, the overall proportions of lengths per bin did not change significantly (Figure 4). The gillnet length compositions were updated to include 2012 to 2015 using the same methods as used in the benchmark assessment.

### 3.5 Age Composition

Age data were available from the commercial reduction fishery. Ages greater than four were pooled to create a plus group. Fishery age compositions were updated to include 2012 to 2015 using the same methods as in the last benchmark assessment (Table 5).

# 4 Stock Assessment Model and Results

## 4.1 Model Methods

### 4.1.1 Overview

The Beaufort Assessment Model (BAM) that was developed for the Gulf menhaden benchmark during SEDAR 32A was updated in this assessment. The BAM applies a statistical catch-age formulation (Williams and Shertzer 2015) and was implemented with the AD Model Builder software (ADMB Foundation 2011).

### 4.1.2 Data Sources

The catch-age model included data from two sets of fishery-independent surveys and one fleet consisting of the commercial reduction landings, commercial bait landings, and recreational landings. The data sources used for this assessment were the same as those used for the benchmark assessment. The model was fitted to annual landings, annual age compositions of landings, two indices of abundance (seine juvenile abundance index and gillnet adult abundance index), and annual length compositions of the gillnet adult abundance index. Data used in the model are described and tabulated in Section 3 of this report.

### 4.1.3 Base Model Configuration

Base model configuration was identical to the base model configuration during the SEDAR 32A benchmark assessment. A general description of the base run configuration follows.

**Stock Dynamics:** In the assessment model, new biomass was acquired through growth and recruitment, while abundance of existing cohorts experienced exponential decay from fishing and natural mortality. The population was assumed closed to immigration and emigration. The model included age classes 0 to 4+, where the oldest age class 4+ allowed for the accumulation of fish (i.e., plus group).

**Initialization:** Initial (1977) abundance at age was assumed equal to the equilibrium age structure given initial fishing mortality estimated in the model. The equilibrium age structure was computed for ages 0 to 4 based on natural and fishing mortality, where $F$ was set equal to the initial fishing mortality rate estimated in the model based on fitting to the available data.

**Natural Mortality Rate:** The natural mortality rate ($M$) was assumed constant over time, but decreasing with age. The form of $M$ as a function of age was based on Lorenzen (1996). The Lorenzen estimates at age, $M_a$, were rescaled such that the age-2 $M$ was equal to the natural mortality estimated from a tagging study (Ahrenholz 1981), as was done in the benchmark assessment.

**Growth:** Mean size at age of the population (fork length, FL) was modeled with the von Bertalanffy growth equation where the parameters were estimated in the model. Weight at age was fixed and an input into the model, as was done for the benchmark assessment. For fitting length composition data, the distribution of size at age was assumed normal with the coefficient of variation (CV) estimated by the assessment model.

**Female Maturity:** Females were modeled to be fully mature at age-2, while the proportion mature at ages 0 and 1 were fixed at 0.0.

**Spawning Stock:** Spawning stock was modeled using fecundity, which is a product of the number of females, the proportion mature, and the mean fecundity at age. For Gulf menhaden, spawning was considered to occur on January 1, the same date at which the fish turned a year older.

**Recruitment:** Expected recruitment of age-0 fish was predicted from the spawning stock using the Beverton-Holt spawner-recruit model with the steepness parameter fixed at 0.75. Annual variation in recruitment was assumed to occur with lognormal deviations for the years 1977 – 2015. Annual recruitment variation was informed by annual age composition data during 1977 – 2015 and an index of abundance for recruitment during 1996 – 2015. Autocorrelation in recruitment deviations was assumed to be zero.

**Landings:** The model included a time series of landings that was a combination of landings from the commercial reduction purse seine fleet, commercial bait landings, and recreational landings for 1977 – 2015. A large portion of the landings, ~99%, are from the commercial reduction fleet. Landings were modeled with the Baranov catch equation (Baranov 1918) and were fitted in units of 1,000s of metric tons (mt).

**Fishing Mortality:** The assessment model estimated an annual full fishing mortality rate (*F*) for each year of the landings time series. Age specific rates were then computed as the product of full *F* and selectivity at age.

**Selectivities:** The selectivity curve applied to landings was age-specific, dome-shaped, and fixed for most ages. Age-0 selectivity was fixed at 0.0, age-2 selectivity was fixed at 1.0, ages-3 and -4 selectivities were fixed at 0.35, and age-1 selectivity was estimated, as was done during the benchmark assessment. Selectivity for the recruitment index (seine index) was 1.0 for age-0 and 0.0 for all other ages. Finally, selectivity for the gillnet index was estimated as a logistic or flat-topped function with two parameters being estimated.

**Indices of Abundance:** The model was fitted to two indices of relative abundance: a seine index (1996 – 2015) and a gillnet index (1988 – 2015). The seine index was considered to represent relative changes in recruitment over time, and the gillnet index was considered to represent relative changes in adult abundance over time. Predicted indices were conditional on the selectivity specified or estimated and were computed from abundance at the beginning of the year for the seine index and the mid-point of the year for the gillnet index.

**Catchability:** In the BAM, catchability scales indices of relative abundance to estimated exploitable abundance at large. Following the methodology used in the SEDAR 32A base run, the update assessment assumed time-invariant catchability for both the seine index and the gillnet index.

**Fitting Criterion**: The fitting criterion was a penalized likelihood approach in which observed landings were fitted closely, and observed composition data and abundance indices were fitted to the degree that they were compatible. Landings and index data were fitted using lognormal likelihoods. Composition data were fitted using robust multinomial likelihoods (Francis 2011). For the robust multinomial likelihood for the age compositions, the number of purse seine sets sampled was used as the measure of effective sample size. For the robust multinomial likelihood for the length compositions, the number of gillnet sets sampled was used as the measure of effective sample size.

The model includes the capability for each component of the likelihood to be weighted by user-supplied values. For data components, these weights were applied by either adjusting CVs (lognormal components) or adjusting effective samples sizes (multinomial components). In this application to Gulf menhaden, CVs of landings (in arithmetic space) were assumed equal to 0.04. Weights on other data components (indices, age and length compositions) were adjusted iteratively until the standard deviation of the normalized residuals (SDNR) were near 1.0, as was done in the last assessment. The SDNR for the age compositions was near 0.5, as in the last assessment.

**Parameters Estimated:** The model estimated annual fishing mortality rates, selectivity parameters, catchability coefficients for each index, parameters of the spawner-recruit model, annual recruitment deviations, and growth parameters. All parameters were estimated as described in SEDAR 32A.

### 4.1.4 Per Recruit and Equilibrium Analyses

Spawning potential ratio was computed as a function of $F$, as were equilibrium landings and spawning biomass. Equilibrium analyses applied the most recent selectivity pattern.

### 4.1.5 Biological Reference Points

The biological reference points (benchmarks) of interest for this assessment are spawning potential ratio (SPR) based. Given the uncertainty with the spawner-recruit curve and the fact that steepness was fixed, the MAC decided to use SPR-based reference points. The fishing mortality reference points are $F_{30\%}$ for the threshold and $F_{35\%}$ for the target. The spawning stock is measured in total population fecundity and is the fecundity associated with the fishing mortality rate benchmarks, $SSB_{30\%}$ and $SSB_{35\%}$. The benchmarks are conditional on the estimated selectivity function. Therefore, overfishing is defined as $F > F_{30\%}$, and overfished is defined as $SSB < SSB_{30\%}$. Current status of the stock is represented by $SSB$ in the latest assessment year (2015), and current status of the fishery is represented by the *F* from the terminal year (2015). The calculation of reference points was done exactly as it was done in the SEDAR 32A benchmark assessment.

#### 4.1.6 Sensitivity and Retrospective Analyses

Three sets of sensitivity runs were completed in order to explore different parameterizations of the model, new or different data inputs, or if a retrospective pattern exists.

First, sensitivity runs were completed with different parameterizations of the base run of the stock assessment. A sensitivity run was completed allowing steepness (*h*) of the stock-recruitment curve to be estimated freely, as opposed to being fixed at 0.75, as in the base run. This sensitivity run allowed exploring estimability of the steepness parameter, which might be possible given that there is more contrast in the data during recent years. A sensitivity run was also completed allowing the selectivity for ages-3 and -4 for the commercial reduction fishery to be estimated freely, as opposed to being fixed at 0.35, as in the base run. This sensitivity allowed for the exploration of the estimability of the selectivity curve for the fishery given the additional contrast in the input data.

Second, sensitivity runs were completed considering different options for data that were input in the benchmark stock assessment. A sensitivity run was completed with bait landings treated as they were in the benchmark assessment. Specifically, gear codes 100 and 125 were censored from the bait landings. This allowed the MAC to determine the influence of the bait landings from those codes on the outcomes of the assessment. The censoring of those landings was expected to have very little influence on the overall outcomes of the stock assessment. A sensitivity run was also completed using the seine index from the last benchmark assessment. Given the changes in the seine survey over time in the state of LA, the MAC wanted to see the impact of the decision to include the 2011-2015 data into the seine index.

Third, sensitivity runs were completed to consider the new life history information available from Brown-Peterson et al. (In review). Specifically, the interest was in seeing the response to changes in the updated maturity ogive and the updated mean age specific fecundity vector. The MAC was interested to determine how the updates to these data would impact assessment outcomes both as standalone changes and as changes in tandem. As a result, five sensitivity runs were completed. The first run increased age-1 maturity from 0.0 to 0.68 indicating that a large proportion of fish that are age-1 on January 1 are mature. The second run changed the fecundity vector to the lower end fecundity estimated from Brown-Peterson et al. (In review) based on the lowest number of spawns per season by age. The third run changed the fecundity vector to the higher end fecundity estimated from Brown-Peterson et al. (In review) based on the highest number of spawns per season by age. The fourth run changed the fecundity vector to the lower estimate and changed the maturity at age-1 to 0.68. The fifth run changed the fecundity vector to the higher estimate and changed the maturity at age-1 to 0.68.

Finally, a retrospective analysis was completed by sequentially removing the last year of data from the assessment such that the terminal year was 2014, 2013, 2012, and 2011. This analysis was completed to see how influential additional years of data are on the outcomes of the stock assessment and is a common diagnostic of stock assessments.

List of sensitivity runs:

1. Steepness freely estimating
2. Freely estimating ages-3 and -4 selectivity for the commercial reduction fishery
3. Using seine index from last benchmark assessment
4. Excluding gears 100 and 125 from the bait landings
5. Retrospecitve with the terminal year of 2014
6. Retrospecitve with the terminal year of 2013
7. Retrospecitve with the terminal year of 2012
8. Retrospecitve with the terminal year of 2011
9. Maturity at age-1 = 0.68
10. Fecundity vector changed to low values from Brown-Peterson
11. Fecundity vector changed to high values from Brown-Peterson
12. Fecundity vector changed to low values from Brown-Peterson, maturity at age-1 = 0.68
13. Fecundity vector changed to high values from Brown-Peterson, maturity at age-1 = 0.68

### 4.1.7 Uncertainty and Measures of Precision

Uncertainty was explored using the sensitivity runs described above and a mixed Monte Carlo and bootstrap procedure (MCBs) described here. MCBs were configured as they were configured during the benchmark stock assessment. The MCBs captured the full expectation of uncertainty given the input data, fixed parameters, and life history data.

In this update assessment, the BAM was successively refit to n = 5,000 trials that differed from the original inputs by bootstrapping on data sources and by Monte Carlo sampling of several key input parameters. Runs with extremely large values for $R_0$ were trimmed from the final uncertainty characterization (these runs also had other parameters that were considered unrealistic). The set-up of the MCB runs for this update was the same as the specifications described in SEDAR 32A.

The MCB analysis should be interpreted as providing an approximation to the uncertainty associated with each output. The results are approximate for two related reasons. First, not all combinations of Monte Carlo parameter inputs are equally likely, as biological parameters might be correlated. Second, all runs are given equal weight in the results, yet some might provide better fits to data than others.

## 4.2 Model Results

### 4.2.1 Base Run Results

**Measures of Overall Model Fit:** Generally, the BAM fit the available data well. The model was configured to fit observed commercial landings closely (Figure 5). The model was configured to fit the observed seine and gillnet indices as closely as possible (Figures 6 and 7). Since the late 2000s and early 2010s, the general trend in the gillnet index has been increasing, while at the same time the seine index has indicated several large year classes of recruits occurring in 2010, 2011, and 2014. Predicted length compositions from the gillnet index and predicted age compositions from the reduction fishery were both reasonably close to observed data in most years (Figures 8, 9, and 10).

**Parameter Estimates:** Estimates of all parameters from the catch-age model are shown in Appendix A. Estimates of management quantities and some key parameters are reported in sections below.

**Stock Abundance and Recruitment:** Estimated abundance was relatively stable from 1977 until the mid-2000s, then estimated abundance increased until 2015 yet was more variable (Figure 11). Older ages appear to be more prevalent in the most recent time period. (Table 7). Annual estimated number of recruits is shown to increase in recent years in Table 7 (age-0 column) and in Figure 12. The model has identified the 2010, 2011, and 2014 year classes as being strong. The benchmark assessment during SEDAR 32A also identified 2010 and 2011 as being likely to be strong year classes.

**Total and Spawning Biomass (Fecundity):** Estimated biomass and biomass at age exhibited a largely similar pattern to that of abundance (Figures 13 and 14; Table 8). Total biomass was stable from 1977 until the mid-2000s, when the biomass started to increase. Estimated fecundity was stable from 1977 to the mid-1990s after which fecundity has increased until 2015 (Figure 15).

**Selectivity:** The selectivity estimate for age-1 fish captured in the commercial reduction fishery was similar to the estimate during the last benchmark assessment (Figure 16). The selectivity for all of the other ages was fixed and resulted in dome-shaped selectivity, as was done in the benchmark assessment. The gillnet index selectivity was logistic or flat-topped and was fully selected at age-3 and nearly fully selected at age-2 (Figure 17).

**Fishing Mortality:** Estimated fishing mortality rates (*F*) were high from 1977 to the mid-1990s with the highest fishing mortality rates occurring in the mid- to late-1980s (Figure 18; Tables 9 and 10). After the mid-1990s, the fishing mortality rate has continued to decline, but at a slower rate. Figure 5 shows total predicted landings in weight. Commercial harvest exceeded 800,000 mt during much of the 1980s, but declined afterwards to stabilize between 400,000 and 500,000 mt for much of the past decade (Figure 5).

**Spawner-Recruitment Parameters:** The estimated Beverton-Holt spawner-recruit curve is shown in Figure 19. Values of recruitment-related parameters were as follows: assumed steepness, $h$ = 0.75; unfished age-0 recruitment, $R_0$ = 126.81; unfished spawning biomass per recruit, $\phi_0$ = 1090.26; and assumed standard deviation of recruitment residuals in log space, $\sigma$ = 0.60 (which resulted in a bias correction, $\varsigma$ = 1.20). Uncertainty in these quantities was estimated through the MCB analysis.

### 4.2.2 Per Recruit and Equilibrium Analyses

Yield per recruit and spawning potential ratio were computed as functions of $F$ (Figure 20). These analyses applied the most recent selectivity pattern. The *Fs* that provide 30% and 35% SPR are 5.98 and 4.28, respectively (Table 11).

As in per recruit analyses, equilibrium landings and spawning biomass were computed as functions of $F$ (Figure 20). Equilibrium landings for SPR values of 30% and 35% were 862,361 mt and 829,737 mt, respectively. Equilibrium spawning biomass for SPR values of 30% and 35% were 41,605 and 50,635 billions of eggs, respectively.

### 4.2.3 Benchmarks/Reference Points

Biological reference points (benchmarks) were derived analytically assuming equilibrium dynamics. The Gulf menhaden fishery is managed using spawning potential ratio (SPR) benchmarks, as outlined in the Fishery Management Plan (FMP; VanderKooy and Smith 2015). The current threshold for fishing mortality is $F_{30\%}$, and the current threshold for spawning stock biomass, measured as fecundity, is $SSB_{30\%}$. The current target for fishing mortality is $F_{35\%}$, and the current target for spawning stock biomass, measured as fecundity, is $SSB_{35\%}$. Standard errors of benchmarks were approximated as those from the MCB analysis. Estimates of benchmarks are summarized in Table 11. Point estimates of the benchmarks were $F_{30\%}$ = 5.98, $F_{35\%}$ = 4.28, $SSB_{30\%}$ = 41,605, and $SSB_{35\%}$ = 50,635.

### 4.2.4 Status of the Stock and Fishery

Base run estimates of spawning stock biomass showed stability near the threshold during 1977 until the mid-1990s after which the SSB increased (Figure 15; Table 9). Current stock status in the base run was estimated to be $SSB_{2015}/SSB_{30\%}$ = 3.51 (Table 11). MCB analysis suggests that the stock status determination of being not overfished (i.e., $SSB > SSB_{30\%}$) has a low degree of uncertainty (Figures 21, 22, and 23). Over 99% of MCB runs were greater than $SSB_{30\%}$ in the terminal year.

The estimated time series of $F/F_{30\%}$ suggests that overfishing has occurred historically, but only prior to 1990 (Figure 21; Table 9). Current fishery status in the terminal year is estimated in the base run to be $F_{2015}/F_{30\%}$ = 0.11 (Table 11). This estimate indicates that overfishing is not occurring and appears robust across MCB trials (Figures 22 and 23). Across all MCB runs, 99% of runs were less than $F_{30\%}$ in the terminal year.

The Gulf of Mexico Gulf menhaden population is **not overfished** and **overfishing is not occurring**. The base run and all sensitivity runs indicate the same stock status. In addition, most of the MCB trials indicated the same stock status. In general, there is very little risk of overfishing or of being overfished (Figure 24).

### 4.2.5 Sensitivity and Retrospective Analyses

Sensitivity runs, described above, are useful to evaluate the implications of decisions that were made during the benchmark assessment and to determine if new data inform the model better for some parameter estimates. All of the sensitivity analyses indicated similar stock status to the base run (Figures 25 and 26; Table 12). For the sensitivity run that estimated steepness freely, the estimated value was 0.59, while steepness was fixed at 0.75 in the base run.

Retrospective analysis generally indicated no pattern in overestimation or underestimation. The fully selected fishing mortality rate looks very well-estimated regardless of how many years of data are peeled off (Figure 27). The biomass, spawning stock biomass, and recruitment show little retrospective pattern (Figures 28, 29, and 30) with differences attributable to high variability in terminal year data. For example, recruitment is variable as the BAM is trying to fit the terminal year seine index, which is highly variable with large year classes in the last several years. Finally, the reference point time series do not seem to indicate a pattern in overestimation or underestimation of stock status (Figures 31 and 32).

### 4.2.6 Comparison with Previous Assessment

Spawning stock biomass (fecundity) and recruitment estimated by this assessment show trends similar to those from SEDAR 32A in the earliest years of the assessments (Figures 33 and 34). However, in the most recent years, the estimated stock trajectory in the update assessment is increasing at a greater rate. This is likely due to a number of factors including increased recruitment as indicated by the seine index, which then shows up as an increased level of adults in the gillnet index. The estimated $R_0$ was much larger for the update of the stock assessment than for the benchmark assessment during SEDAR 32A. A likelihood profile was run on the estimate of $R_0$ to make sure that the data were informative, and the result were that $R_0$ was well defined by the data.

## 5 Discussion

### 5.1 Recommendations for the Next Benchmark Assessment

The MAC recommends that the next peer-reviewed assessment occur during 2018. Gulf menhaden are a short-lived species and would benefit from a shorter time between assessments such as 2-3 years.

During the next benchmark assessment four data items should warrant further consideration or are recommended by the MAC. First, bait landings should be more fully investigated in order to elucidate the magnitude and trajectory of landings over time. In particular, codes 100 and 125 should be investigated further to more clearly delineate the extent of bait landings versus landing offloaded at the reduction facility. While the magnitude of the landings is low in comparison to the commercial reduction landings, it is nonetheless important to provide as accurate of a picture of landings as possible. Therefore, the MAC also recommends that biological samples (length, weight, and a scale sample) be collected from the bait boat in LA in order to characterize the composition of the catch. Second, investigation and consideration of the new maturity and fecundity data provided by Brown-Peterson et al. (In review) should be undertaken. Preliminary sensitivity runs indicate that the changes in maturity and fecundity at age will lead to differences in the scale of the population spawning stock biomass. Third, the MAC recommends that biological samples (length, weight, and a scale sample) be collected from the state surveys being used to provide the indices of abundance. The biological samples will provide information to the assessment on the ages of fish captured during the surveys and that are represented in the indices of abundance. Fourth, the MAC recommends further consideration of the genetic data currently available. Genetic data can be used to inform the species range for the assessment. However, the main interest from the MAC regarding the genetic data is whether or not data need to be censored east of the 88-degree longitude line for the surveys comprising the abundance indices.

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## 7 Tables

Table 1. Life history characteristics at age of Gulf menhaden, including maturity, natural mortality (*M*), fecundity, and weight (g) at spawning.

| Age | Maturity | *M* | Fecundity | Weight at spawning |
|---|---|---|---|---|
| 0 | 0.0 | 1.66 | 0 | 0.0 |
| 1 | 0.0 | 1.30 | 9423 | 50.7 |
| 2 | 1.0 | 1.10 | 21100 | 97.6 |
| 3 | 1.0 | 1.01 | 34680 | 146.1 |
| 4+ | 1.0 | 0.96 | 48028 | 190.3 |

Table 2. Observed total landings in 1,000s of mt by year for the Gulf menhaden fishery. Landings include reduction landings, bait landings, and recreational landings.

| Year | Landings |
|---|---|
| 1977 | 447.60 |
| 1978 | 820.60 |
| 1979 | 779.83 |
| 1980 | 702.50 |
| 1981 | 553.73 |
| 1982 | 855.53 |
| 1983 | 925.26 |
| 1984 | 985.12 |
| 1985 | 884.53 |
| 1986 | 830.88 |
| 1987 | 911.66 |
| 1988 | 640.19 |
| 1989 | 583.53 |
| 1990 | 539.52 |
| 1991 | 552.83 |
| 1992 | 432.73 |
| 1993 | 551.29 |
| 1994 | 774.92 |
| 1995 | 472.02 |
| 1996 | 491.75 |
| 1997 | 623.48 |
| 1998 | 495.66 |
| 1999 | 694.16 |
| 2000 | 590.78 |
| 2001 | 528.56 |
| 2002 | 582.62 |
| 2003 | 524.27 |
| 2004 | 473.74 |
| 2005 | 438.18 |
| 2006 | 467.65 |
| 2007 | 457.38 |
| 2008 | 425.57 |
| 2009 | 457.69 |
| 2010 | 379.93 |
| 2011 | 613.95 |
| 2012 | 579.77 |
| 2013 | 498.74 |
| 2014 | 400.67 |
| 2015 | 540.29 |

Table 3. Observed indices of abundance and coefficient of variation (CV) from the seine survey and the gillnet survey.

| Year | Gillnet | Gillnet CV | Seine | Seine CV |
|---|---|---|---|---|
| 1988 | 0.21 | 0.09 | | |
| 1989 | 0.17 | 0.09 | | |
| 1990 | 0.19 | 0.10 | | |
| 1991 | 0.20 | 0.11 | | |
| 1992 | 0.18 | 0.13 | | |
| 1993 | 0.31 | 0.15 | | |
| 1994 | 0.68 | 0.15 | | |
| 1995 | 0.42 | 0.15 | | |
| 1996 | 0.56 | 0.13 | 0.97 | 0.27 |
| 1997 | 1.01 | 0.13 | 0.34 | 0.27 |
| 1998 | 0.71 | 0.13 | 0.74 | 0.28 |
| 1999 | 0.63 | 0.13 | 0.48 | 0.35 |
| 2000 | 0.79 | 0.12 | 0.31 | 0.73 |
| 2001 | 1.24 | 0.12 | 0.73 | 0.43 |
| 2002 | 0.82 | 0.12 | 0.42 | 0.38 |
| 2003 | 0.85 | 0.12 | 0.71 | 0.42 |
| 2004 | 0.69 | 0.13 | 0.53 | 0.27 |
| 2005 | 1.00 | 0.12 | 0.69 | 0.29 |
| 2006 | 0.99 | 0.11 | 1.04 | 0.30 |
| 2007 | 0.77 | 0.12 | 0.61 | 0.27 |
| 2008 | 3.10 | 0.11 | 0.24 | 0.30 |
| 2009 | 2.15 | 0.10 | 0.98 | 0.27 |
| 2010 | 0.57 | 0.13 | 2.16 | 0.26 |
| 2011 | 1.71 | 0.10 | 4.47 | 0.26 |
| 2012 | 1.80 | 0.10 | 0.80 | 0.31 |
| 2013 | 2.05 | 0.15 | 0.70 | 0.37 |
| 2014 | 2.69 | 0.14 | 2.16 | 0.39 |
| 2015 | 1.49 | 0.15 | 0.91 | 0.29 |

Table 4. Sample sizes (number of sets) for length (len) and age (age) compositions by fleet and survey. Data sources include the commercial reduction fishery (cR) and the gillnet survey.

| Year | cR | Gillnet |
|---|---|---|
| 1977 | 1492 | |
| 1978 | 1300 | |
| 1979 | 1163 | |
| 1980 | 1014 | |
| 1981 | 1042 | |
| 1982 | 1076 | |
| 1983 | 1485 | |
| 1984 | 1599 | |
| 1985 | 1324 | |
| 1986 | 1652 | |
| 1987 | 1647 | |
| 1988 | 1240 | |
| 1989 | 1392 | |
| 1990 | 1152 | |
| 1991 | 1164 | |
| 1992 | 1524 | |
| 1993 | 1537 | |
| 1994 | 1680 | |
| 1995 | 1470 | |
| 1996 | 1506 | 225 |
| 1997 | 1124 | 247 |
| 1998 | 1073 | 264 |
| 1999 | 1183 | 245 |
| 2000 | 969 | 300 |
| 2001 | 740 | 262 |
| 2002 | 836 | 277 |
| 2003 | 1066 | 283 |
| 2004 | 942 | 250 |
| 2005 | 899 | 258 |
| 2006 | 594 | 336 |
| 2007 | 657 | 286 |
| 2008 | 594 | 316 |
| 2009 | 748 | 351 |
| 2010 | 461 | 218 |
| 2011 | 835 | 397 |
| 2012 | 1087 | 447 |
| 2013 | 852 | 199 |
| 2014 | 878 | 195 |
| 2015 | 1145 | 177 |

Table 5. Annual proportion at age from the commercial reduction fishery input to the Gulf menhaden model.

| Year | Age-0 | Age-1 | Age-2 | Age-3 | Age-4+ |
|---|---|---|---|---|---|
| 1977 | 0.000 | 0.763 | 0.218 | 0.018 | 0.001 |
| 1978 | 0.000 | 0.708 | 0.286 | 0.005 | 0.001 |
| 1979 | 0.000 | 0.593 | 0.363 | 0.043 | 0.001 |
| 1980 | 0.009 | 0.472 | 0.452 | 0.060 | 0.007 |
| 1981 | 0.000 | 0.763 | 0.189 | 0.044 | 0.005 |
| 1982 | 0.000 | 0.571 | 0.366 | 0.056 | 0.007 |
| 1983 | 0.000 | 0.526 | 0.428 | 0.043 | 0.003 |
| 1984 | 0.000 | 0.697 | 0.259 | 0.039 | 0.004 |
| 1985 | 0.000 | 0.758 | 0.218 | 0.020 | 0.003 |
| 1986 | 0.000 | 0.456 | 0.522 | 0.019 | 0.003 |
| 1987 | 0.000 | 0.603 | 0.358 | 0.038 | 0.001 |
| 1988 | 0.000 | 0.660 | 0.319 | 0.019 | 0.002 |
| 1989 | 0.000 | 0.766 | 0.224 | 0.009 | 0.000 |
| 1990 | 0.000 | 0.668 | 0.306 | 0.023 | 0.002 |
| 1991 | 0.000 | 0.462 | 0.487 | 0.045 | 0.006 |
| 1992 | 0.000 | 0.559 | 0.384 | 0.050 | 0.007 |
| 1993 | 0.001 | 0.666 | 0.292 | 0.037 | 0.004 |
| 1994 | 0.000 | 0.496 | 0.437 | 0.060 | 0.007 |
| 1995 | 0.000 | 0.351 | 0.622 | 0.026 | 0.001 |
| 1996 | 0.000 | 0.391 | 0.550 | 0.055 | 0.004 |
| 1997 | 0.000 | 0.544 | 0.403 | 0.046 | 0.007 |
| 1998 | 0.000 | 0.392 | 0.563 | 0.041 | 0.004 |
| 1999 | 0.000 | 0.544 | 0.386 | 0.067 | 0.003 |
| 2000 | 0.000 | 0.362 | 0.564 | 0.062 | 0.012 |
| 2001 | 0.000 | 0.250 | 0.672 | 0.074 | 0.005 |
| 2002 | 0.000 | 0.317 | 0.573 | 0.107 | 0.003 |
| 2003 | 0.000 | 0.362 | 0.571 | 0.064 | 0.003 |
| 2004 | 0.000 | 0.560 | 0.353 | 0.080 | 0.008 |
| 2005 | 0.019 | 0.394 | 0.541 | 0.043 | 0.003 |
| 2006 | 0.000 | 0.459 | 0.470 | 0.065 | 0.006 |
| 2007 | 0.000 | 0.463 | 0.510 | 0.024 | 0.004 |
| 2008 | 0.000 | 0.266 | 0.683 | 0.044 | 0.006 |
| 2009 | 0.000 | 0.126 | 0.731 | 0.129 | 0.013 |
| 2010 | 0.000 | 0.529 | 0.404 | 0.061 | 0.006 |
| 2011 | 0.007 | 0.632 | 0.317 | 0.037 | 0.007 |
| 2012 | 0.003 | 0.309 | 0.658 | 0.029 | 0.001 |
| 2013 | 0.002 | 0.245 | 0.727 | 0.025 | 0.001 |
| 2014 | 0.006 | 0.258 | 0.596 | 0.134 | 0.006 |
| 2015 | 0.000 | 0.625 | 0.309 | 0.062 | 0.005 |

Table 6. Annual proportion at length from the gillnet survey input to the Gulf menhaden model. Each column is indicated by the mid-point of the length bin.

| Year | 85 | 95 | 105 | 115 | 125 | 135 | 145 | 155 | 165 | 175 | 185 | 195 | 205 | 215 | 225 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1996 | 0.01 | 0.02 | 0.01 | 0.02 | 0.07 | 0.16 | 0.16 | 0.09 | 0.11 | 0.11 | 0.07 | 0.05 | 0.04 | 0.04 | 0.03 |
| 1997 | 0.00 | 0.01 | 0.00 | 0.02 | 0.06 | 0.14 | 0.14 | 0.11 | 0.11 | 0.12 | 0.09 | 0.07 | 0.06 | 0.03 | 0.03 |
| 1998 | 0.00 | 0.01 | 0.01 | 0.02 | 0.07 | 0.18 | 0.19 | 0.11 | 0.11 | 0.12 | 0.07 | 0.04 | 0.03 | 0.02 | 0.02 |
| 1999 | 0.00 | 0.01 | 0.01 | 0.03 | 0.07 | 0.16 | 0.14 | 0.09 | 0.11 | 0.12 | 0.09 | 0.06 | 0.06 | 0.03 | 0.02 |
| 2000 | 0.00 | 0.01 | 0.01 | 0.02 | 0.06 | 0.14 | 0.11 | 0.07 | 0.07 | 0.12 | 0.12 | 0.09 | 0.08 | 0.06 | 0.04 |
| 2001 | 0.00 | 0.01 | 0.01 | 0.01 | 0.06 | 0.11 | 0.10 | 0.08 | 0.12 | 0.13 | 0.09 | 0.08 | 0.08 | 0.05 | 0.07 |
| 2002 | 0.00 | 0.01 | 0.01 | 0.03 | 0.06 | 0.14 | 0.14 | 0.09 | 0.09 | 0.10 | 0.09 | 0.06 | 0.07 | 0.06 | 0.05 |
| 2003 | 0.00 | 0.01 | 0.01 | 0.03 | 0.09 | 0.19 | 0.19 | 0.10 | 0.10 | 0.13 | 0.07 | 0.02 | 0.02 | 0.02 | 0.01 |
| 2004 | 0.00 | 0.01 | 0.02 | 0.04 | 0.11 | 0.18 | 0.17 | 0.11 | 0.10 | 0.08 | 0.07 | 0.04 | 0.04 | 0.02 | 0.01 |
| 2005 | 0.00 | 0.01 | 0.01 | 0.03 | 0.06 | 0.15 | 0.18 | 0.12 | 0.12 | 0.12 | 0.08 | 0.04 | 0.04 | 0.02 | 0.01 |
| 2006 | 0.01 | 0.01 | 0.01 | 0.02 | 0.08 | 0.16 | 0.15 | 0.15 | 0.10 | 0.11 | 0.08 | 0.05 | 0.04 | 0.02 | 0.01 |
| 2007 | 0.01 | 0.01 | 0.01 | 0.01 | 0.04 | 0.13 | 0.17 | 0.15 | 0.14 | 0.13 | 0.08 | 0.04 | 0.03 | 0.02 | 0.01 |
| 2008 | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 | 0.12 | 0.14 | 0.10 | 0.12 | 0.15 | 0.10 | 0.08 | 0.06 | 0.04 | 0.02 |
| 2009 | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 | 0.08 | 0.14 | 0.11 | 0.11 | 0.12 | 0.12 | 0.08 | 0.08 | 0.05 | 0.03 |
| 2010 | 0.00 | 0.01 | 0.01 | 0.03 | 0.07 | 0.14 | 0.12 | 0.08 | 0.09 | 0.11 | 0.10 | 0.08 | 0.06 | 0.06 | 0.03 |
| 2011 | 0.00 | 0.01 | 0.02 | 0.03 | 0.08 | 0.16 | 0.15 | 0.08 | 0.08 | 0.10 | 0.10 | 0.06 | 0.07 | 0.04 | 0.02 |
| 2012 | 0.00 | 0.00 | 0.01 | 0.02 | 0.07 | 0.17 | 0.18 | 0.10 | 0.11 | 0.12 | 0.08 | 0.05 | 0.05 | 0.03 | 0.01 |
| 2013 | 0.00 | 0.02 | 0.01 | 0.02 | 0.06 | 0.12 | 0.14 | 0.11 | 0.14 | 0.14 | 0.10 | 0.06 | 0.06 | 0.03 | 0.01 |
| 2014 | 0.00 | 0.00 | 0.02 | 0.01 | 0.04 | 0.13 | 0.17 | 0.09 | 0.09 | 0.12 | 0.13 | 0.09 | 0.05 | 0.03 | 0.01 |
| 2015 | 0.01 | 0.01 | 0.01 | 0.03 | 0.09 | 0.18 | 0.16 | 0.06 | 0.06 | 0.11 | 0.10 | 0.07 | 0.07 | 0.04 | 0.01 |

Table 7. Estimated total abundance at age (in billions of fish) at the start of the year.

| Year | Age-0 | Age-1 | Age-2 | Age-3 | Age-4+ |
|---|---|---|---|---|---|
| 1977 | 139.41 | 18.84 | 1.63 | 0.00 | 0.01 |
| 1978 | 126.31 | 26.49 | 3.43 | 0.00 | 0.00 |
| 1979 | 69.07 | 24.00 | 4.45 | 0.00 | 0.00 |
| 1980 | 143.36 | 13.13 | 4.53 | 0.02 | 0.00 |
| 1981 | 151.06 | 27.24 | 2.26 | 0.01 | 0.00 |
| 1982 | 116.37 | 28.71 | 5.36 | 0.02 | 0.00 |
| 1983 | 125.17 | 22.12 | 5.76 | 0.05 | 0.00 |
| 1984 | 185.12 | 23.79 | 4.05 | 0.02 | 0.00 |
| 1985 | 116.94 | 35.16 | 3.33 | 0.00 | 0.00 |
| 1986 | 101.42 | 22.22 | 6.27 | 0.01 | 0.00 |
| 1987 | 79.17 | 19.28 | 4.60 | 0.08 | 0.00 |
| 1988 | 86.20 | 15.04 | 2.89 | 0.00 | 0.00 |
| 1989 | 101.60 | 16.38 | 2.19 | 0.00 | 0.00 |
| 1990 | 72.42 | 19.30 | 2.40 | 0.00 | 0.00 |
| 1991 | 74.48 | 13.76 | 3.48 | 0.01 | 0.00 |
| 1992 | 142.27 | 14.15 | 2.57 | 0.01 | 0.00 |
| 1993 | 144.33 | 27.04 | 2.77 | 0.02 | 0.00 |
| 1994 | 111.87 | 27.43 | 5.58 | 0.04 | 0.00 |
| 1995 | 120.72 | 21.26 | 5.85 | 0.11 | 0.01 |
| 1996 | 151.27 | 22.95 | 5.19 | 0.54 | 0.03 |
| 1997 | 122.43 | 28.76 | 5.53 | 0.41 | 0.12 |
| 1998 | 173.63 | 23.27 | 6.73 | 0.31 | 0.11 |
| 1999 | 159.12 | 33.01 | 5.77 | 0.74 | 0.10 |
| 2000 | 116.24 | 30.25 | 7.69 | 0.31 | 0.16 |
| 2001 | 115.97 | 22.10 | 7.48 | 0.83 | 0.12 |
| 2002 | 97.54 | 22.05 | 5.51 | 0.89 | 0.24 |
| 2003 | 138.86 | 18.54 | 5.22 | 0.36 | 0.23 |
| 2004 | 122.61 | 26.40 | 4.37 | 0.32 | 0.12 |
| 2005 | 157.53 | 23.31 | 6.28 | 0.30 | 0.09 |
| 2006 | 223.30 | 29.95 | 5.82 | 0.76 | 0.10 |
| 2007 | 191.27 | 42.45 | 7.45 | 0.67 | 0.22 |
| 2008 | 79.19 | 36.37 | 10.86 | 1.19 | 0.25 |
| 2009 | 141.05 | 15.06 | 9.51 | 2.25 | 0.45 |
| 2010 | 261.26 | 26.82 | 3.89 | 1.71 | 0.80 |
| 2011 | 312.79 | 49.67 | 6.73 | 0.50 | 0.66 |
| 2012 | 201.64 | 59.47 | 12.34 | 0.76 | 0.30 |
| 2013 | 142.84 | 38.34 | 15.44 | 2.33 | 0.32 |
| 2014 | 416.90 | 27.16 | 10.10 | 3.47 | 0.85 |
| 2015 | 175.17 | 79.27 | 7.13 | 2.18 | 1.37 |

Table 8. Estimated biomass at age (1,000s mt) at start of year.

| Year | Age-1 | Age-2 | Age-3 | Age-4+ |
|---|---|---|---|---|
| 1977 | 955.41 | 158.75 | 0.63 | 2.05 |
| 1978 | 1343.10 | 334.32 | 0.71 | 0.21 |
| 1979 | 1216.81 | 434.45 | 0.60 | 0.06 |
| 1980 | 665.45 | 442.12 | 3.02 | 0.07 |
| 1981 | 1381.07 | 220.43 | 1.05 | 0.22 |
| 1982 | 1455.54 | 523.45 | 2.50 | 0.16 |
| 1983 | 1121.37 | 562.66 | 7.47 | 0.36 |
| 1984 | 1205.94 | 395.69 | 2.78 | 0.73 |
| 1985 | 1782.85 | 324.53 | 0.08 | 0.11 |
| 1986 | 1126.67 | 612.38 | 1.17 | 0.01 |
| 1987 | 977.29 | 448.69 | 12.36 | 0.18 |
| 1988 | 762.57 | 282.39 | 0.22 | 0.52 |
| 1989 | 830.25 | 213.48 | 0.09 | 0.02 |
| 1990 | 978.53 | 233.99 | 0.08 | 0.00 |
| 1991 | 697.68 | 339.86 | 0.96 | 0.01 |
| 1992 | 717.58 | 251.00 | 2.10 | 0.10 |
| 1993 | 1370.86 | 270.66 | 2.69 | 0.27 |
| 1994 | 1390.80 | 544.74 | 5.32 | 0.45 |
| 1995 | 1078.02 | 571.08 | 15.69 | 0.99 |
| 1996 | 1163.53 | 506.17 | 78.28 | 4.98 |
| 1997 | 1458.03 | 539.42 | 59.84 | 23.60 |
| 1998 | 1179.99 | 656.47 | 45.38 | 20.08 |
| 1999 | 1673.53 | 562.68 | 107.71 | 19.80 |
| 2000 | 1533.54 | 750.99 | 45.53 | 31.06 |
| 2001 | 1120.36 | 730.11 | 120.95 | 22.56 |
| 2002 | 1117.77 | 537.91 | 129.70 | 46.01 |
| 2003 | 940.11 | 509.25 | 51.92 | 44.56 |
| 2004 | 1338.35 | 426.47 | 46.76 | 23.07 |
| 2005 | 1181.77 | 613.23 | 43.98 | 17.87 |
| 2006 | 1518.43 | 568.44 | 111.30 | 19.46 |
| 2007 | 2152.38 | 727.46 | 98.47 | 41.63 |
| 2008 | 1843.71 | 1060.42 | 174.47 | 48.51 |
| 2009 | 763.33 | 928.48 | 328.21 | 85.78 |
| 2010 | 1359.66 | 379.74 | 249.28 | 151.86 |
| 2011 | 2518.23 | 656.88 | 72.52 | 126.11 |
| 2012 | 3014.89 | 1204.27 | 111.43 | 56.71 |
| 2013 | 1943.71 | 1506.60 | 340.71 | 61.17 |
| 2014 | 1376.90 | 985.94 | 507.19 | 161.33 |
| 2015 | 4018.74 | 696.06 | 319.08 | 259.99 |

Table 9. Estimated time series of status indicators, fishing mortality, and spawning stock biomass (fecundity). Fishing mortality rate is full *F*. Spawning biomass (SSB, fecundity) is at the start of the year (time of peak spawning).

| Year | $F$ | $F/F_{30\%}$ | $SSB$ | $SSB/SSB_{30\%}$ |
|---|---|---|---|---|
| 1977 | 4.71 | 0.79 | 17494 | 0.42 |
| 1978 | 5.63 | 0.94 | 36249 | 0.87 |
| 1979 | 4.27 | 0.71 | 47040 | 1.13 |
| 1980 | 5.35 | 0.89 | 48157 | 1.16 |
| 1981 | 3.78 | 0.63 | 23980 | 0.58 |
| 1982 | 3.55 | 0.59 | 56898 | 1.37 |
| 1983 | 4.61 | 0.77 | 61752 | 1.48 |
| 1984 | 7.77 | 1.30 | 43195 | 1.04 |
| 1985 | 4.93 | 0.82 | 35103 | 0.84 |
| 1986 | 3.21 | 0.54 | 66336 | 1.59 |
| 1987 | 6.94 | 1.16 | 49991 | 1.20 |
| 1988 | 7.31 | 1.22 | 30616 | 0.74 |
| 1989 | 7.23 | 1.21 | 23090 | 0.55 |
| 1990 | 4.80 | 0.80 | 25303 | 0.61 |
| 1991 | 4.39 | 0.73 | 36852 | 0.89 |
| 1992 | 3.84 | 0.64 | 27394 | 0.66 |
| 1993 | 3.23 | 0.54 | 29611 | 0.71 |
| 1994 | 2.85 | 0.48 | 59572 | 1.43 |
| 1995 | 1.29 | 0.22 | 63719 | 1.53 |
| 1996 | 1.44 | 0.24 | 64633 | 1.55 |
| 1997 | 1.78 | 0.30 | 68387 | 1.64 |
| 1998 | 1.11 | 0.19 | 78880 | 1.90 |
| 1999 | 1.82 | 0.30 | 76105 | 1.83 |
| 2000 | 1.13 | 0.19 | 90501 | 2.18 |
| 2001 | 1.03 | 0.17 | 96122 | 2.31 |
| 2002 | 1.64 | 0.27 | 79346 | 1.91 |
| 2003 | 1.69 | 0.28 | 66833 | 1.61 |
| 2004 | 1.58 | 0.26 | 54559 | 1.31 |
| 2005 | 1.01 | 0.17 | 73761 | 1.77 |
| 2006 | 1.06 | 0.18 | 77110 | 1.85 |
| 2007 | 0.73 | 0.12 | 95574 | 2.30 |
| 2008 | 0.48 | 0.08 | 141453 | 3.40 |
| 2009 | 0.62 | 0.10 | 150143 | 3.61 |
| 2010 | 0.96 | 0.16 | 89797 | 2.16 |
| 2011 | 1.08 | 0.18 | 95525 | 2.30 |
| 2012 | 0.57 | 0.09 | 150556 | 3.62 |
| 2013 | 0.39 | 0.07 | 211012 | 5.07 |
| 2014 | 0.43 | 0.07 | 187129 | 4.50 |
| 2015 | 0.63 | 0.11 | 145920 | 3.51 |

Table 10. Estimated instantaneous fishing mortality rate (per year) at age.

| Year | Age-0 | Age-1 | Age-2 | Age-3 | Age-4+ |
|---|---|---|---|---|---|
| 1977 | 0.00 | 0.40 | 4.71 | 1.65 | 1.65 |
| 1978 | 0.00 | 0.48 | 5.63 | 1.97 | 1.97 |
| 1979 | 0.00 | 0.37 | 4.27 | 1.50 | 1.50 |
| 1980 | 0.00 | 0.46 | 5.35 | 1.87 | 1.87 |
| 1981 | 0.00 | 0.33 | 3.78 | 1.32 | 1.32 |
| 1982 | 0.00 | 0.31 | 3.55 | 1.24 | 1.24 |
| 1983 | 0.00 | 0.40 | 4.61 | 1.61 | 1.61 |
| 1984 | 0.00 | 0.67 | 7.77 | 2.72 | 2.72 |
| 1985 | 0.00 | 0.42 | 4.93 | 1.72 | 1.72 |
| 1986 | 0.00 | 0.28 | 3.21 | 1.12 | 1.12 |
| 1987 | 0.00 | 0.60 | 6.94 | 2.43 | 2.43 |
| 1988 | 0.00 | 0.63 | 7.31 | 2.56 | 2.56 |
| 1989 | 0.00 | 0.62 | 7.23 | 2.53 | 2.53 |
| 1990 | 0.00 | 0.41 | 4.80 | 1.68 | 1.68 |
| 1991 | 0.00 | 0.38 | 4.39 | 1.54 | 1.54 |
| 1992 | 0.00 | 0.33 | 3.84 | 1.34 | 1.34 |
| 1993 | 0.00 | 0.28 | 3.23 | 1.13 | 1.13 |
| 1994 | 0.00 | 0.25 | 2.85 | 1.00 | 1.00 |
| 1995 | 0.00 | 0.11 | 1.29 | 0.45 | 0.45 |
| 1996 | 0.00 | 0.12 | 1.44 | 0.50 | 0.50 |
| 1997 | 0.00 | 0.15 | 1.78 | 0.62 | 0.62 |
| 1998 | 0.00 | 0.10 | 1.11 | 0.39 | 0.39 |
| 1999 | 0.00 | 0.16 | 1.82 | 0.64 | 0.64 |
| 2000 | 0.00 | 0.10 | 1.13 | 0.40 | 0.40 |
| 2001 | 0.00 | 0.09 | 1.03 | 0.36 | 0.36 |
| 2002 | 0.00 | 0.14 | 1.64 | 0.57 | 0.57 |
| 2003 | 0.00 | 0.15 | 1.69 | 0.59 | 0.59 |
| 2004 | 0.00 | 0.14 | 1.58 | 0.55 | 0.55 |
| 2005 | 0.00 | 0.09 | 1.01 | 0.35 | 0.35 |
| 2006 | 0.00 | 0.09 | 1.06 | 0.37 | 0.37 |
| 2007 | 0.00 | 0.06 | 0.73 | 0.26 | 0.26 |
| 2008 | 0.00 | 0.04 | 0.48 | 0.17 | 0.17 |
| 2009 | 0.00 | 0.05 | 0.62 | 0.22 | 0.22 |
| 2010 | 0.00 | 0.08 | 0.96 | 0.34 | 0.34 |
| 2011 | 0.00 | 0.09 | 1.08 | 0.38 | 0.38 |
| 2012 | 0.00 | 0.05 | 0.57 | 0.20 | 0.20 |
| 2013 | 0.00 | 0.03 | 0.39 | 0.14 | 0.14 |
| 2014 | 0.00 | 0.04 | 0.43 | 0.15 | 0.15 |
| 2015 | 0.00 | 0.05 | 0.63 | 0.22 | 0.22 |

Table 11. Estimated status indicators, benchmarks, and related quantities from the Beaufort catch-age model conditional on estimated current selectivity. Rate estimates (*F*) are in units of $y^{-1}$, and status indicators are dimensionless. Spawning stock biomass is measured in total fecundity in billions of eggs.

| Quantities | Units | Estimates |
|---|---|---|
| $F_{30\%}$ | $y^{-1}$ | 5.98 |
| $F_{35\%}$ | $y^{-1}$ | 4.28 |
| $SSB_{30\%}$ | Billions of eggs | 41,605 |
| $SSB_{35\%}$ | Billions of eggs | 50,635 |
| $F_{2015}/F_{30\%}$ | - | 0.11 |
| $F_{2015}/F_{35\%}$ | - | 0.15 |
| $SSB_{2015}/SSB_{30\%}$ | - | 3.51 |
| $SSB_{2015}/SSB_{35\%}$ | - | 2.88 |

Table 12. Estimated status indicators, benchmarks, and related quantities from the Beaufort catch-age model for each sensitivity run completed and for the retrospective analysis. Rate estimates (*F*) are in units of $y^{-1}$, and status indicators are dimensionless. Spawning stock biomass is measured in total fecundity in billions of eggs.

| Run | $F_{30\%}$ | $F_{35\%}$ | $SSB_{30\%}$ | $SSB_{35\%}$ | $F_{2015}/F_{30\%}$ | $F_{2015}/F_{35\%}$ | $SSB_{2015}/SSB_{30\%}$ | $SSB_{2015}/SSB_{35\%}$ |
|---|---|---|---|---|---|---|---|---|
| Base run | 5.98 | 4.28 | 41605 | 50635 | 0.11 | 0.15 | 3.51 | 2.88 |
| h estimating | 5.71 | 4.09 | 38133 | 50432 | 0.09 | 0.13 | 4.47 | 3.38 |
| cR age3&4 select est. | 5.59 | 4.07 | 47622 | 57957 | 0.12 | 0.16 | 4.18 | 3.44 |
| seine index from 32A | 5.65 | 4.05 | 43032 | 52372 | 0.11 | 0.15 | 3.58 | 2.94 |
| Bait landings from 32A | 5.99 | 4.28 | 41384 | 50362 | 0.11 | 0.15 | 3.5 | 2.88 |
| Age-1 mat | 10 | 10 | 106519 | 106519 | 0.08 | 0.08 | 3.29 | 3.29 |
| low fec | 5.17 | 3.58 | 620649 | 755326 | 0.12 | 0.18 | 3.49 | 2.86 |
| high fec | 5.17 | 3.58 | 1290297 | 1570282 | 0.12 | 0.18 | 3.49 | 2.86 |
| low fec, mat | 10 | 10 | 1231096 | 1231096 | 0.07 | 0.07 | 3.71 | 3.71 |
| high fec, mat | 10 | 10 | 2515881 | 2515881 | 0.07 | 0.07 | 3.73 | 3.73 |
| Base run | 5.98 | 4.28 | 41605 | 50635 | 0.11 | 0.15 | 3.51 | 2.88 |
| Retrospective 2014 | 6.26 | 4.46 | 41588 | 50613 | 0.06 | 0.08 | 5.14 | 4.22 |
| Retrospective 2013 | 6.17 | 4.4 | 40583 | 49391 | 0.05 | 0.07 | 6.28 | 5.16 |
| Retrospective 2012 | 6.35 | 4.52 | 40063 | 48758 | 0.07 | 0.1 | 4.45 | 3.66 |
| Retrospective 2011 | 6.68 | 4.74 | 39250 | 47767 | 0.15 | 0.21 | 2.37 | 1.95 |

# 8 Figures

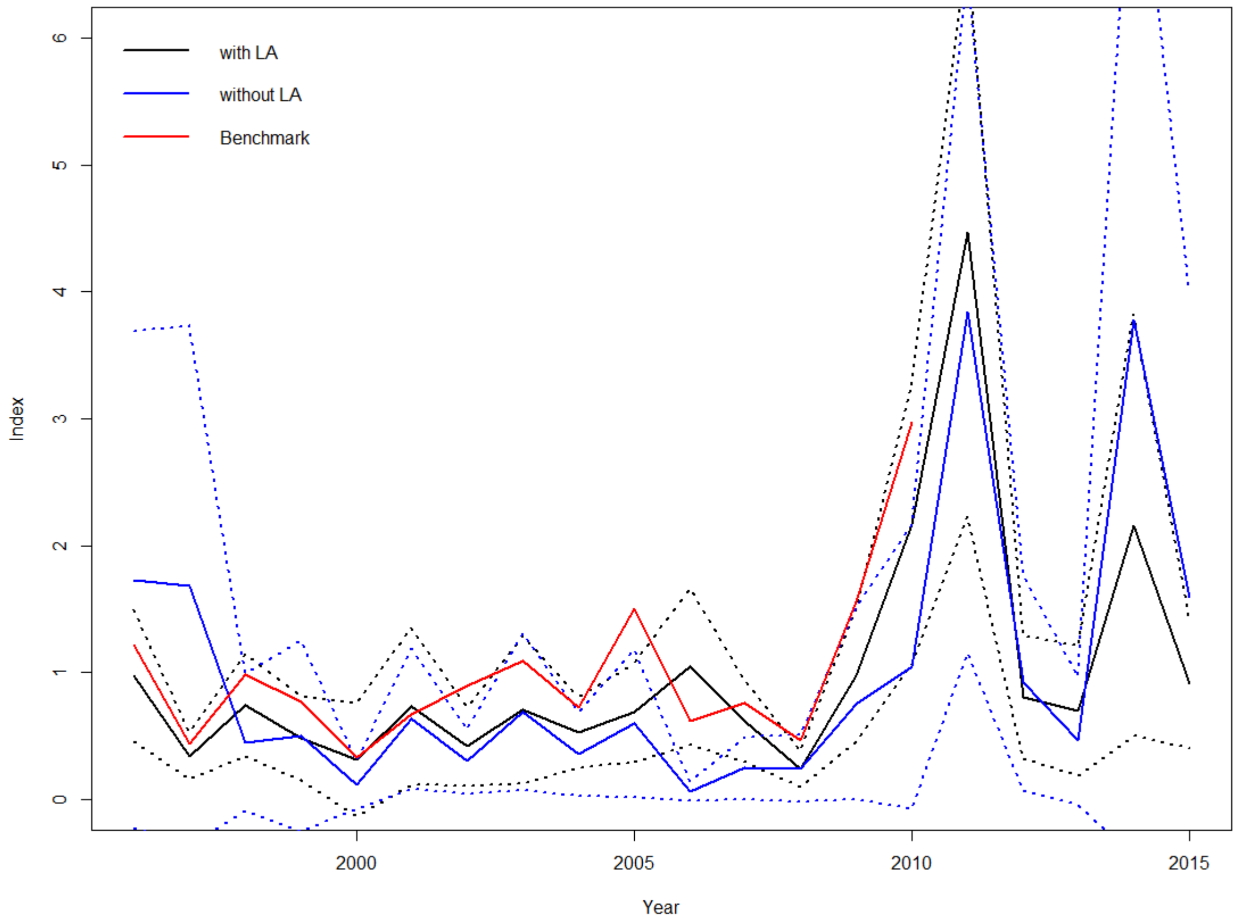



Figure 1. The seine survey index standardized to include LA, MS, and AL (labeled with LA); MS and AL only (labeled without LA); and from the last benchmark assessment. Dashed lines are the 95% confidence intervals for the indices.

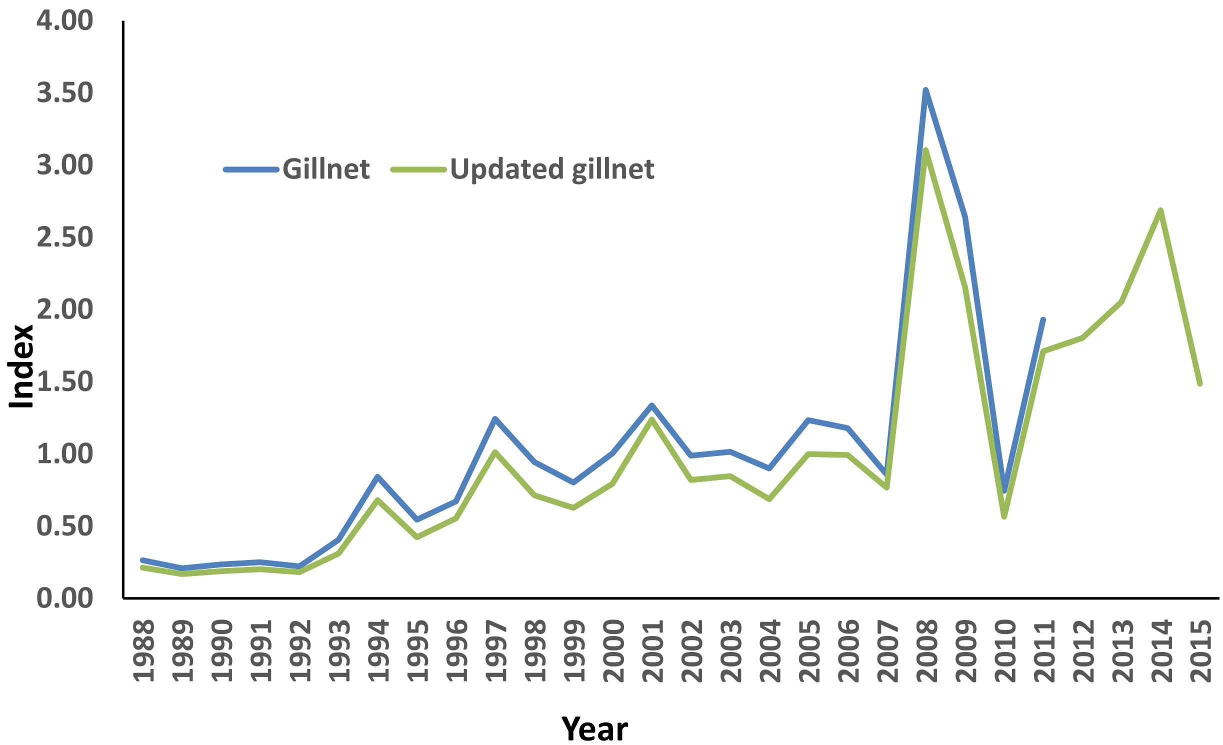



Figure 2. The gillnet index from the benchmark SEDAR 32A assessment (labeled Gillnet) and updated for the current assessment (labeled Updated gillnet).

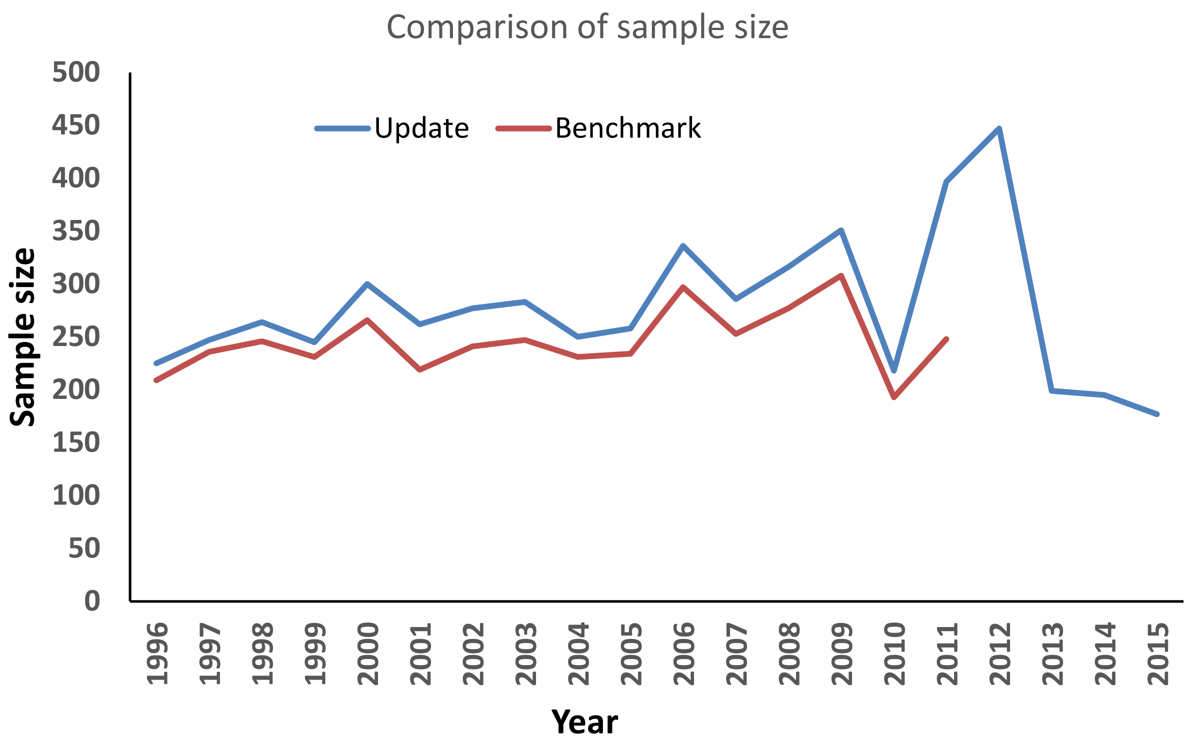



Figure 3. Comparison of length sample sizes annually from the LA gillnet survey. These data were used to calculate the length compositions for the adult gillnet index.

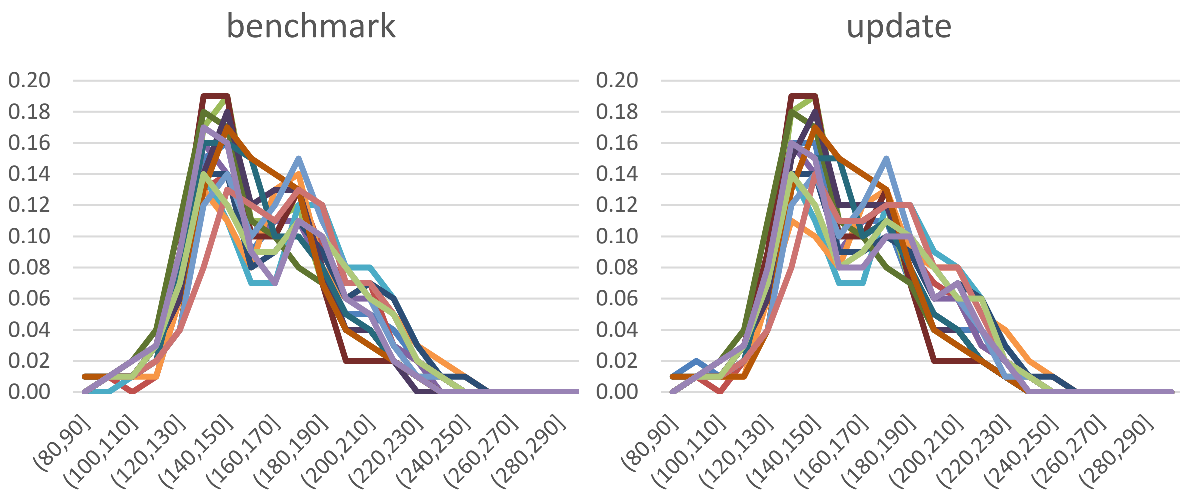



Figure 4. Comparison of annual length composition data from the benchmark assessment (left) and for the update assessment (right).

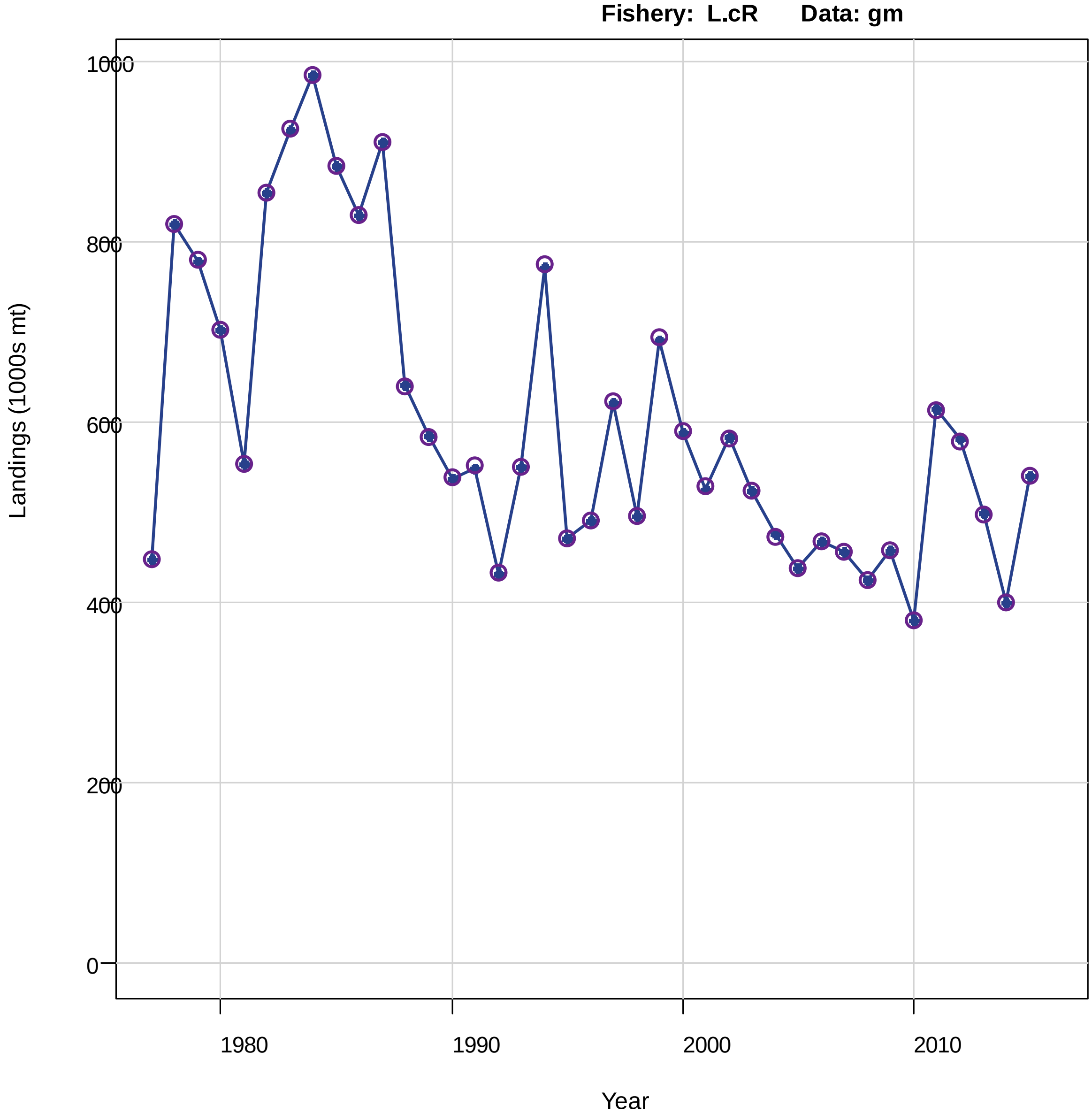



Figure 5. Observed (open circles) and estimated (line, solid circles) commercial reduction, commercial bait, and recreational landings (1,000s mt).

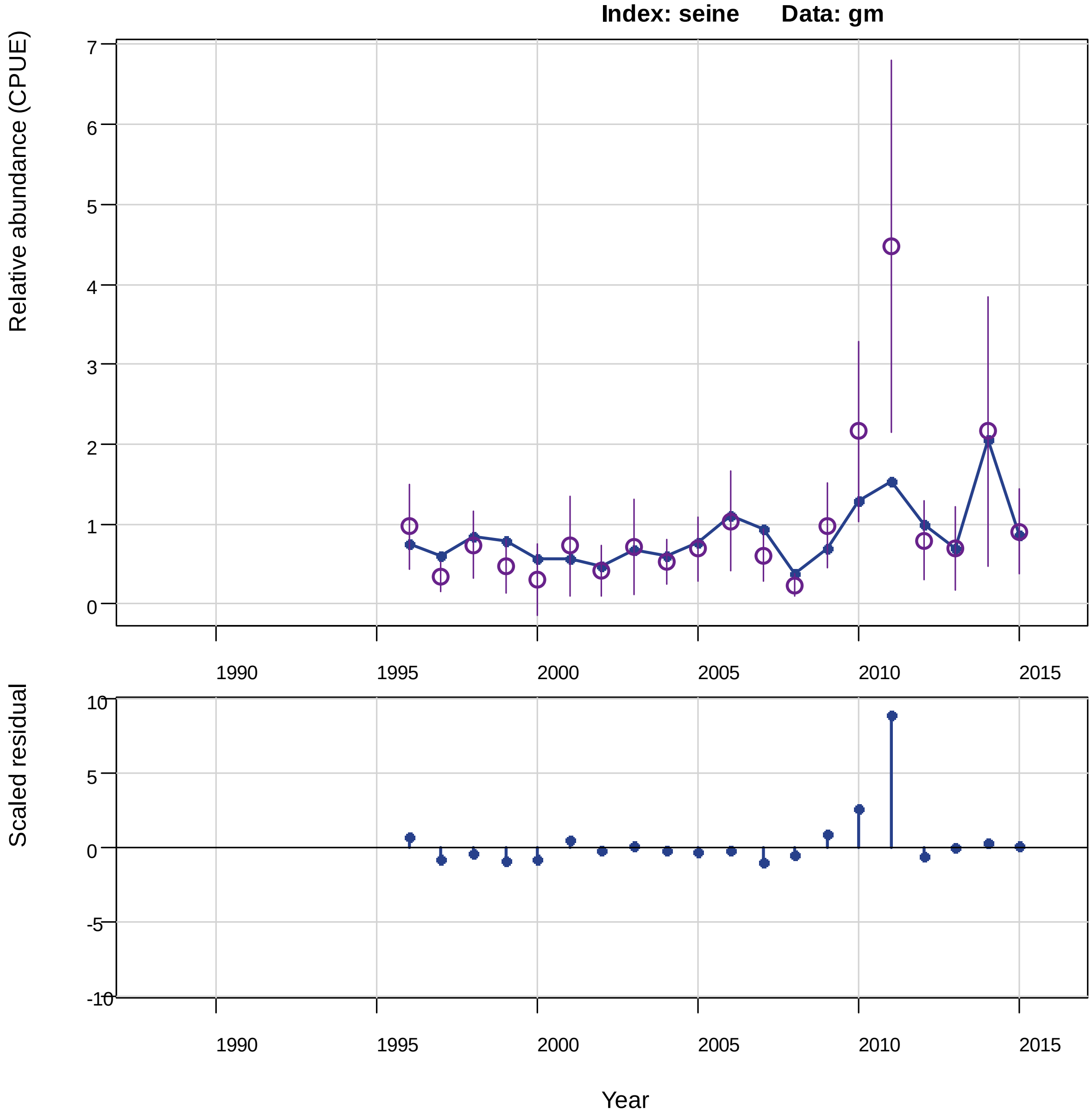



Figure 6. Observed (open circles) and estimated (line, solid circles) index of abundance from the seine surveys in LA, MS, and AL.

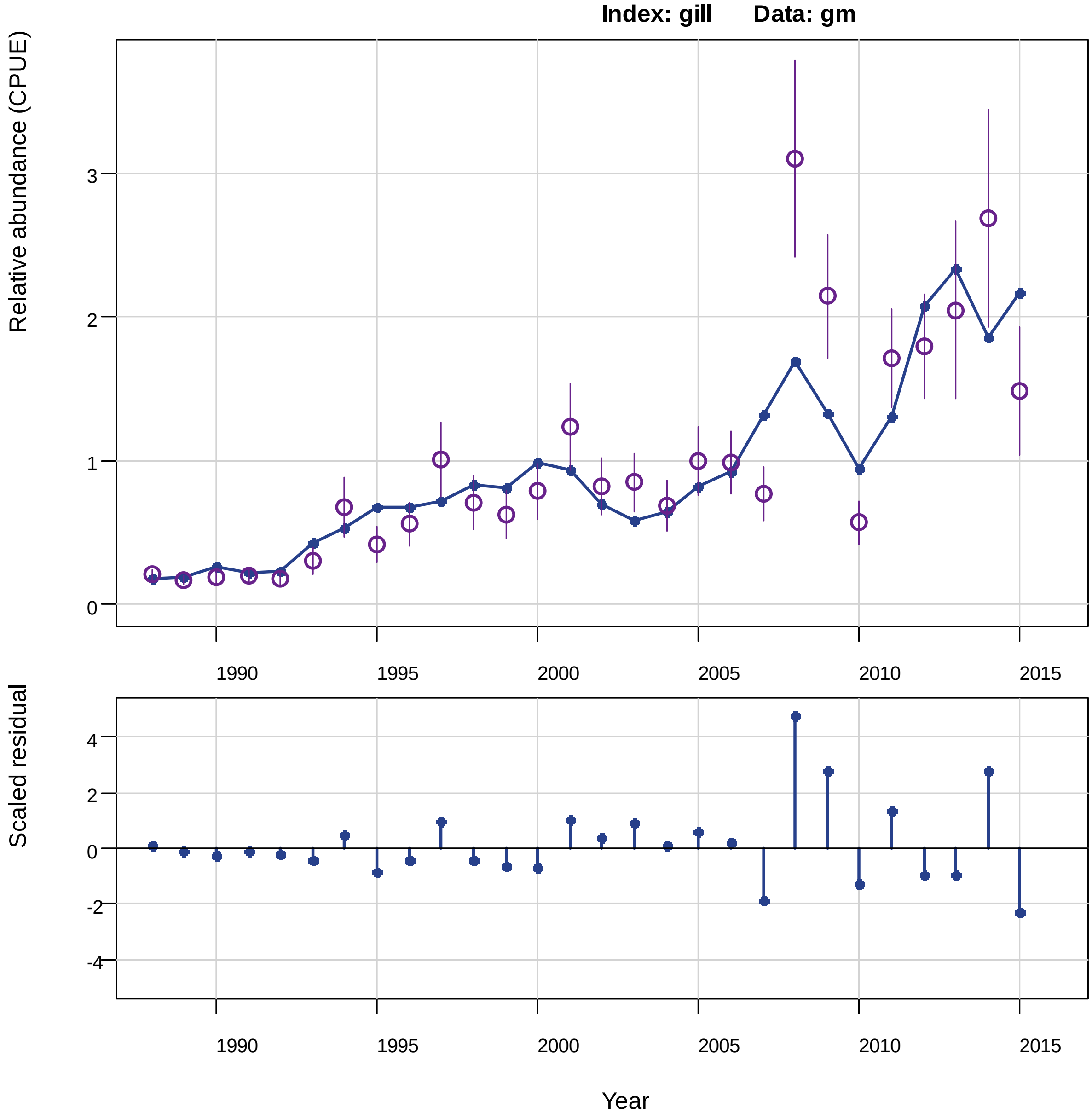



Figure 7. Observed (open circles) and estimated (line, solid circles) index of abundance from the LA gillnet survey.

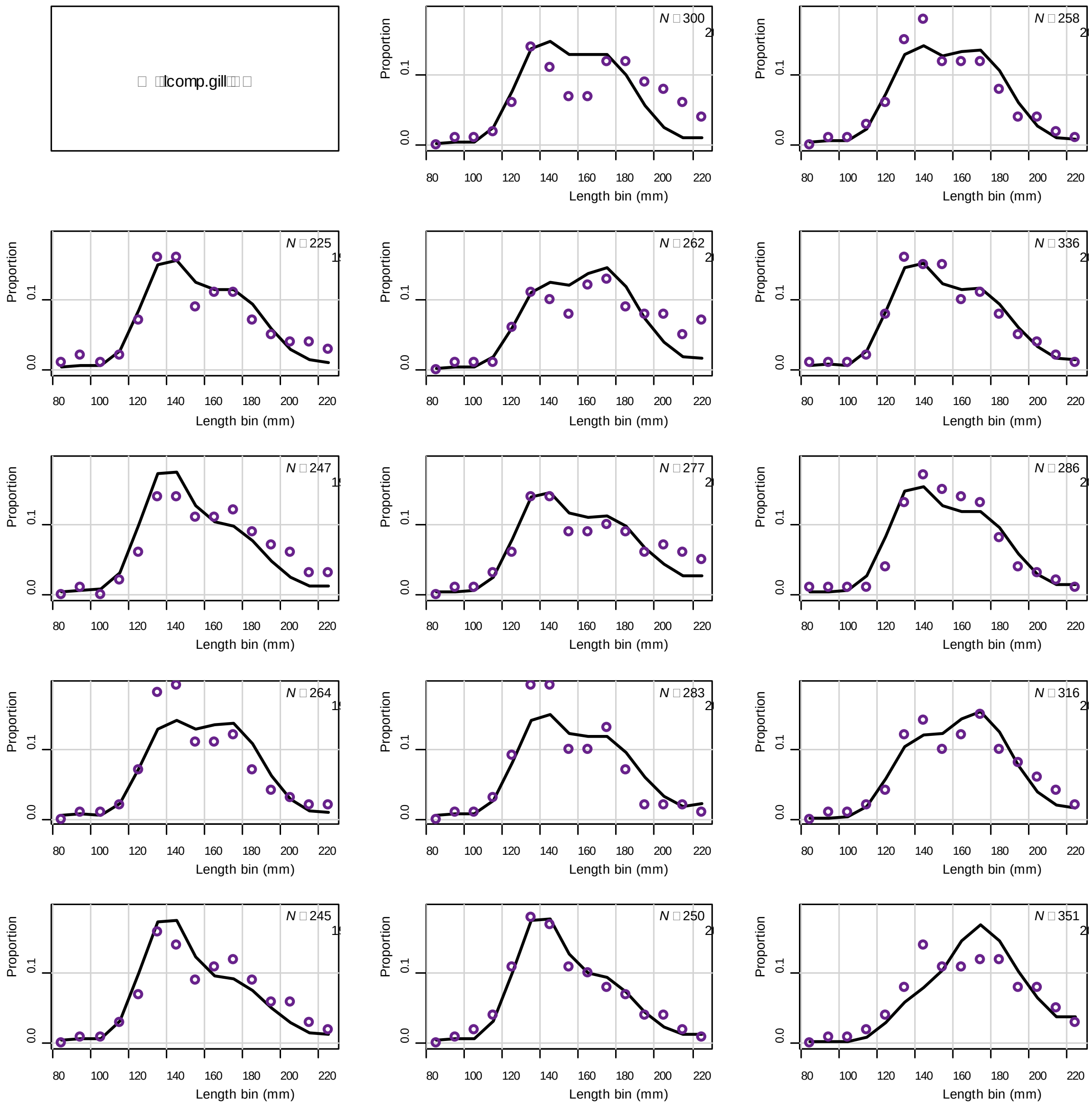


Figure 8. Observed (open circles) and estimated (solid line) annual length and age compositions by fleet or survey. In panels indicating the data set, lcomp refers to length compositions, acomp to age compositions, cR to commercial reduction, and gill to the gillnet survey. N indicates the number of trips from which individual fish samples were taken.

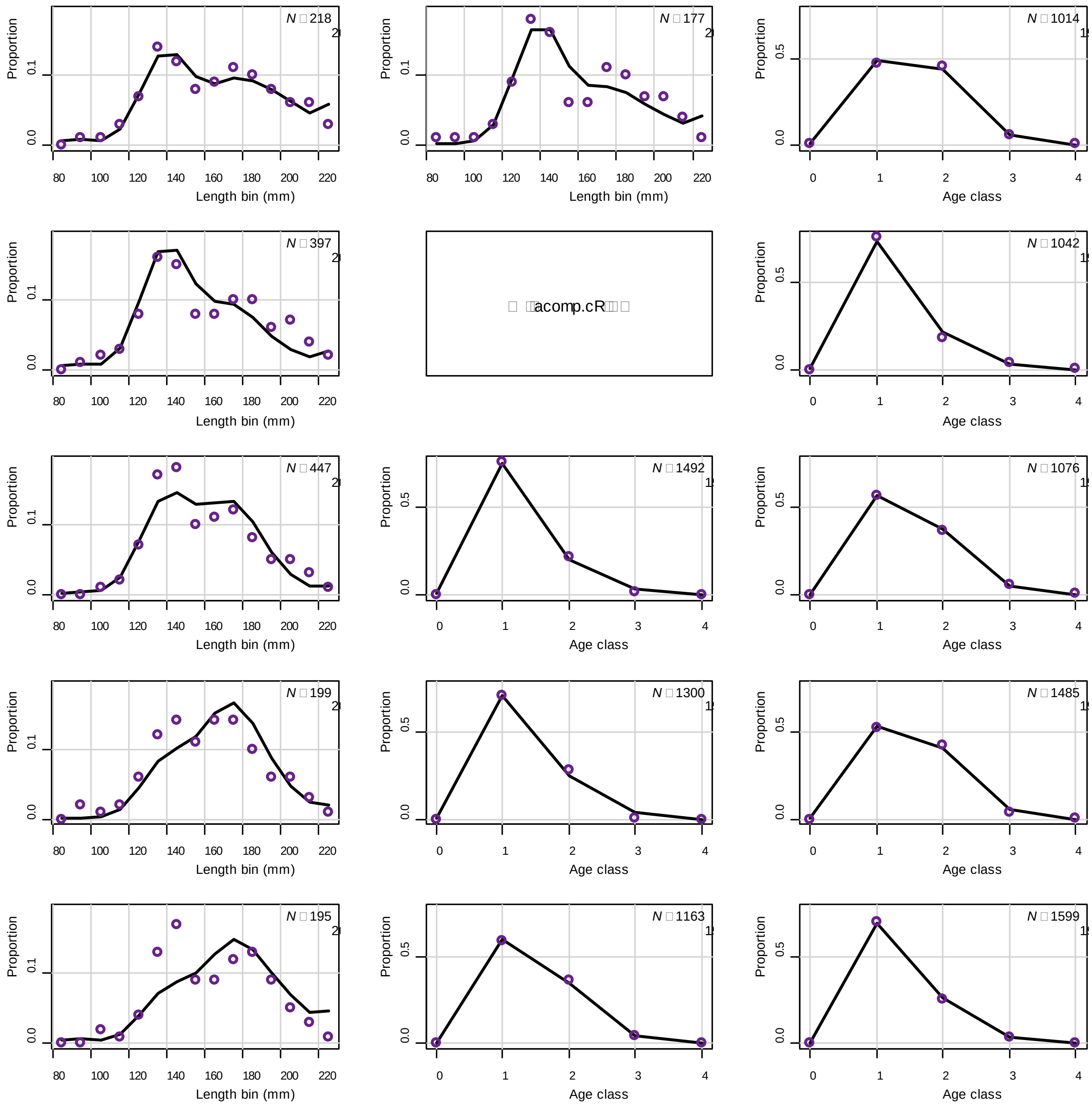



Figure 8. (Continued) Observed (open circles) and estimated (solid line) annual length and age compositions by fleet or survey. In panels indicating the data set, lcomp refers to length compositions, acomp to age compositions, cR to commercial reduction, and gill to the gillnet survey. N indicates the number of trips from which individual fish samples were taken.

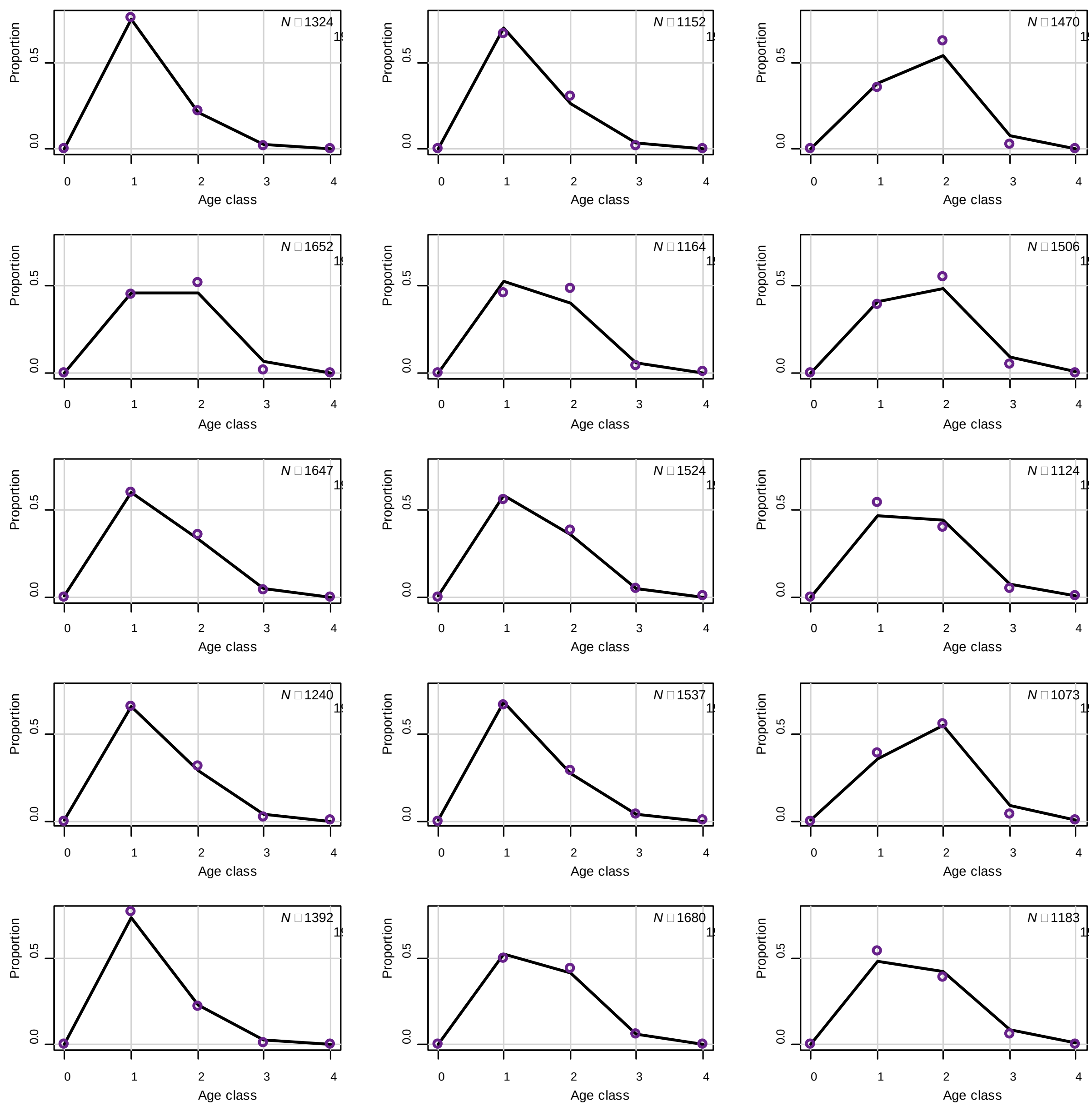


Figure 8. (Continued) Observed (open circles) and estimated (solid line) annual length and age compositions by fleet or survey. In panels indicating the data set, lcomp refers to length compositions, acomp to age compositions, cR to commercial reduction, and gill to the gillnet survey. N indicates the number of trips from which individual fish samples were taken.

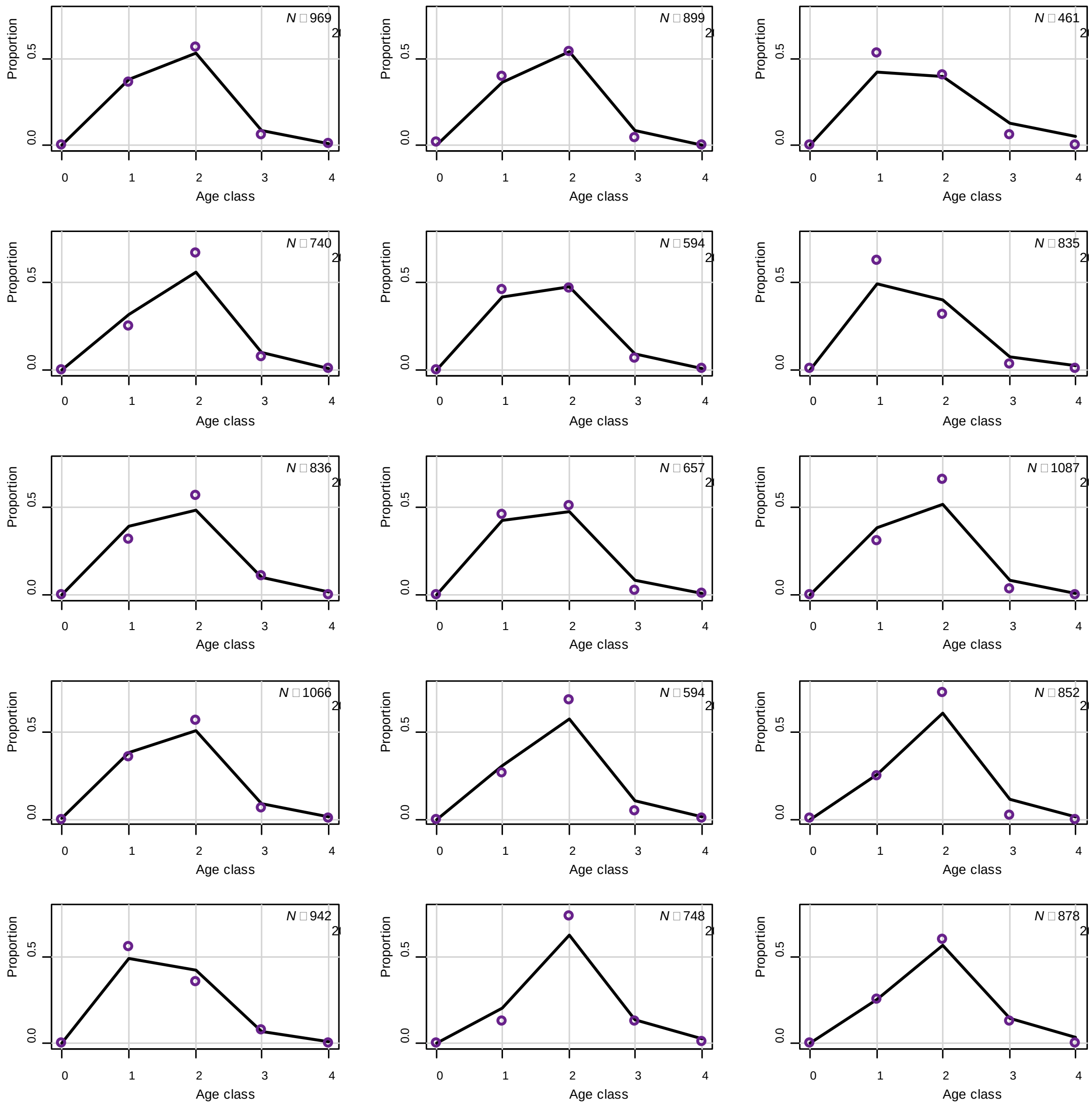



Figure 8. (Continued) Observed (open circles) and estimated (solid line) annual length and age compositions by fleet or survey. In panels indicating the data set, lcomp refers to length compositions, acomp to age compositions, cR to commercial reduction, and gill to the gillnet survey. N indicates the number of trips from which individual fish samples were taken.


Figure 8. (Continued) Observed (open circles) and estimated (solid line) annual length and age compositions by fleet or survey. In panels indicating the data set, lcomp refers to length compositions, acomp to age compositions, cR to commercial reduction, and gill to the gillnet survey. N indicates the number of trips from which individual fish samples were taken.

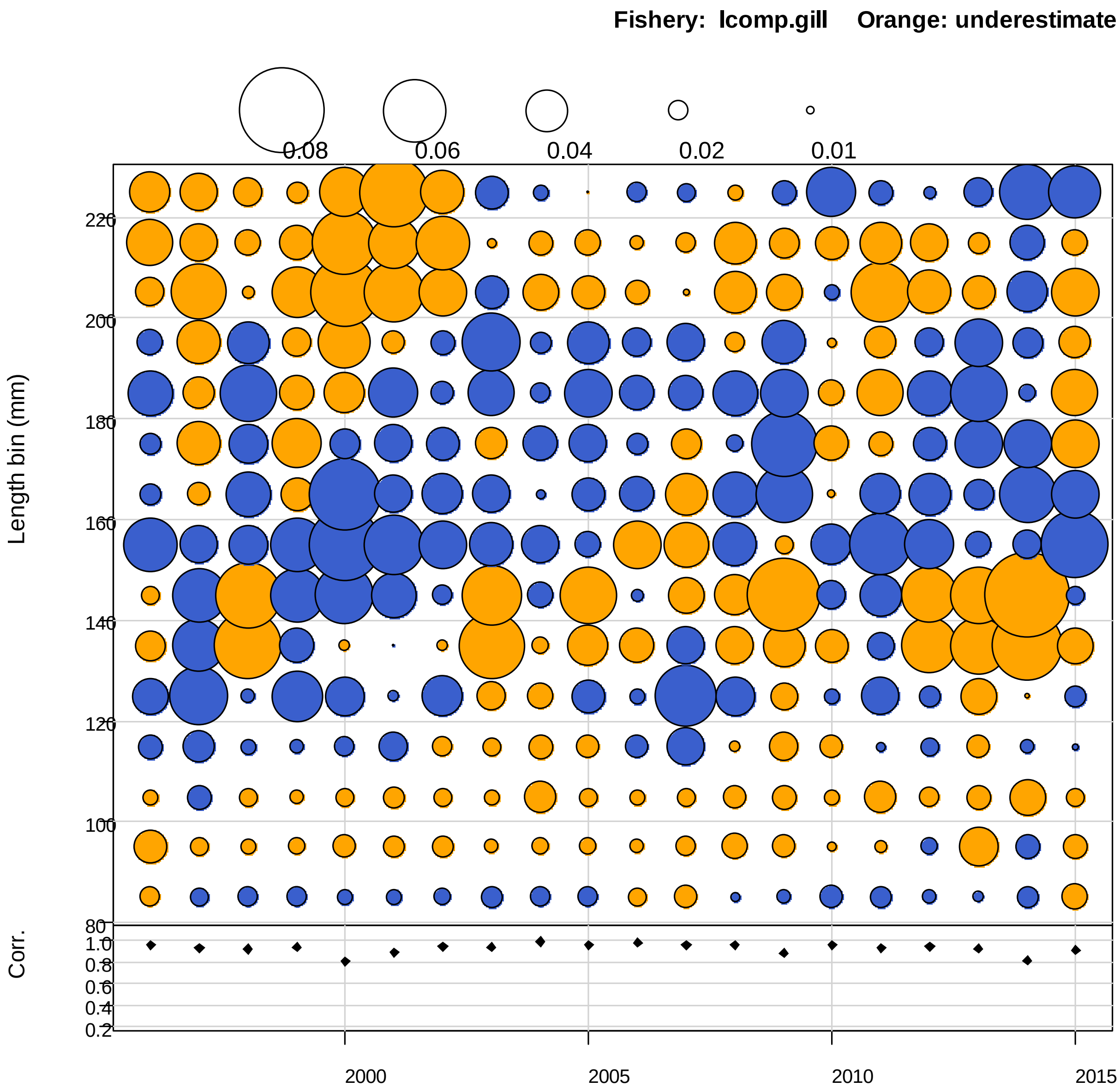



Figure 9. Bubble plot of the gillnet index length compositions for 1988 – 2015. The correlation on the bottom of the figure indicates the correlation between the observed and predicted data.

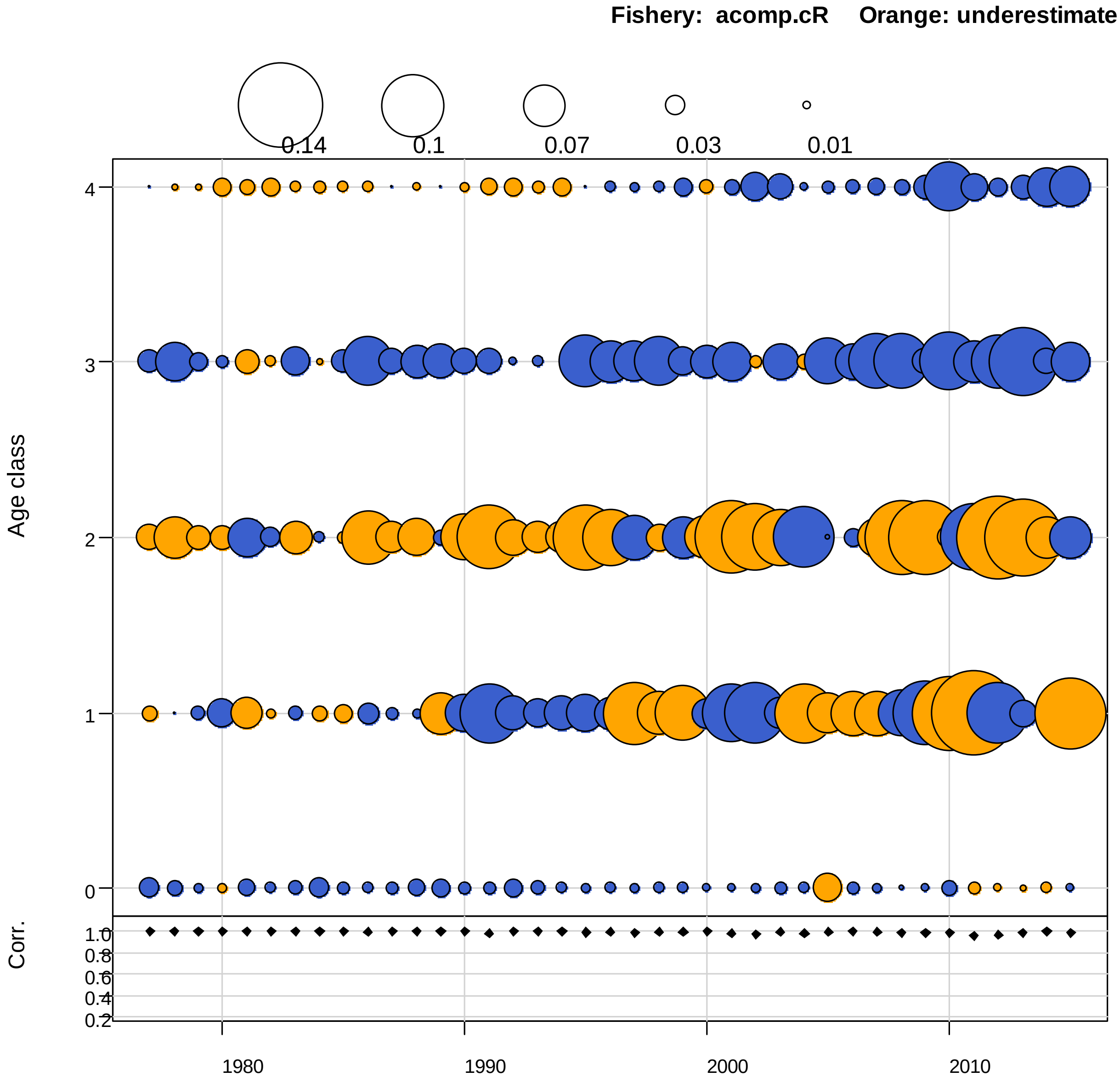



Figure 10. Bubble plot of the commercial reduction fishery age compositions for 1977 – 2015. The correlation on the bottom of the figure indicates the correlation between the observed and predicted data.

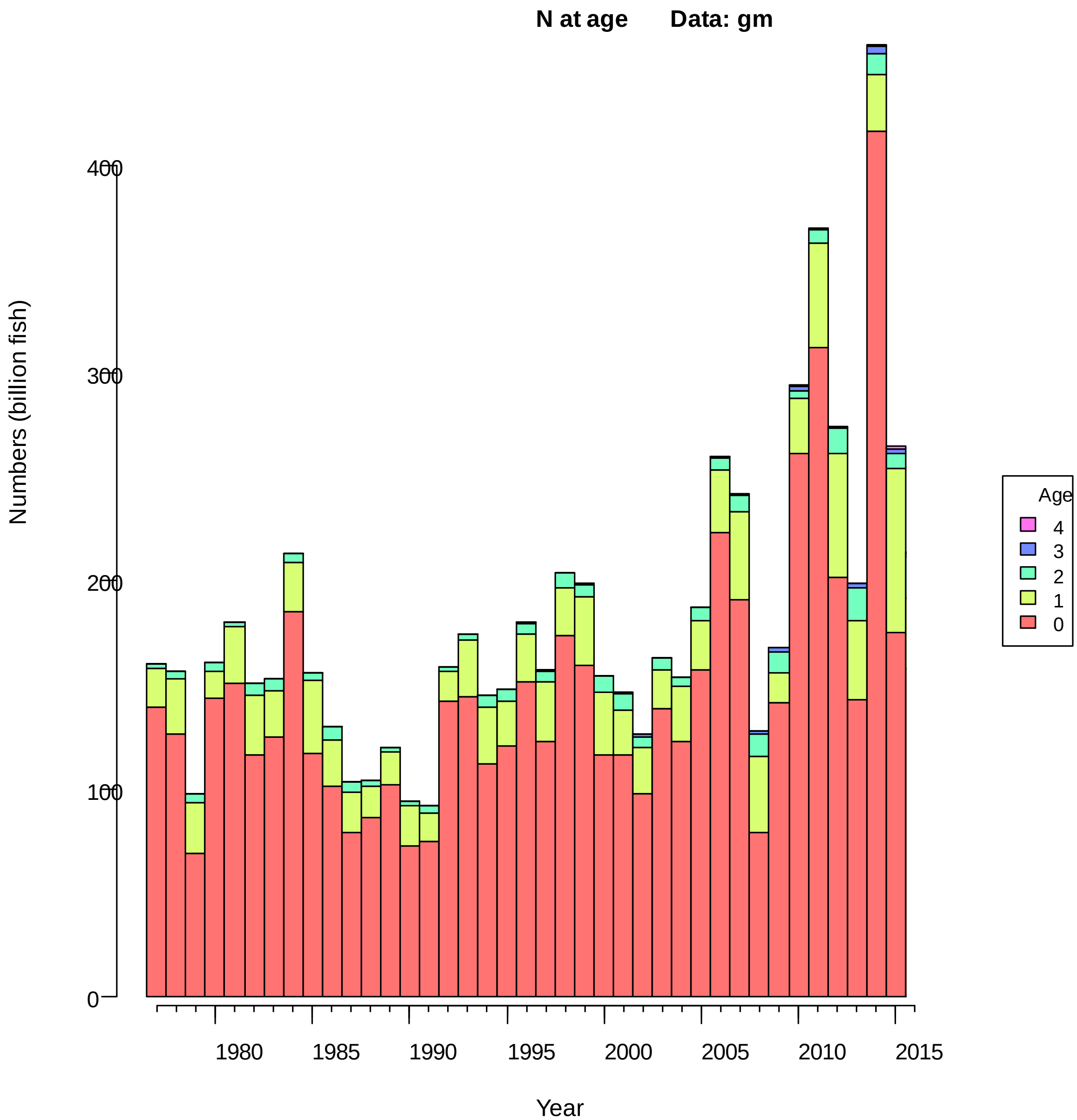



Figure 11. Estimated abundance at age at the start of the year.

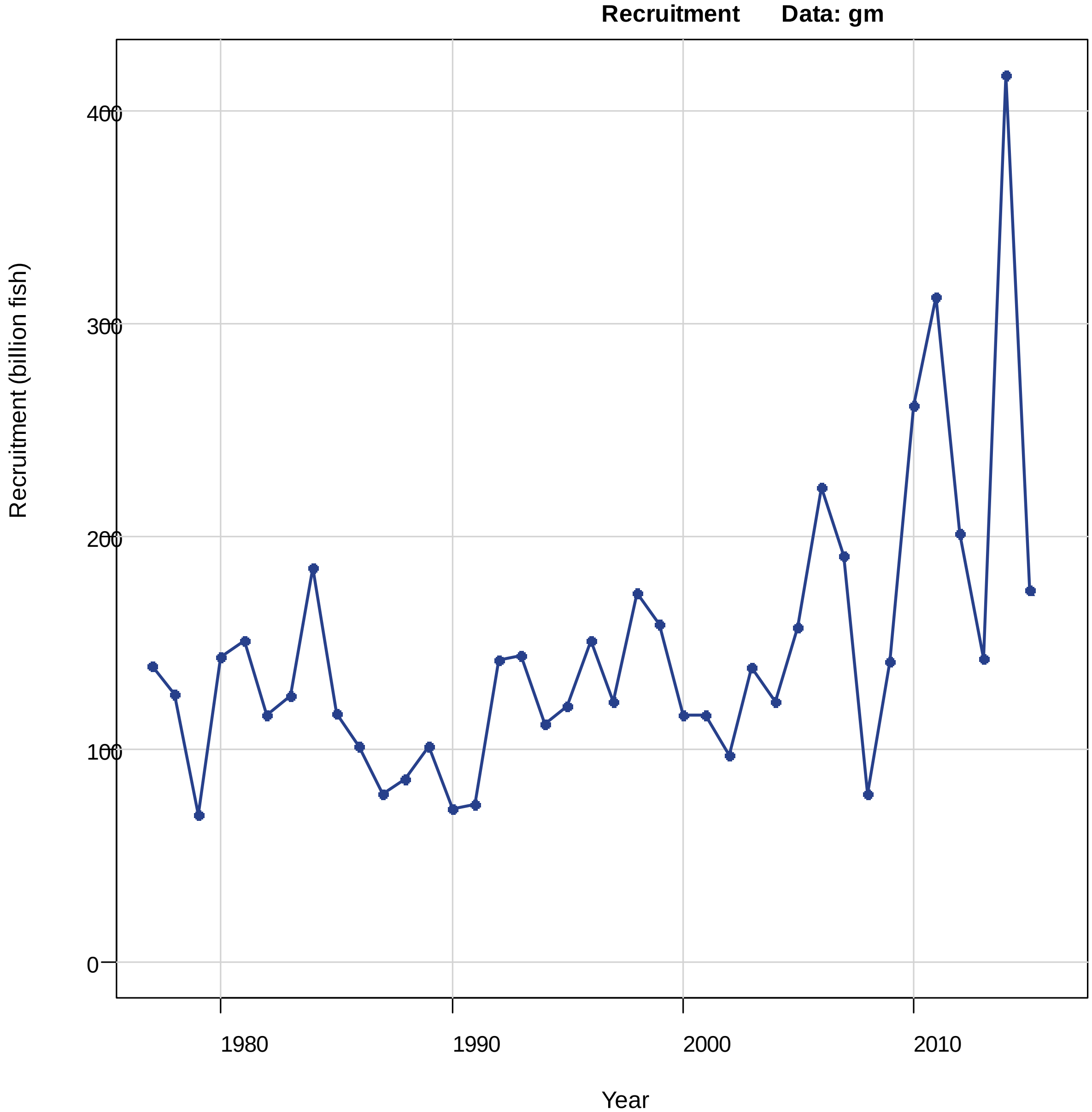



Figure 12. Estimated recruitment of age-0 fish in billions.

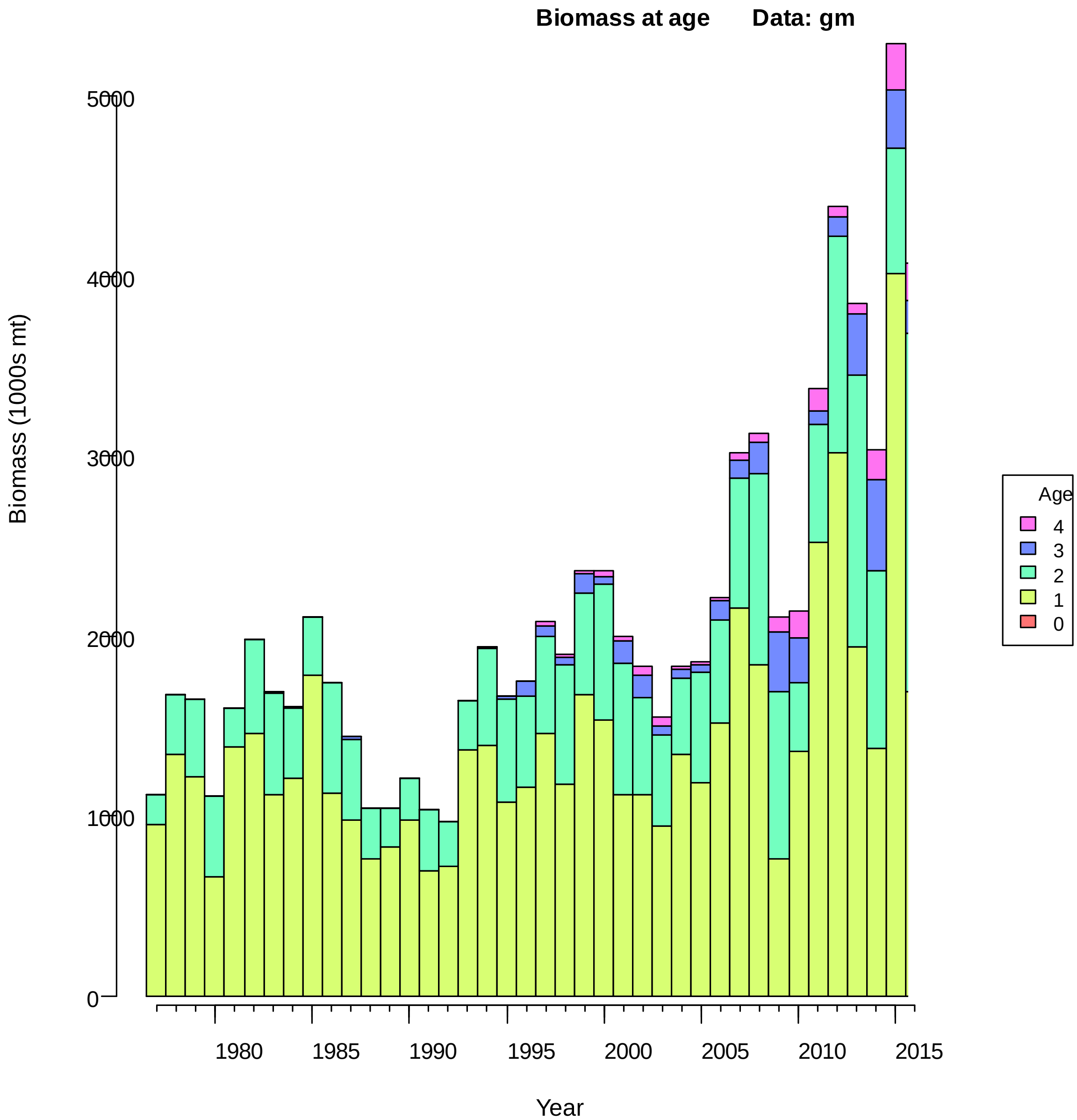



Figure 13. Estimated biomass at age at start of year.

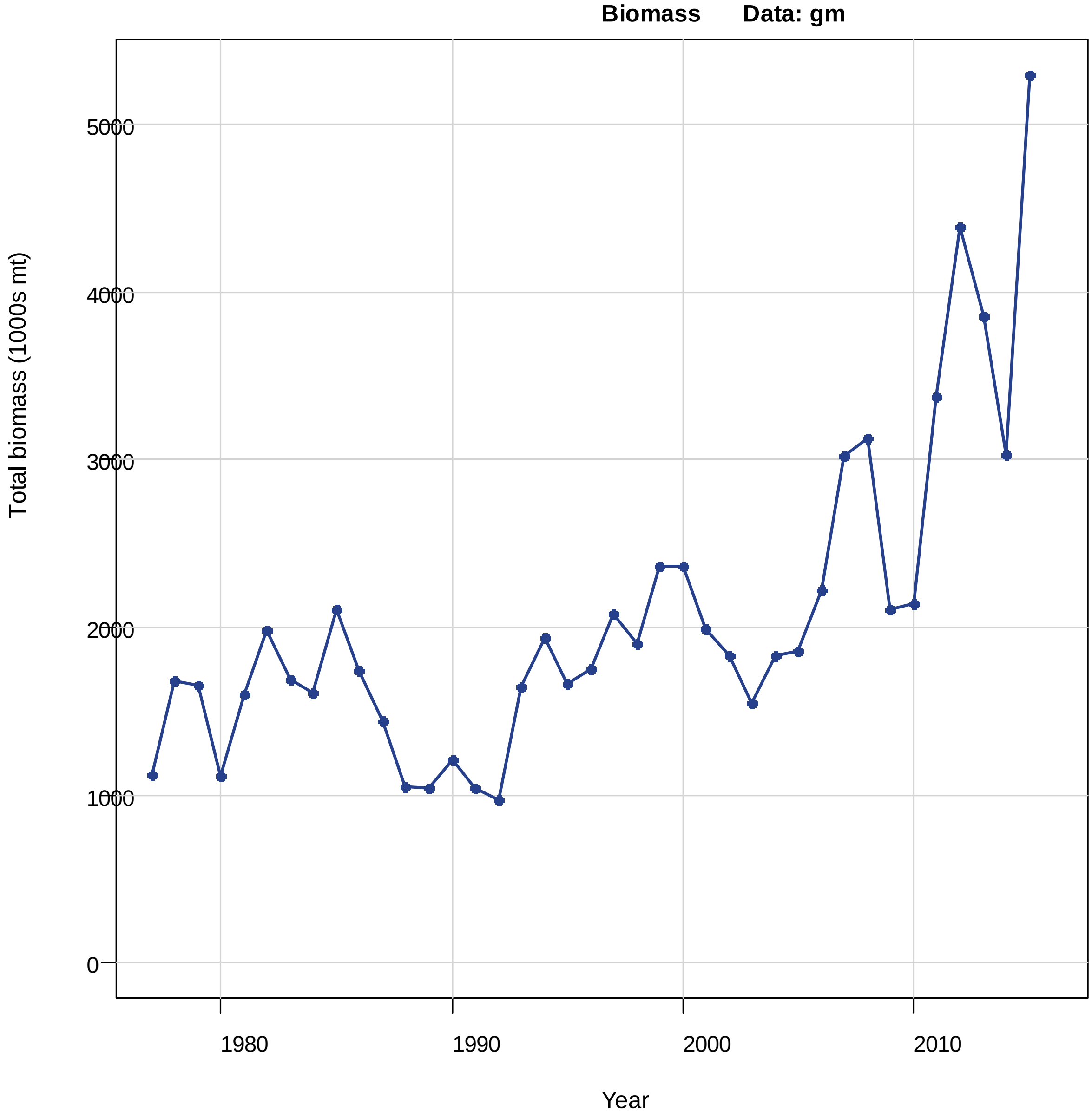



Figure 14. Estimated total biomass (1,000s mt) at start of year.

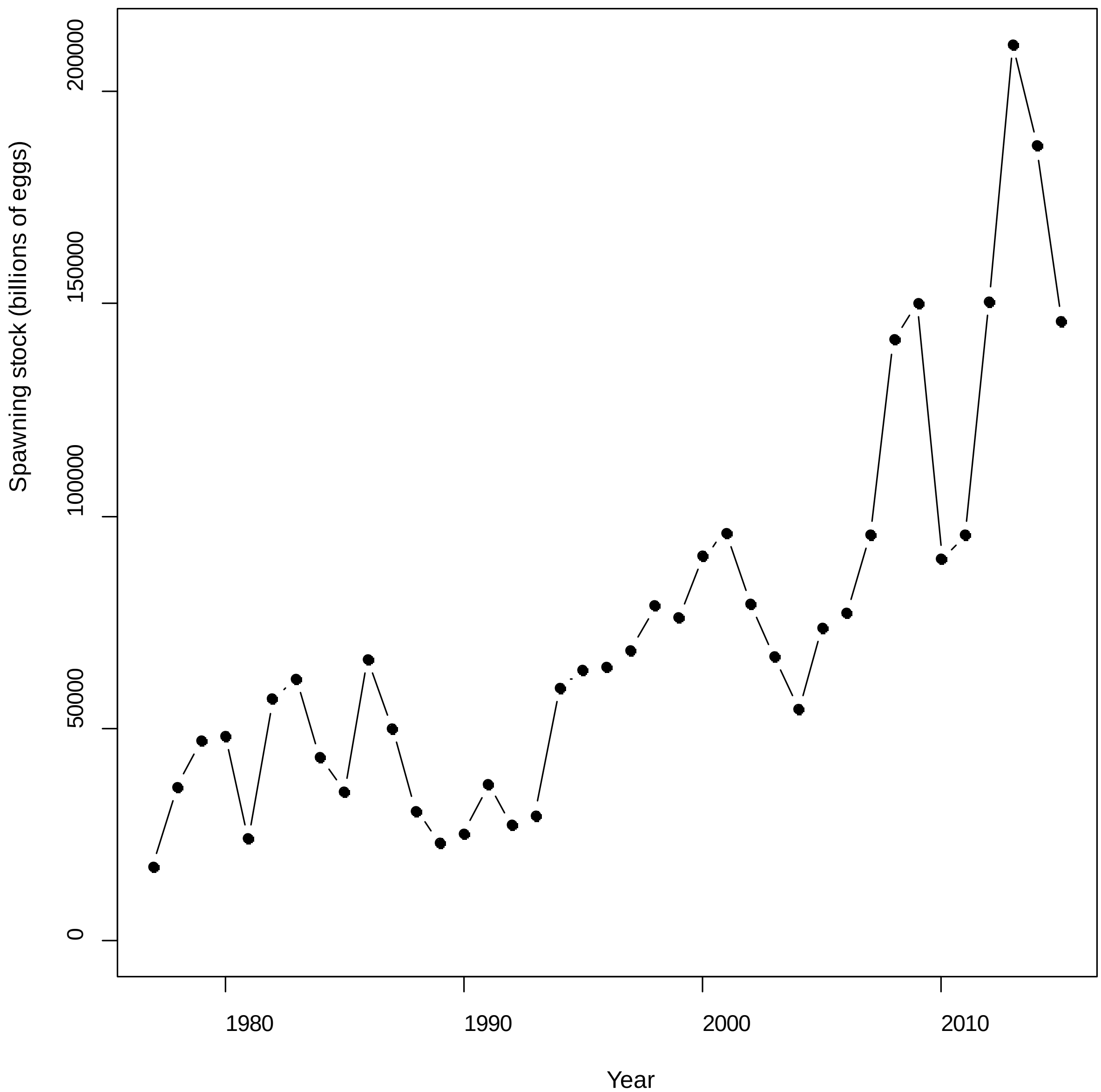



Figure 15. Estimated spawning stock biomass (fecundity in billions of eggs) at time of peak spawning.

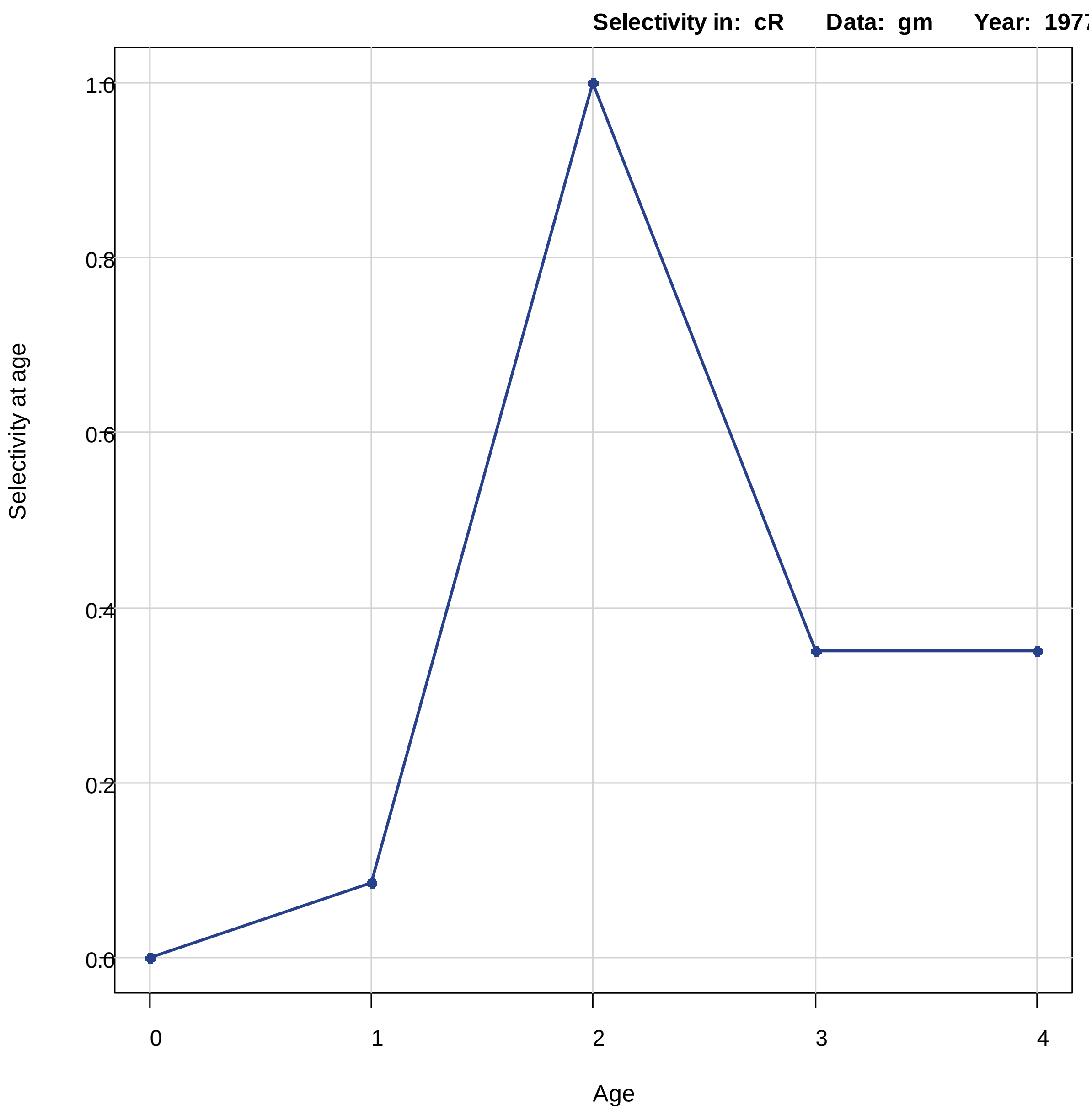


Figure 16. Selectivity of the commercial reduction fleet, 1977 – 2015.

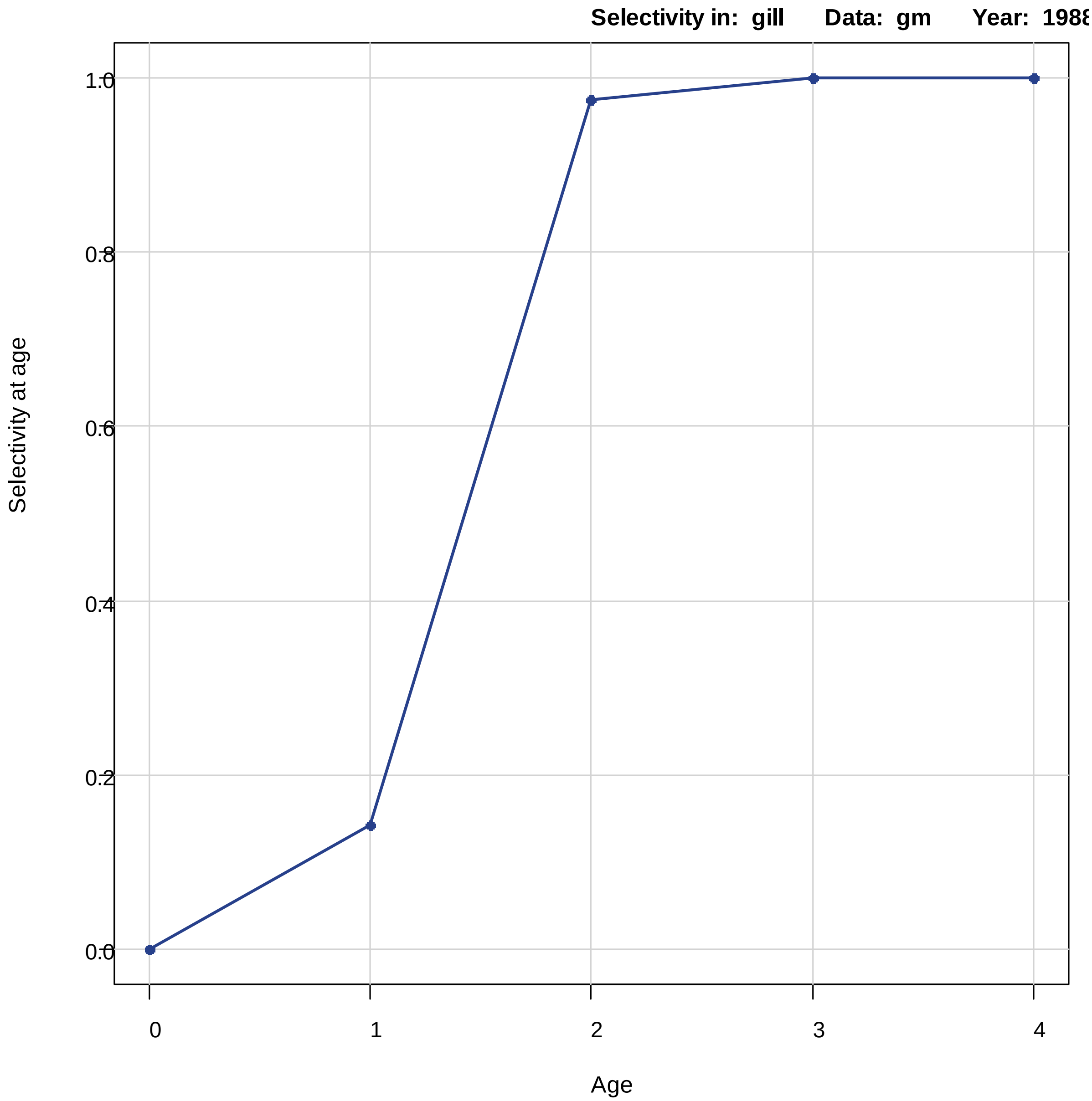



Figure 17. Selectivity of the LA gillnet survey, 1988 – 2015.

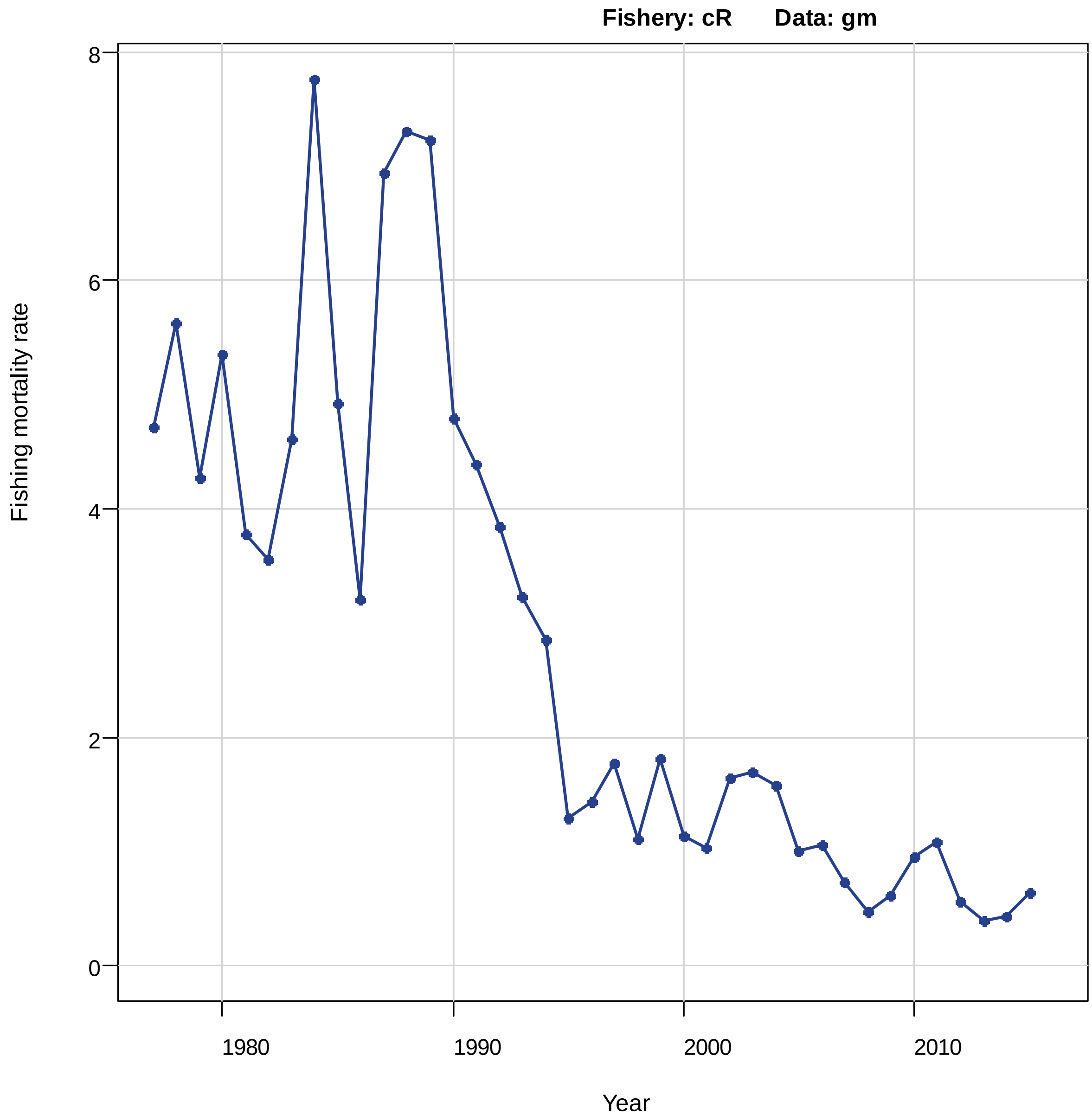



Figure 18. Estimated fully selected fishing mortality rate (per year) for the commercial reduction fishery.

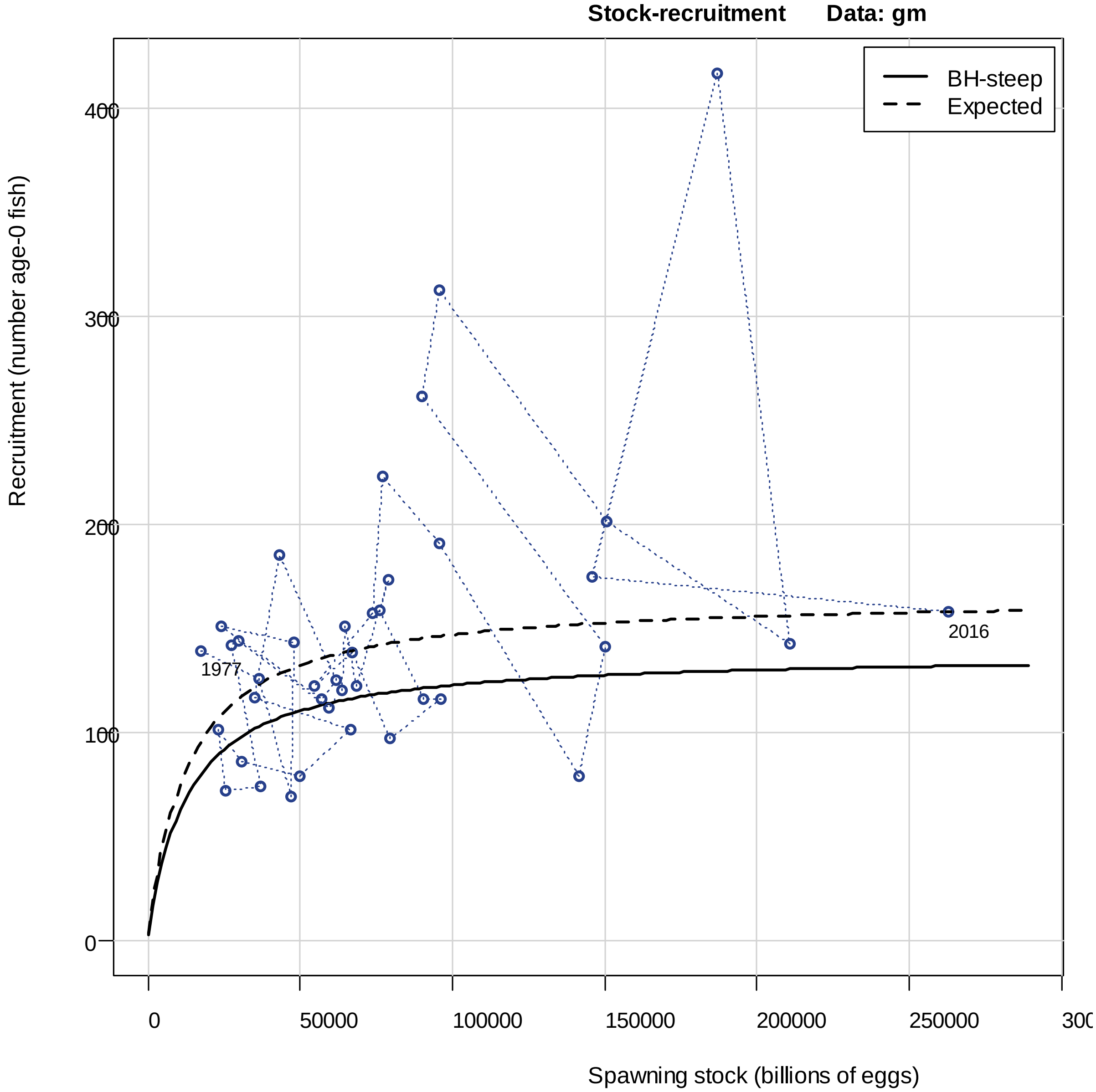



Figure 19. Beverton-Holt spawner-recruit curves, with and without lognormal bias correction. Years within panel indicate year recruitment was generated from spawning biomass in that same year.

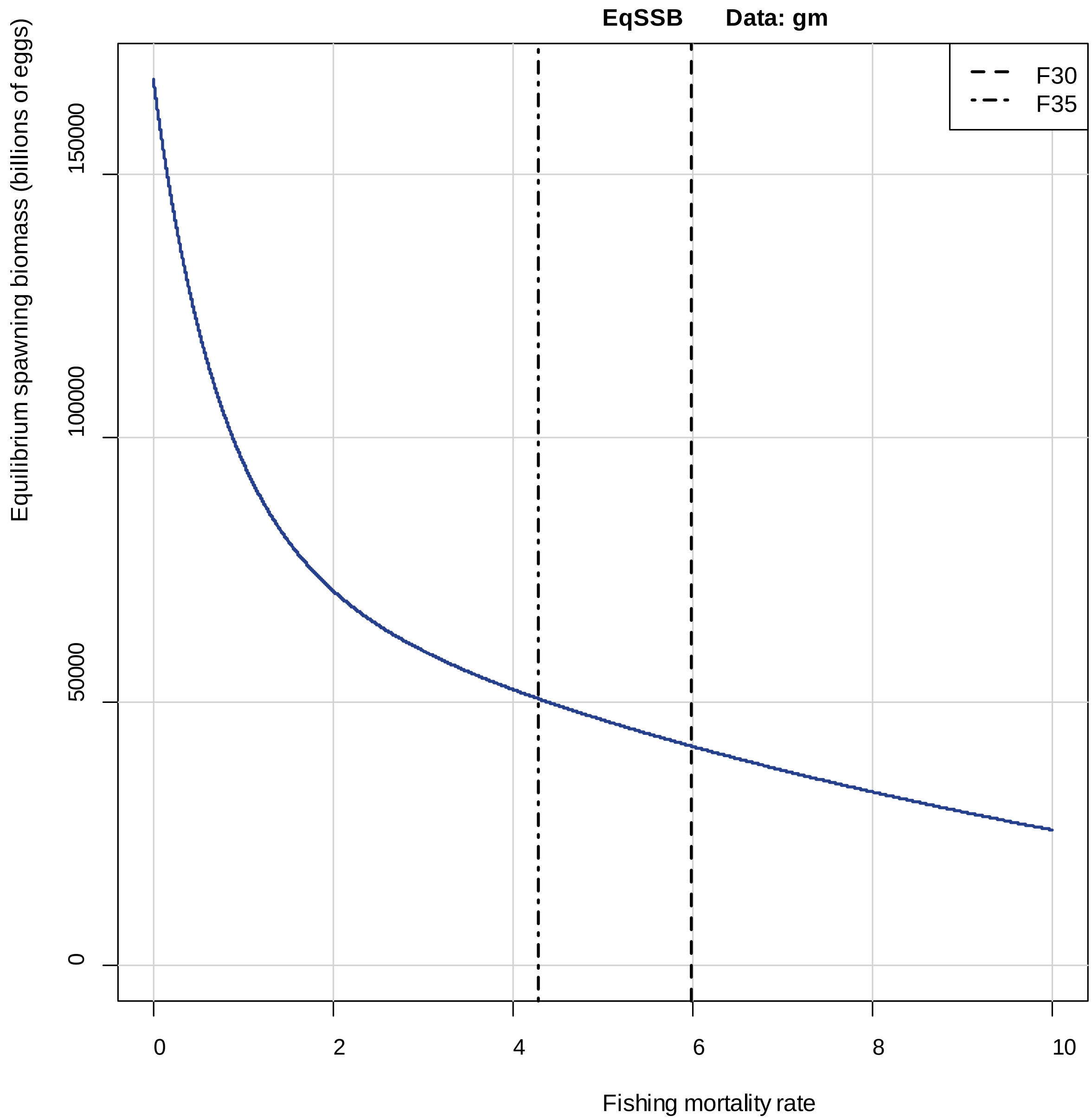



Figure 20. Spawning biomass per recruit relative to that at the unfished level, from which the 30% and 35% levels provide $F_{30\%}$ and $F_{35\%}$.

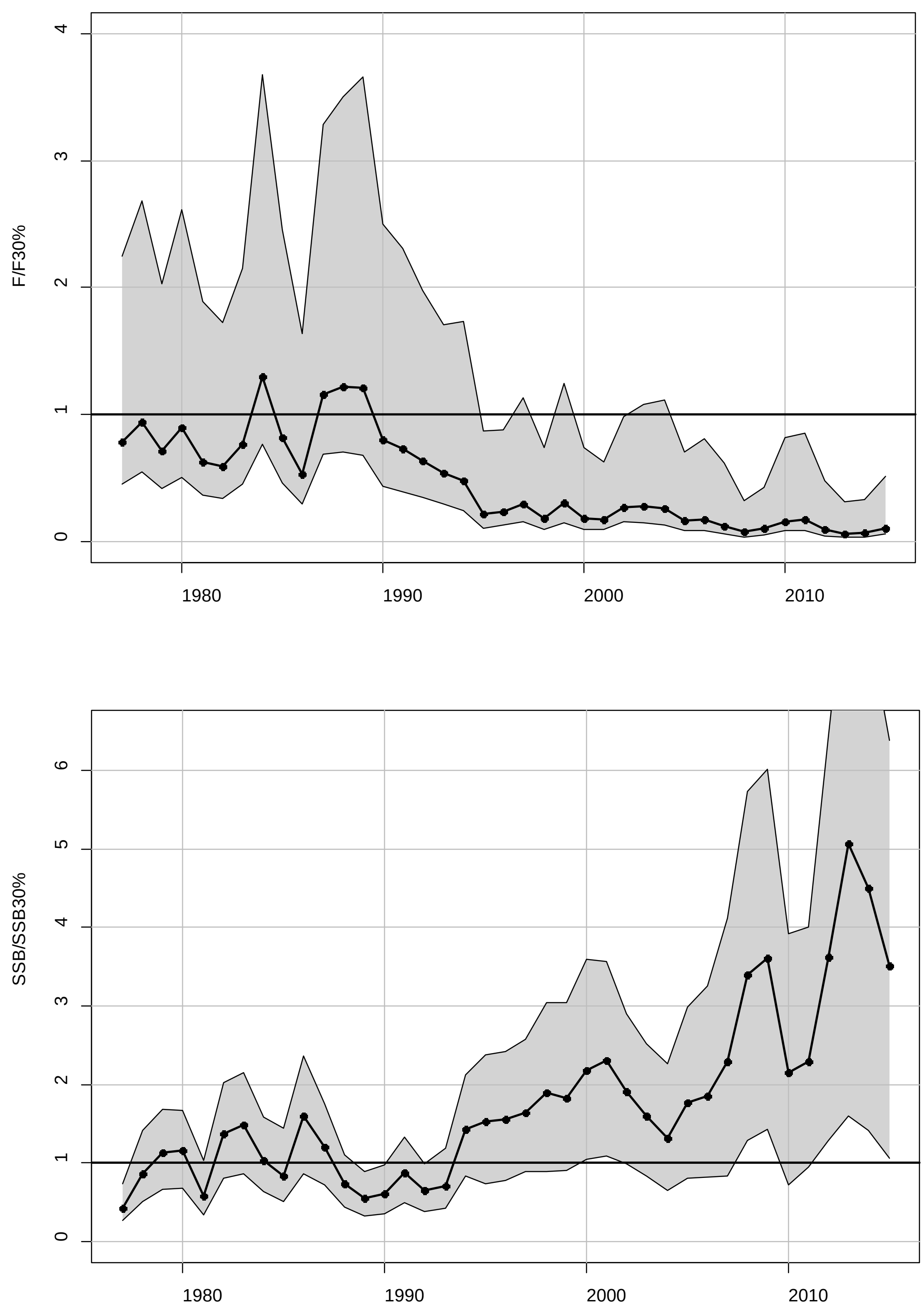
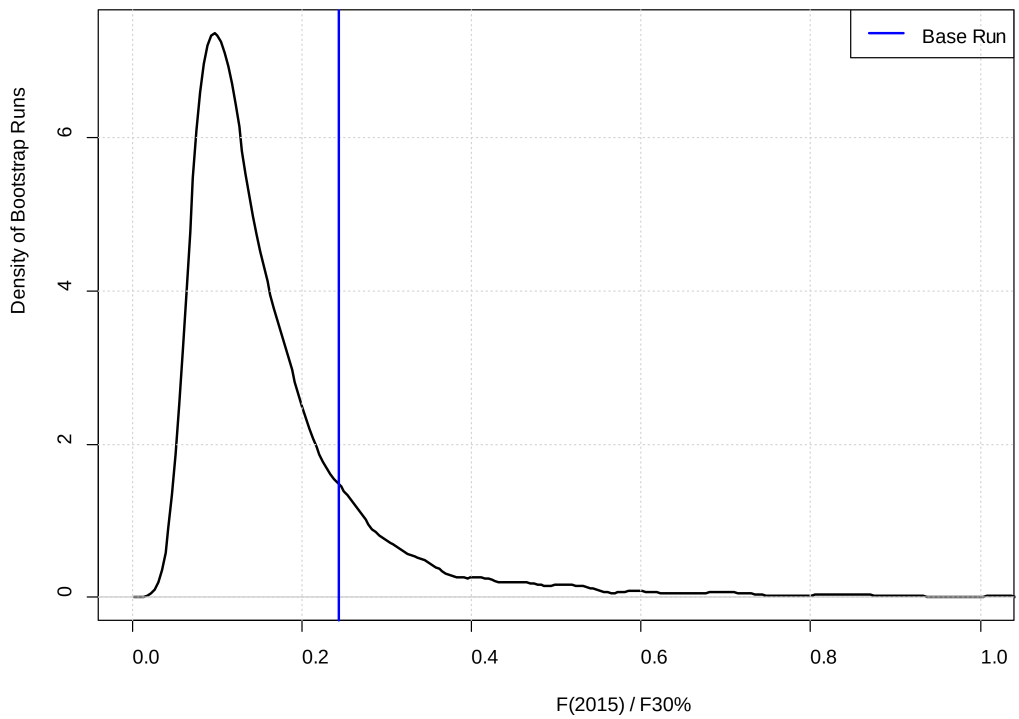



Figure 21. Estimated time series relative to threshold benchmarks. Solid line indicates estimates from base run of the Beaufort Assessment Model; gray error bands indicate 5th and 95th percentiles of the MCB trials. Top panel: *F* relative to $F_{30\%}$. Bottom panel: spawning stock biomass, measured as fecundity, relative to $SSB_{30\%}$.



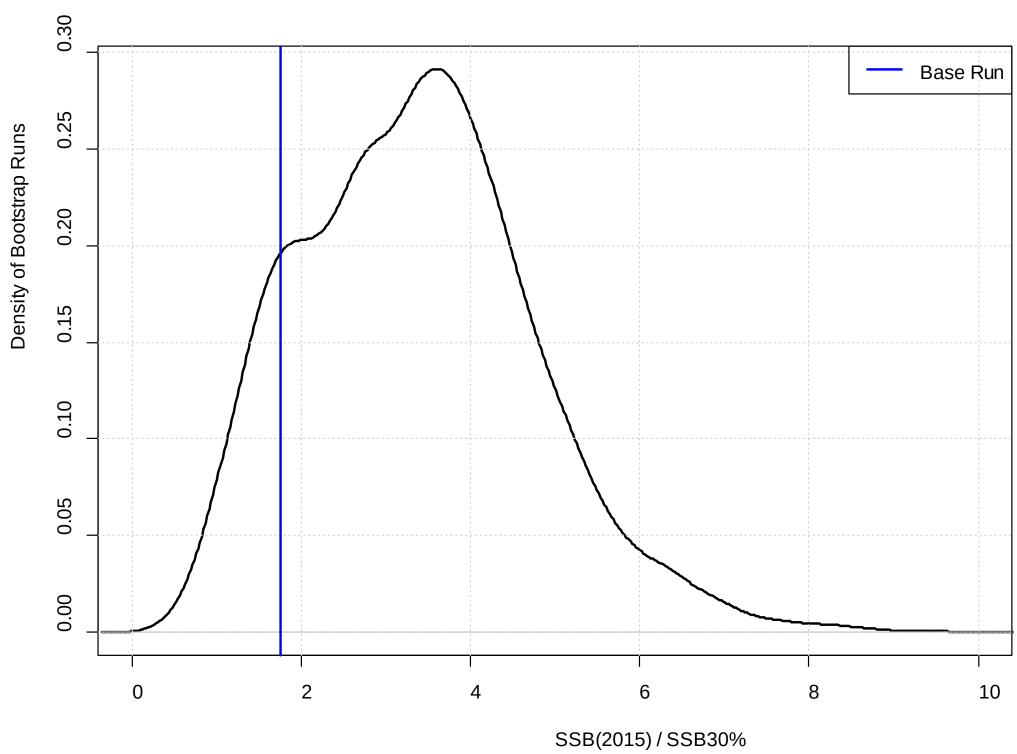




Figure 22. Probability densities of terminal status estimates from MCB analysis of the Beaufort Assessment Model. Vertical lines represent point estimates from the base run.

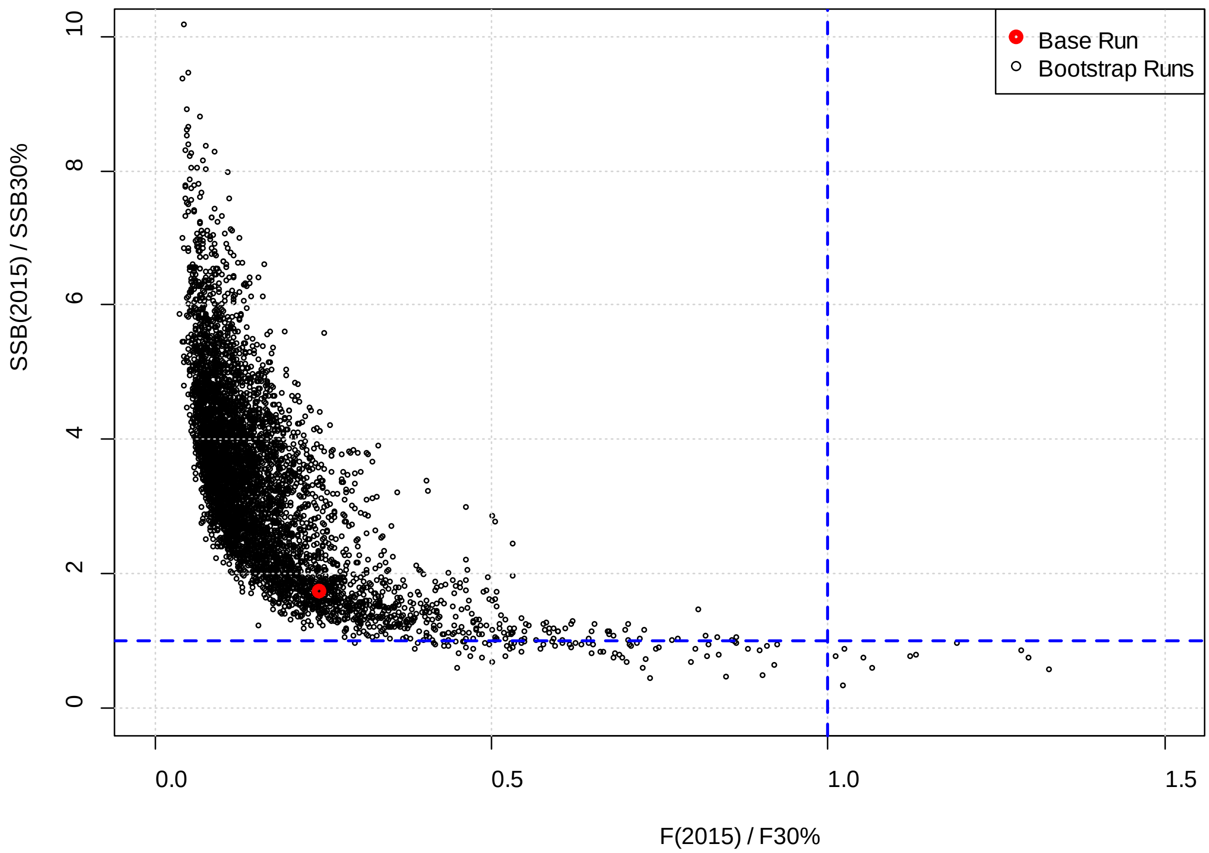



Figure 23. Phase plot of terminal status estimates from MCB analysis of the Beaufort Assessment Model. The red point indicates estimates from the base run; the black points are individual MCB trials.

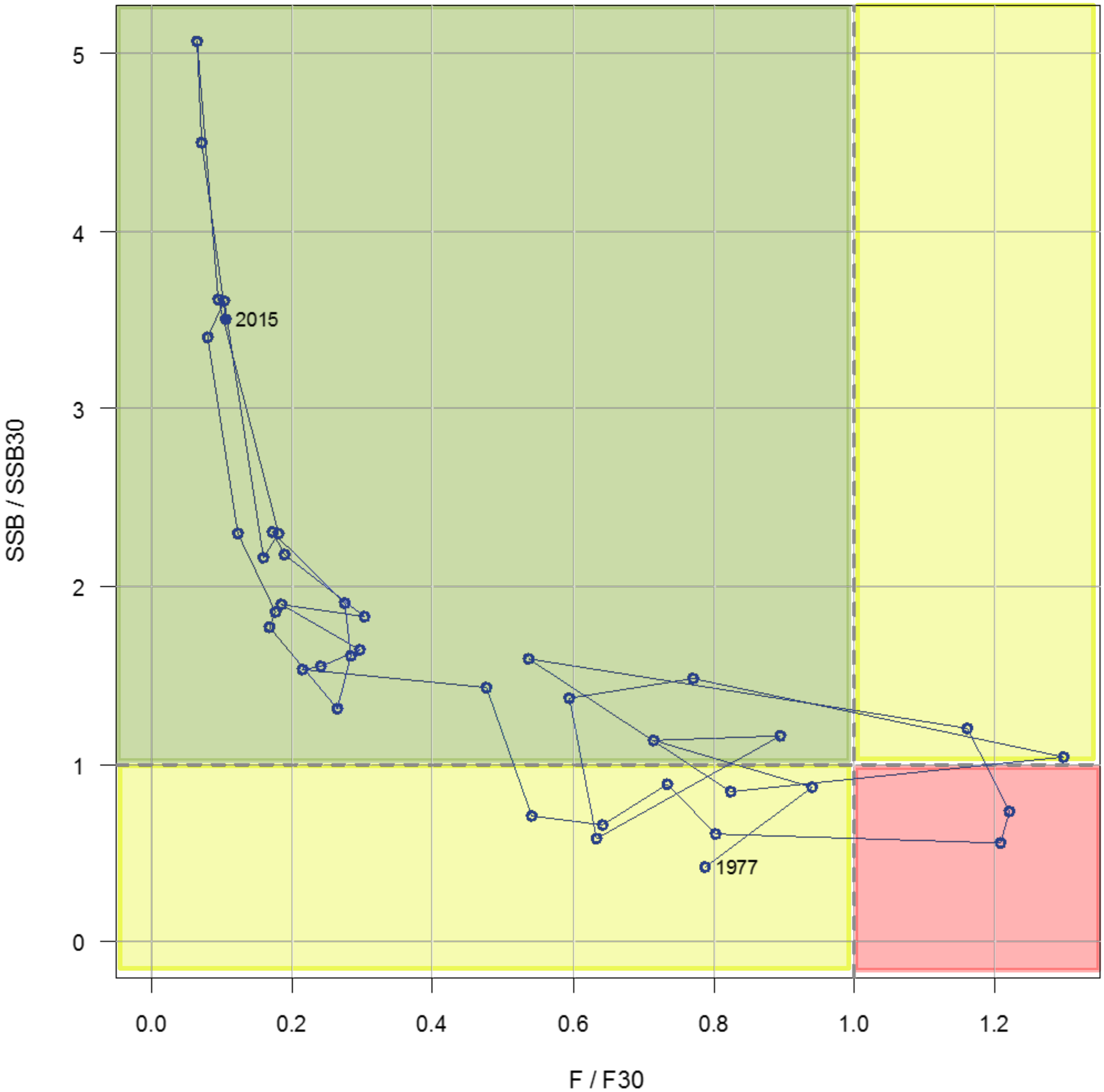



Figure 24. Phase plot of annual estimates of fishing mortality (F) and spawning stock biomass (SSB) or fecundity from the base BAM model. Dashed vertical and horizontal lines indicate the reference point thresholds at $F_{30\%}$ and $SSB_{30\%}$. A year in the green zone indicates that the population is not overfished and that overfishing is not occurring. Placement in the yellow zones would indicate that one of the stock indicator thresholds had been exceeded and red would indicate that both thresholds had been exceeded.

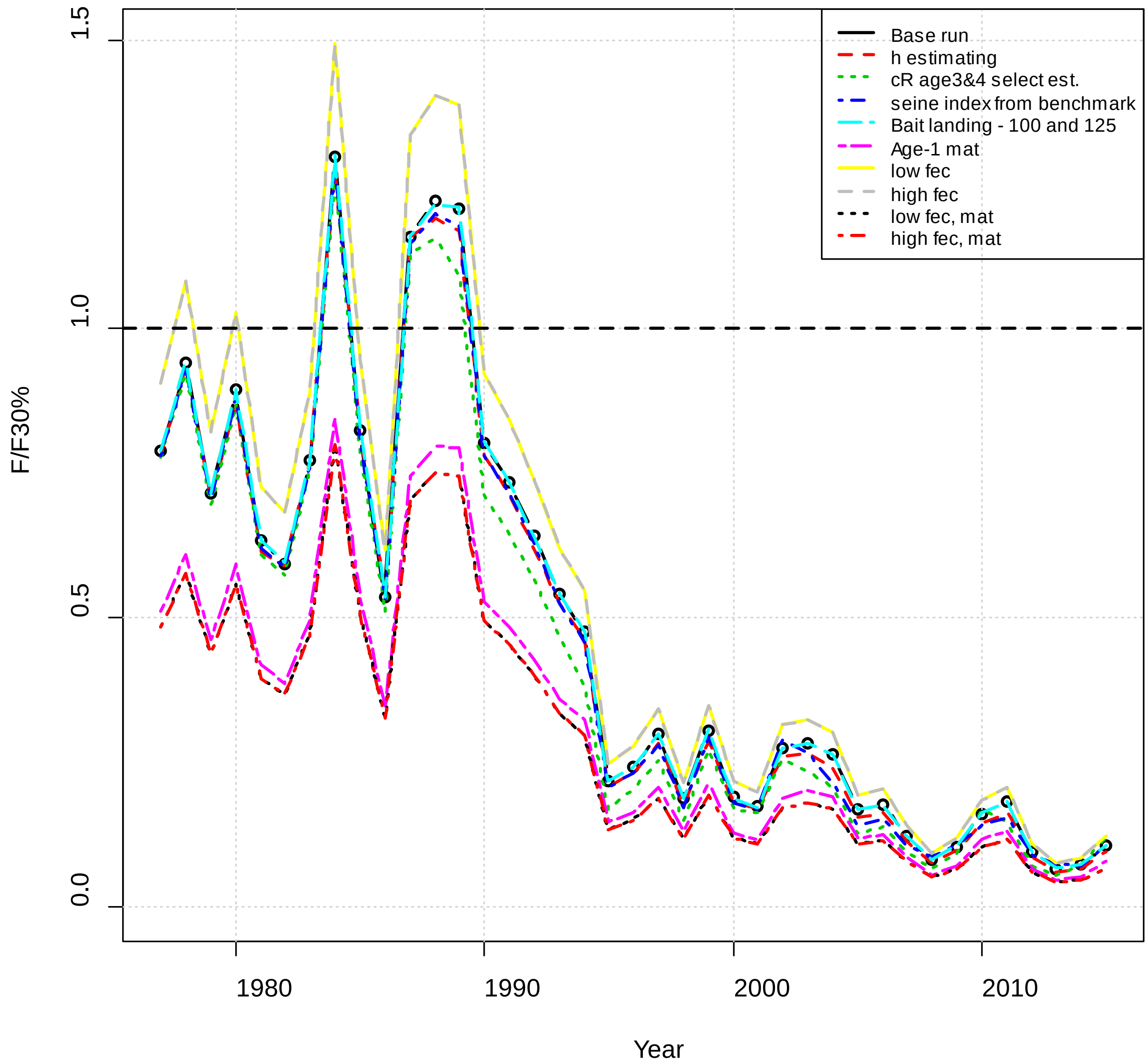



Figure 25. Time series of $F/F_{30\%}$ for the sensitivity runs with the solid black line with open circles being the base run.

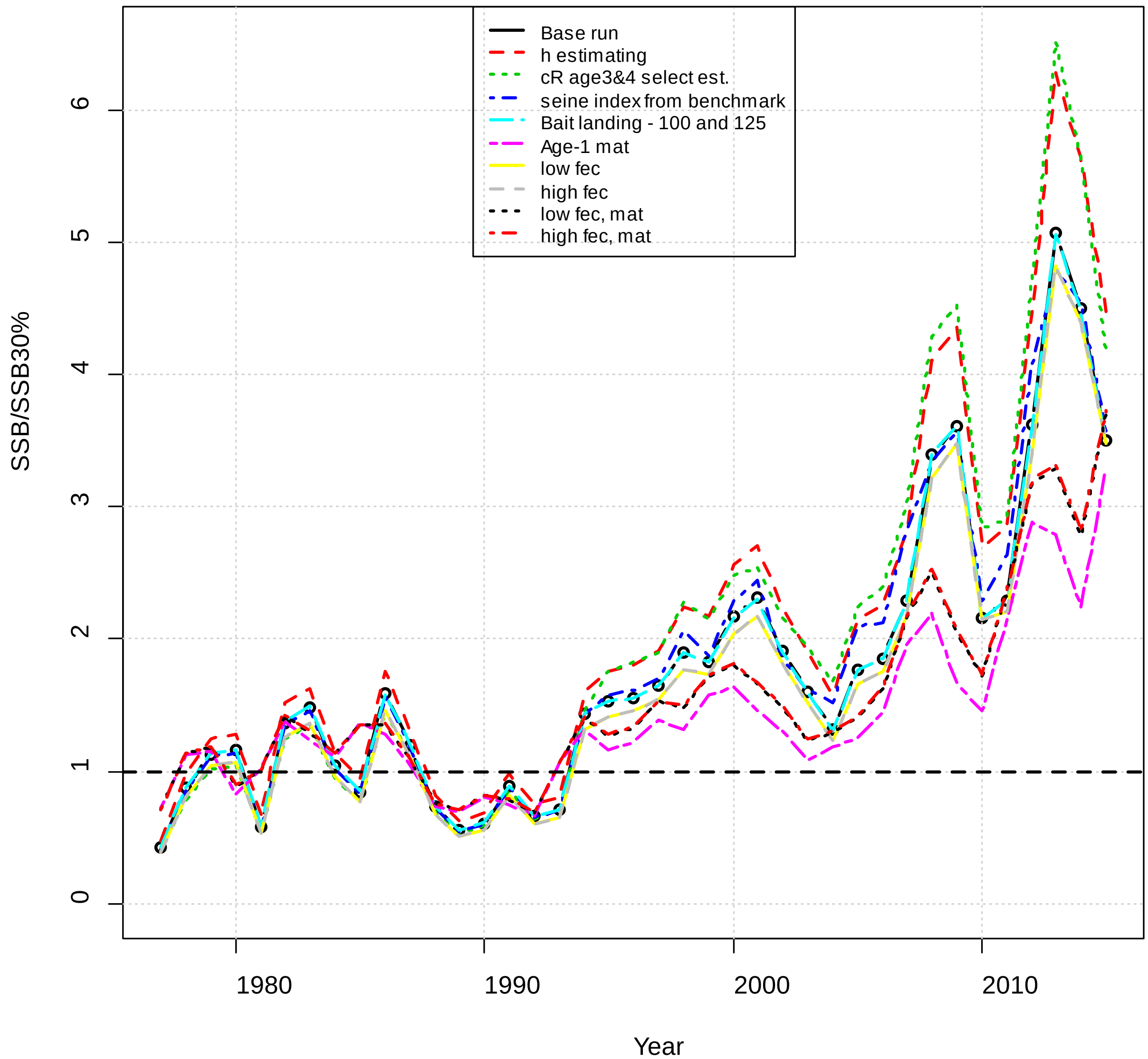



Figure 26. Time series of $SSB/SSB_{30\%}$ for sensitivity runs. The solid black line with open circles is the base run.

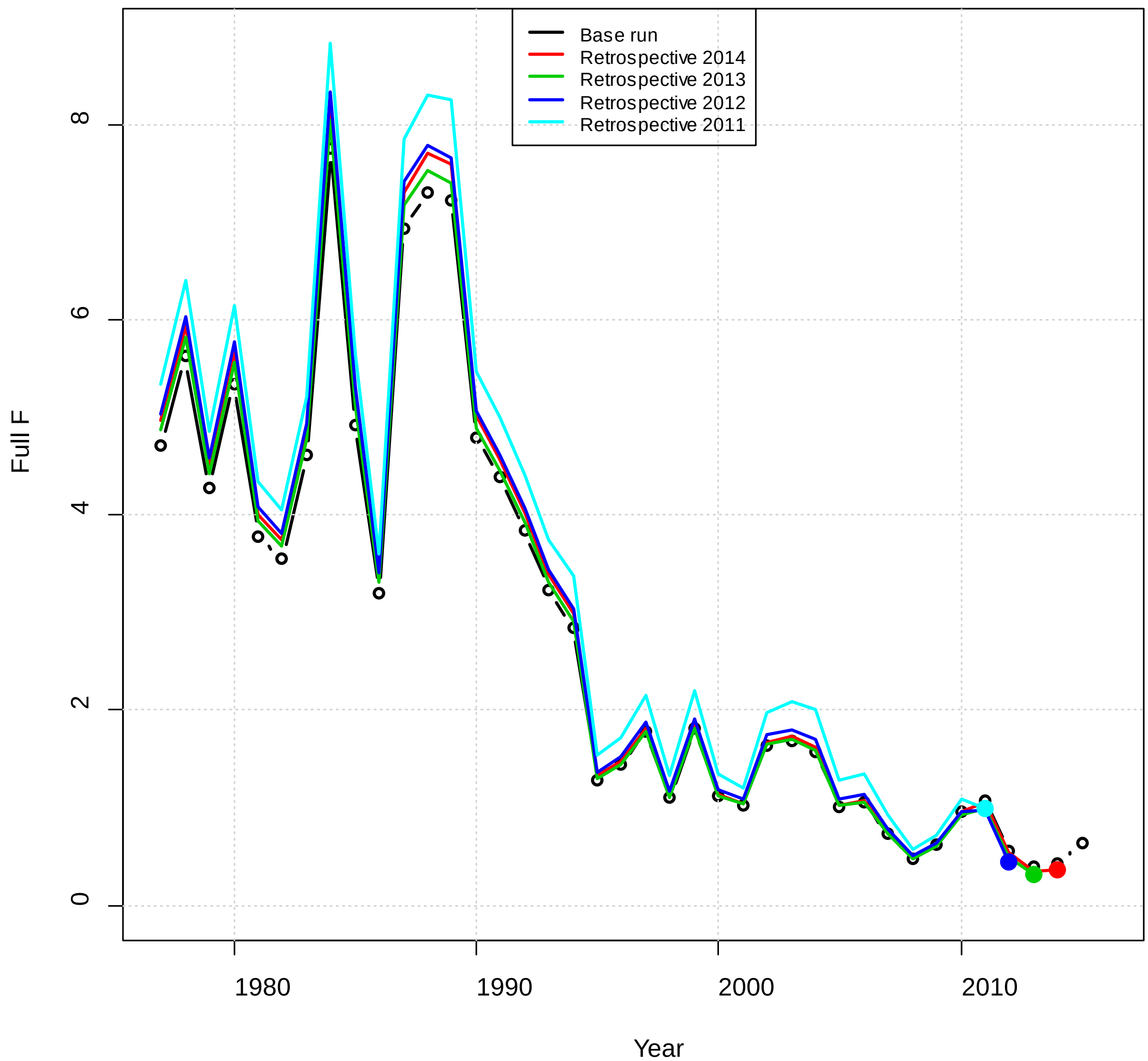



Figure 27. Retrospective analyses. Sensitivity to terminal year of data on the estimation of fishing mortality rate.

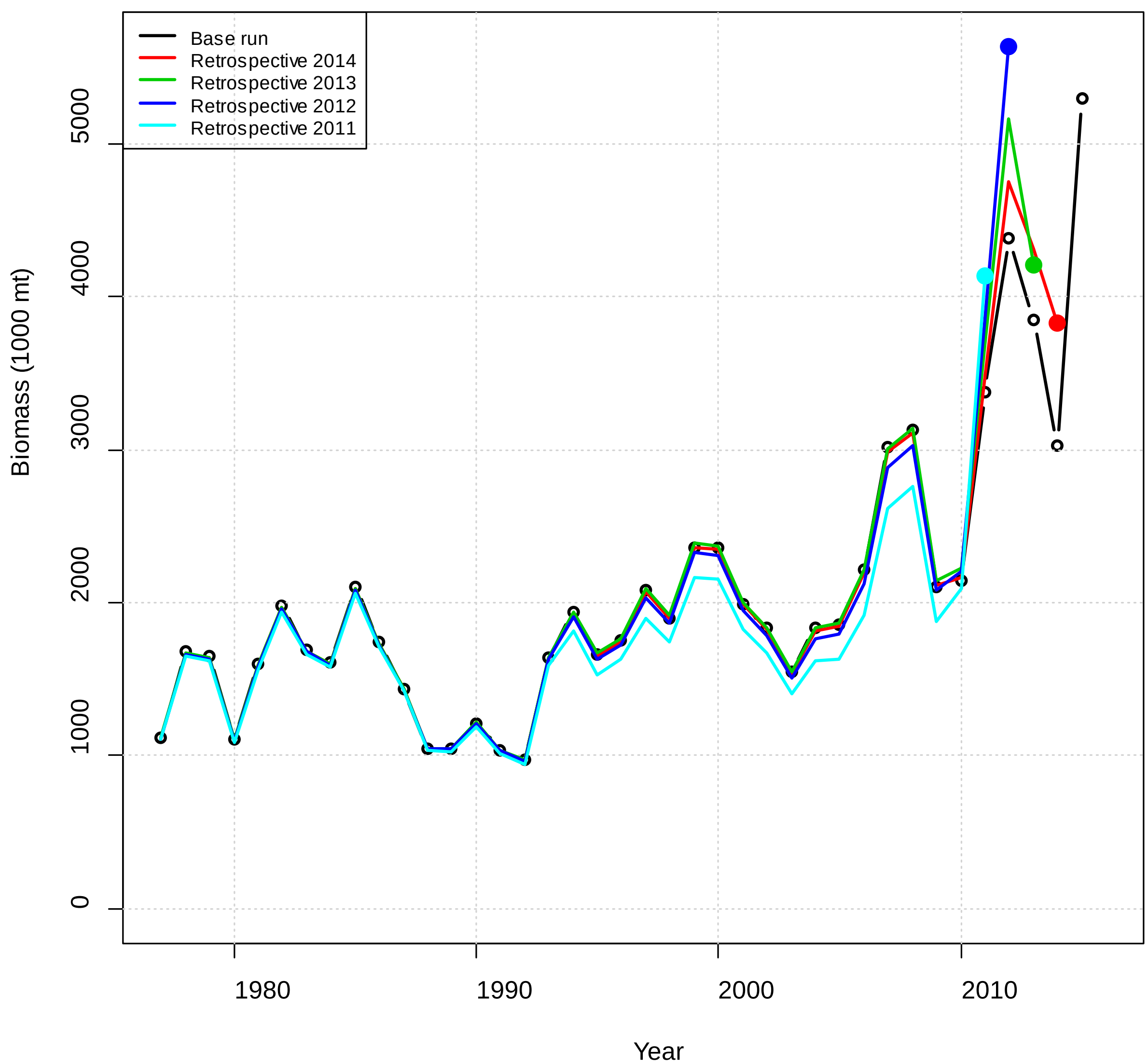



Figure 28. Retrospective analyses. Sensitivity to terminal year of data on the estimation of biomass.

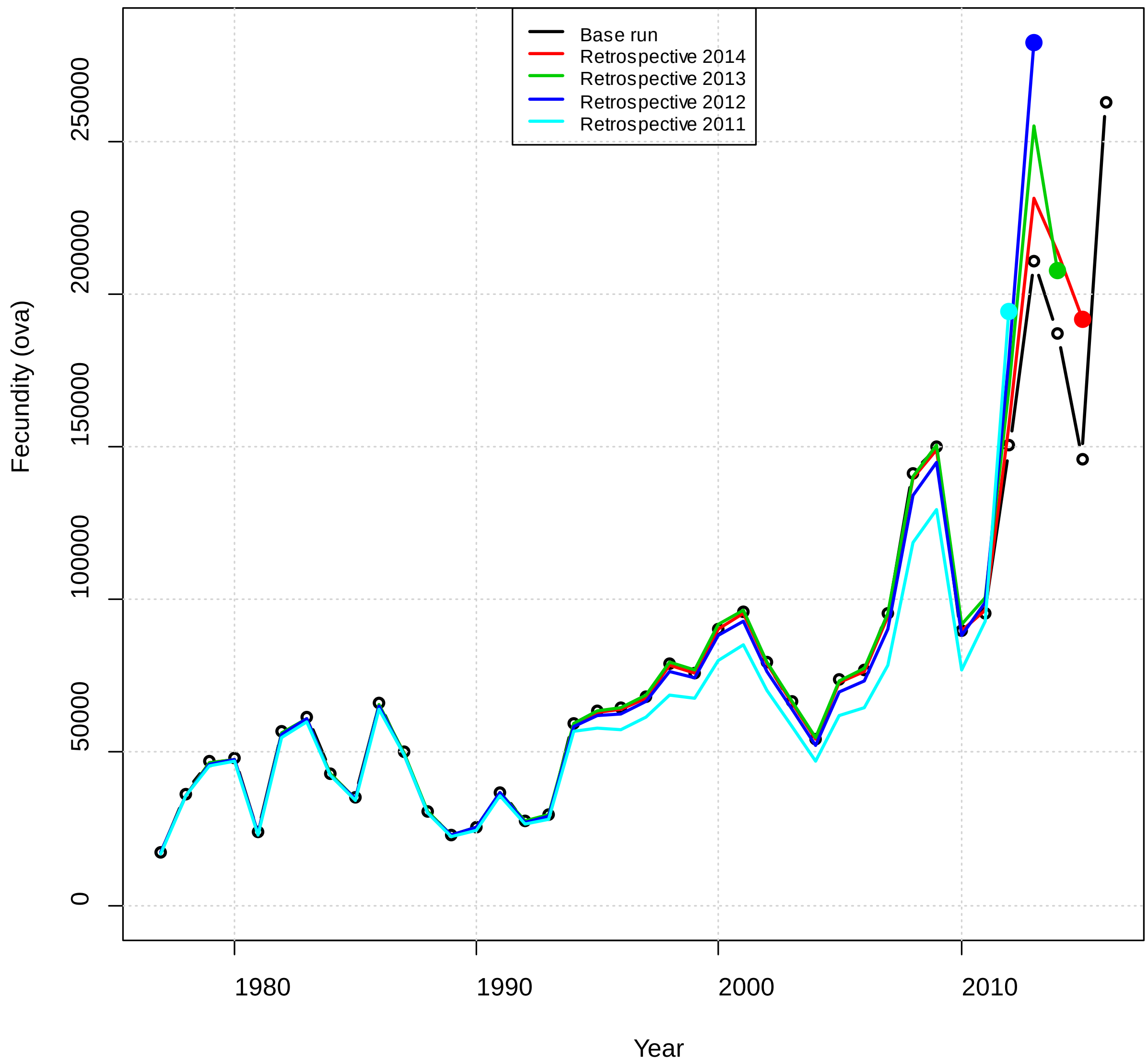



Figure 29. Retrospective analyses. Sensitivity to terminal year of data on the estimation of fecundity.

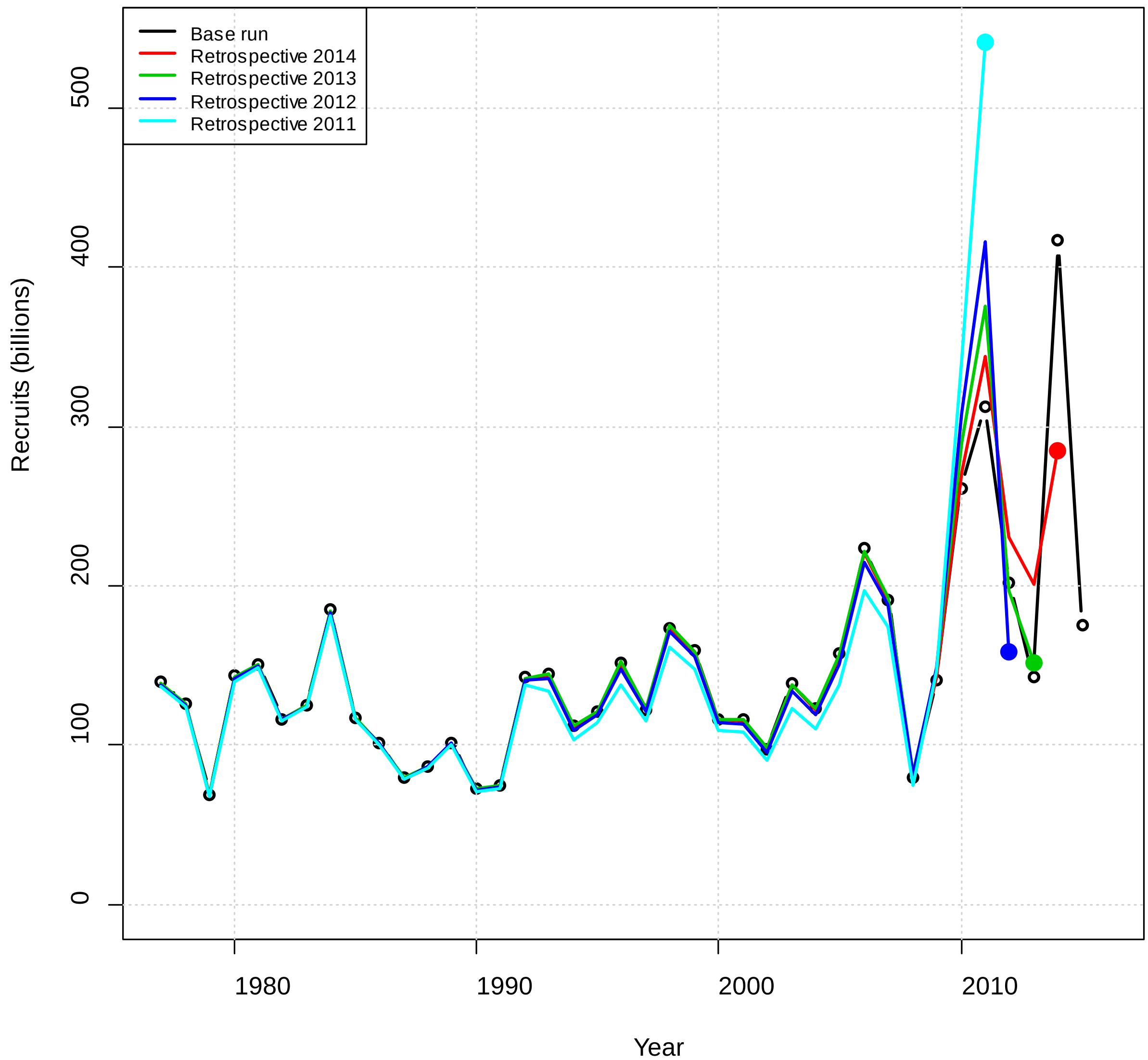



Figure 30. Retrospective analyses. Sensitivity to terminal year of data on the estimation of recruitment.

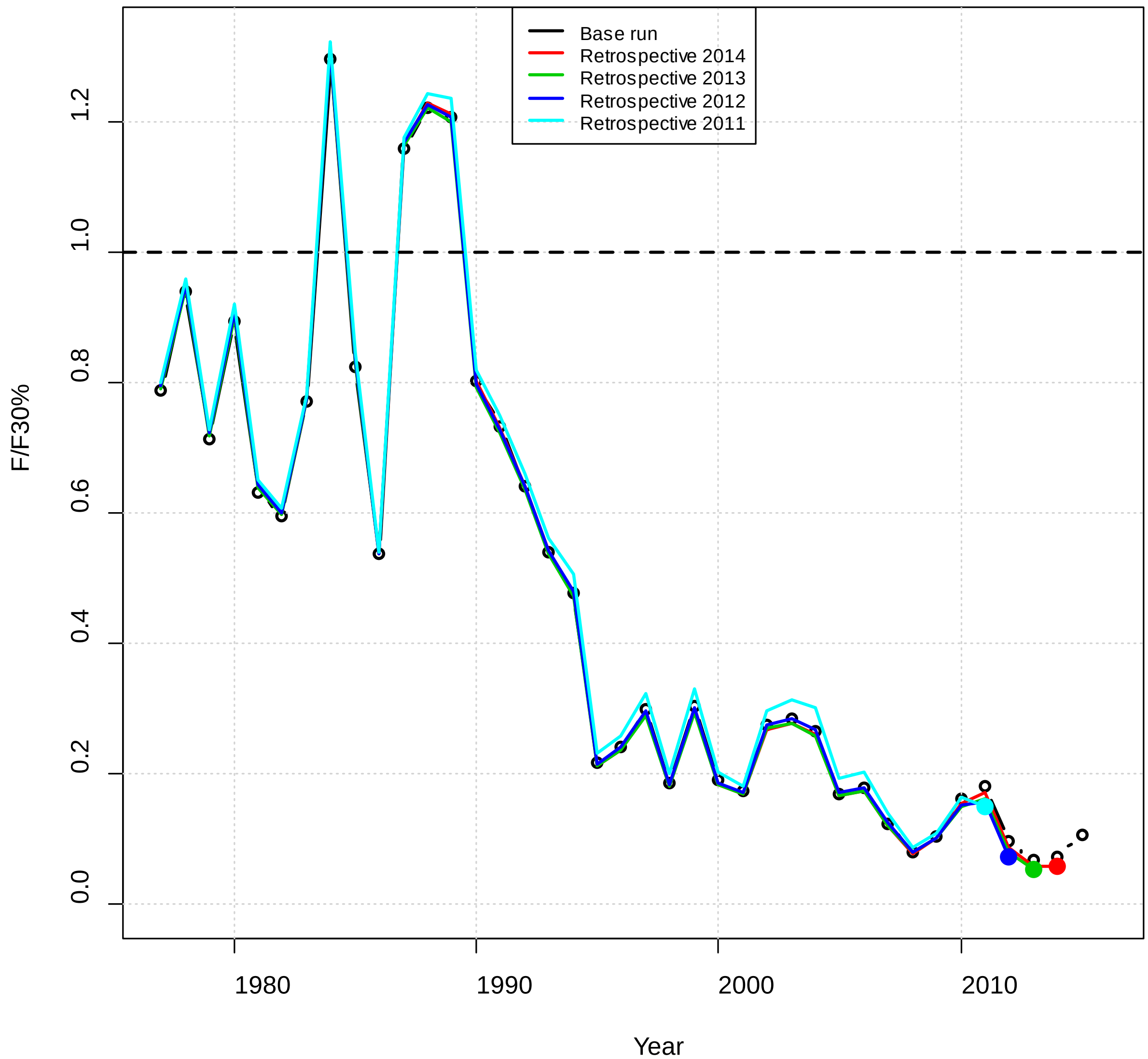



Figure 31. Retrospective analyses. Sensitivity to terminal year of data on the estimation of $F/F_{30\%}$.

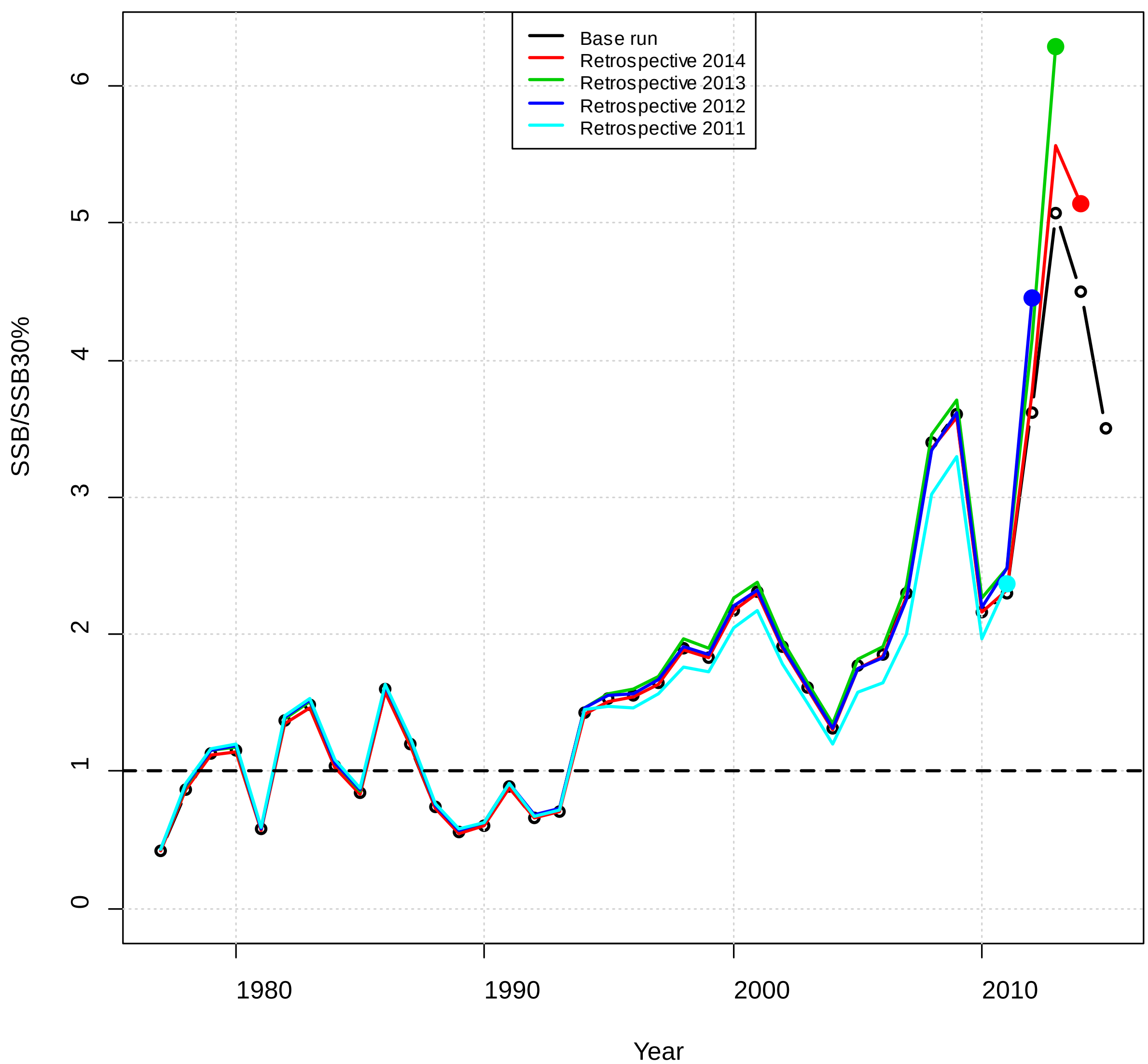



Figure 32. Retrospective analyses. Sensitivity to terminal year of data on the estimation of *SSB/SSB*$_{30\%}$.

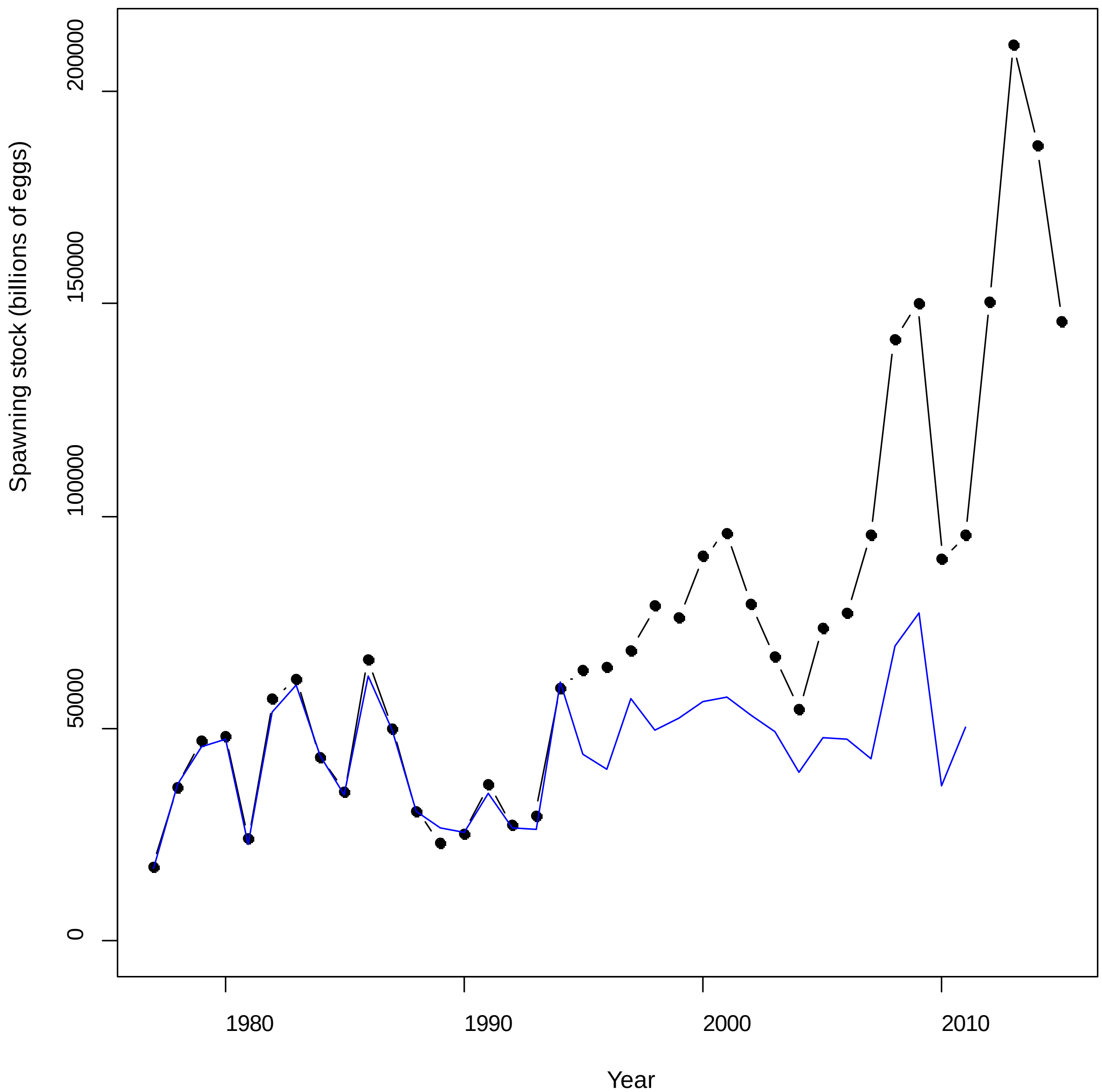



Figure 33. Spawning stock biomass estimates in billions of eggs for the benchmark assessment from SEDAR 32A in blue and for the update assessment in black with points.

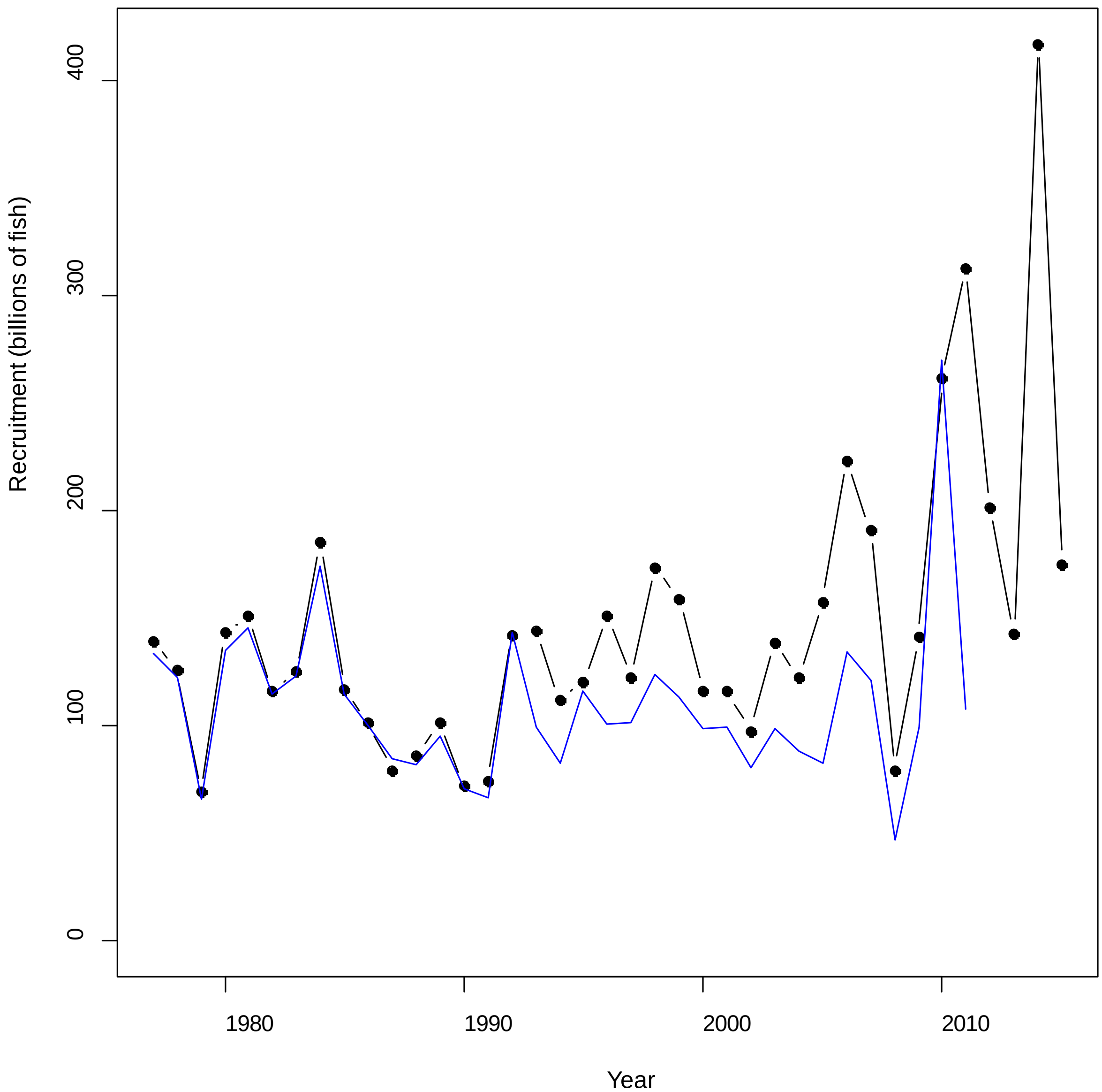



Figure 34. Recruitment time series for the benchmark assessment from SEDAR 32A in blue and for the update assessment in black with points.

**Appendix A.** Parameter estimates and negative log-likelihood values.

| Run | total | unweighted | landings | length comps | age comps | gill net index | seine index | SR fit | sdnr lenc | sdnr agec | sdnr gill | sdnr seine | R0 | Linf | terminal year SSB | q gill net | q seine |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Base run | -648.44 | -636.95 | 0.07 | -425.51 | -235.14 | 13.71 | 9.92 | -11.49 | 1.04 | 0.47 | 1.01 | 1.02 | 126.82 | 264.23 | 95524.81 | 0.2 | 0.01 |
| h estimating | -648.81 | -637.18 | 0.07 | -426.51 | -233.95 | 13.66 | 9.56 | -11.63 | 1.02 | 0.47 | 1.01 | 1 | 155.76 | 267.81 | 108661.8 | 0.18 | 0.01 |
| cR age3&4 select est. | -657.97 | -647.64 | 0.04 | -428.02 | -241.73 | 13.19 | 8.88 | -10.33 | 1.01 | 0.44 | 0.99 | 0.97 | 145.16 | 255.73 | 138513.3 | 0.13 | 0.01 |
| seine index from 32A | -643.61 | -631.67 | 0.09 | -427.02 | -232.47 | 14.9 | 12.82 | -11.94 | 1.01 | 0.49 | 1.05 | 1.35 | 131.17 | 271.63 | 113286.7 | 0.18 | 0.01 |
| Bait landings from 32A | -648.57 | -637.08 | 0.07 | -425.48 | -235.28 | 13.71 | 9.91 | -11.49 | 1.04 | 0.47 | 1.01 | 1.02 | 126.14 | 264.26 | 94903.51 | 0.21 | 0.01 |
| Age-1 mat | -647.82 | -636.25 | 0.08 | -423.79 | -236.44 | 13.75 | 10.14 | -11.57 | 1.08 | 0.46 | 1.01 | 1.03 | 110.9 | 226.84 | 228298.7 | 0.24 | 0.01 |
| low fec | -648.52 | -636.98 | 0.07 | -425.59 | -235.05 | 13.7 | 9.89 | -11.54 | 1.03 | 0.47 | 1.01 | 1.02 | 129.05 | 264.57 | 1373723 | 0.2 | 0.01 |
| high fec | -648.52 | -636.98 | 0.07 | -425.59 | -235.05 | 13.7 | 9.89 | -11.54 | 1.03 | 0.47 | 1.01 | 1.02 | 129.05 | 264.57 | 2855898 | 0.2 | 0.01 |
| low fec, mat | -648.22 | -636.8 | 0.07 | -425 | -235.71 | 13.78 | 10.07 | -11.42 | 1.04 | 0.46 | 1.01 | 1.03 | 116.09 | 261.52 | 2904607 | 0.22 | 0.01 |
| high fec, mat | -648.22 | -636.8 | 0.07 | -425 | -235.71 | 13.78 | 10.06 | -11.43 | 1.04 | 0.46 | 1.01 | 1.03 | 116.21 | 261.56 | 5960146 | 0.22 | 0.01 |
| Base run | -648.44 | -636.95 | 0.07 | -425.51 | -235.14 | 13.71 | 9.92 | -11.49 | 0 | 1.04 | 0.47 | 1.01 | 1.02 | 126.82 | 264.23 | 0.2 | 0.01 |
| Retrospective 2014 | -624.13 | -612.66 | 0.06 | -405.6 | -230.09 | 13.18 | 9.78 | -11.47 | 0 | 1.04 | 0.45 | 1.01 | 1.04 | 126.77 | 278.93 | 0.2 | 0.01 |
| Retrospective 2013 | -598.39 | -586.92 | 0.06 | -384.13 | -224.4 | 13.41 | 8.14 | -11.47 | 0 | 0.98 | 0.46 | 1.04 | 0.98 | 123.7 | 295.78 | 0.2 | 0.01 |
| Retrospective 2012 | -573.21 | -562.54 | 0.06 | -362.8 | -220.46 | 13.7 | 6.96 | -10.67 | 0 | 0.98 | 0.43 | 1.07 | 0.93 | 122.12 | 300.74 | 0.21 | 0.01 |
| Retrospective 2011 | -548.51 | -539.62 | 0.07 | -339.79 | -216.88 | 12.18 | 4.8 | -8.88 | 0 | 1.03 | 0.41 | 1.03 | 0.8 | 119.64 | 301.21 | 0.27 | 0.01 |