**Appendix B: An age-structured model for yelloweye rockfish (*Sebastes rubberimus*) in Southeast Alaska Outside Waters**

# Introduction

This appendix to the 2015 Demersal Shelf Rockfish SAFE represents the current status an age-structured assessment (ASA) model for Yelloweye Rockfish in Southeast Alaska Outside Waters. This model is in response to previous commentary from both the Gulf of Alaska Plan Team and the Sciences and Statistical Committee (SSC) to develop such an assessment. Model data, structure, assumptions and results are presented below.

# Changes from 2014 assessment

## Data

Data from the directed commercial fishery and bycatch in the directed Pacific Halibut (*Hippoglossus stenolepis*) longline commercial fishery have been updated. *Data from the most recent remote operated vehicle (ROV) survey of East Yakutat (EYKT) are not yet available; the EYKT model will be updated with these data by the Plan Team meeting in November, 2015*.

## Natural mortality

Natural mortality is input across a range of values suggested by a review of the literature. For each region, natural mortalities vary from 0.01 to 0.06 in increments of 0.01. Previous model structure estimated a mean total mortality Z drawn from catch-curve analysis of age-composition data from all regions combined. This estimate of Z was then into natural mortality M and full-recruitment fishing mortality F in the model output for each region. This method was replaced due to concerns of using catch composition twice in the model - once to define Z, and again in the age-composition component of the objective function.

## Abundance in Year 1

The current model structure treats abundance-at-age in Year 1 (1985) as a vector of free parameters. Previous model design estimated recruitment and natural mortality *M* beginning in 1896 to populate the first model year (1985) with estimates of cohort abundance, conditioned on age-composition data. Prior to 1985 $M = Z$, as no fisheries data are available despite the existence of commercial fisheries. The previous model structure separated *Z* into two estimates, one applied to 1896 – 1984, the other to 1985 – 2014, for each management area, to prevent higher estimates of *Z* from earlier years from affecting estimates for *Z* for the period 1985 – 2014.

## Parametric bootstrap

A parametric bootstrap was written into the model code. For each estimated model parameter, random draws from normal distributions, defined by the model-estimated mean and variance and conditioned on the model-produced variance-covariance matrix, were used to calculate bootstrapped values for parameters and derived quantities. The random draws were limited by the same initial parameter bounds implemented in the model code; any draw falling outside these bounds resulted in that iteration being discarded. The goal was to identify parameter bounds that were truncating parameter space and possibly producing local minima. Where necessary, bounds were expanded. If this expansion resulted in poor model performance or lack of convergence, more flexible constraints on parameter estimation were implemented in the objective function in the form of small penalties for deviation from a prior value.

10,000 bootstrap iterations were run for each individual model until no iterations were rejected due to draws falling outside any given parameter bound.

## Executive Summary

Anticipated results were observed whereby density and abundance trends were highly sensitive to, and dependent upon, the values of natural mortality. Trends ranged from strongly positive to strongly negative between the lowest to highest values for *M*. Since density is conditioned on the results of the submarine and remote operated vehicle surveys in both the current management methods as well as the ASA model structure, overall estimates of total biomass from both methods were of the same magnitude. Setting values for *M* resulted in overall improved model performance, with generally lower parameter variances and increased stability for parameters such as catchability *q*, but selection of a realistic value for *M* remains problematic.

| **Summary Table**[1] | | | | |
|---|---|---|---|---|
| **Quantity** | **Current assessment** | | **ASA structure** | |
| | **2014** | **2015** | **2014** | **2015** |
| $M$ | 0.02 | | 0.02 | |
| Tier | 4 | | 4 | |
| Biomass - total (metric tons) | 13,274[3] | 10,933[3] | 10,351[3] | 10,504[3] |
| Female spawning biomass (metric tons) | | | 4,451[3] | 4,423[3] |
| $F_{OFL} = F_{35\%}$ | 0.032 | | $F_{35\%} = 0.044$[2] | |
| Max $F_{ABC}$ (maximum = $F_{40\%}$) | 0.026 | | $F_{40\%} = 0.036$[2] | |
| $F_{ABC}$ (*recommended* = $F_{45\%}$) | 0.02 | | $F_{45\%} = 0.03$[2] | |

[1]ASA structures are from models in which natural mortality was set to the Tier 4 assumption that $M = 0.02$

[2]Mean for all management areas scaled by relative area ($km^2$)

[3]Summed for all management areas

**Given the primary difficulty in establishing a robust age-structured assessment model for Yelloweye Rockfish remains the estimation of natural mortality, the authors ask for comments from the Plan Team and the SSC regarding the current methodology, and whether fixing *M* from the literature is considered a valid approach. Towards that end, the current results focus primarily on changes to model estimates of density, spawning biomass, and recruitment over various values for *M*, especially for those models implementing the Tier 4 assumption that *M* = 0.02, instead of a more complete evaluation that includes age composition, selectivity-at-age, etc.**

**The authors would especially like comments from the Plan Team and SSC regarding the value of developing retrospective analyses for each model presented here to evaluate those values of *M* that produce the best fits to observed data.**

## Model Data

Data used in the age-structured model:

1. Total annual catch (metric tons) from the directed DSR commercial fishery in the three SEO management areas (Southern Southeast Outside Waters (SSEO), Central Southeast Outside Waters (CSEO), and East Yakutat (EYKT)) (Table 1);
2. Total annual incidental bycatch (metric tons) from the commercial halibut longline fishery (Table 2);
3. Total annual catch (metric tons) from the sport fishery from 1996 – present (Table 3);
4. Density (individuals per square kilometer) derived from ADF&G submarine and remote operated vehicle (ROV) bottom surveys (Table 4);
5. Estimates of total rockfish habitat per management area in square kilometers derived from sonar and other bathymetric surveys (Table 4);
6. Age composition data from the directed commercial fishery;
7. Age composition data from the commercial Pacific Halibut longline fishery bycatch;
8. Commercial fishery catch-per-unit effort (CPUE) derived from logbooks and fish tickets;
9. International Pacific Halibut Commission (IPHC) longline survey bycatch CPUE from IPHC survey logs;
10. Estimates of length, weight, age, and maturity composition derived from directed commercial fisheries data from 1985 - 2014.

### Total Annual Catch

Estimates of total annual catch were obtained through analyses of fisheries logbook data and fish tickets for each year in which a commercial fishery for Yelloweye Rockfish was implemented in the three management areas. Fisheries data from the early 1990’s and prior are characterized by varied record-keeping methods in addition to changes in management areas and harvest regulations. Logbook data were re-assessed in construction of model data sets, and the numbers presented in Table 1 may differ somewhat from previous DSR stock assessments (Table 1).

### Pacific Halibut Fishery Incidental Catch

In contrast to the intermittent directed commercial fishery for Yelloweye Rockfish, incidental catch removals in the commercial longline Pacific Halibut fishery have occurred every modeled year. These incidental catch data stabilize model performance and compensate for years in which no commercial catch data exist. For years prior to 2006, Yelloweye Rockfish incidental catch data from the commercial halibut longline fishery were taken from Pacific Halibut processor fish tickets; after 2006 these data were taken from the Interagency Electronic Reporting System (IERS), a joint effort between ADF&G, the

IPHC, and the National Marine Fisheries Service (NMFS) to consolidate landing, IFQ, and logbook reporting (Table 2).

## Sport and Subsistence Catch

Sport catch refers to total removal from subsistence and recreational efforts, with an assumption of 100% mortality for any fish released. Total tonnage is calculated as the product of total number and the estimated mean weight over all ages for a given year. Data are available from 2006 – present (Table 3). The assumption of 100% mortality may be relaxed in future assessment with the implementation of mechanisms designed to reduce mortality of released fish.

## Density – Submarine and ROV Surveys

ADF&G utilized a manned submersible to conduct line-transect surveys with direct observations of yelloweye abundance from 1990 - 2009. Survey locations were selected randomly but constrained to fall within rocky habitat considered appropriate for rockfish (a detailed description of ADF&G submarine and ROV survey methods is found in Green et al. 2014). After 2009, the submersible became unavailable, and was replaced by a ROV controlled directly from the survey ship. Surveys utilizing the ROV were conducted from 2012 onward. Line transect methods implemented in the software package DISTANCE 6.0 (Thomas et al. 2010) were used to calculate density of adult and sub-adult Yelloweye Rockfish from count data from both submarine and ROV surveys along with estimates of variance (Table 4). For the purposes of the ASA model, density and variance estimates from the submarine and ROV are assumed equivalent.

## Fishery Age Composition

Estimates of fishery age composition for each management area were derived from data collected through port sampling of catch from the directed commercial fishery and bycatch taken in the commercial halibut longline fishery. Sampled otoliths were sent to the ADF&G Age Determination Unit for aging and the results used to construct length-age relationships. Age-composition was estimated from the catches specific to each area to potentially identify region-specific differences in age composition and recruitment. Years in which sample size was less than 50 were omitted.

## Natural Mortality

O'Connell and Brylinksy (2003) applied catch-curve analysis to "lightly fished" 1984 SSEO commercial longline data and estimated $M$ = 0.017 (under the assumption that $Z$ was roughly equal to $M$ under conditions of little fishing pressure*)*, while alternative methods produced estimates ranging from 0.02 to 0.056 (O'Connell and Brylinksy 2003, Table 3). The current assessment applies a suite of natural mortality values from 0.01 to 0.06 in increments of 0.01 to the stock assessment model.

## CPUE

### IPHC Survey

The IPHC standardizes survey effort into "effective skates" relative to hook spacing and hook type as

$$effskt = noskt(1.52)(1 - e^{-0.06\times hkspc})\left(\frac{nohk}{100}\right)hkadj,$$

where *noskt* = the number of skates hauled, *hkspc* = the mean spacing between hooks on a given skate, *nohk* = mean number of hooks per skate, and *hkadj* = hook type. If no hook type is available, a circle hook is assumed. Prior to 2009, Yelloweye Rockfish were counted for the first 20 hooks of each skate; total skate counted were extrapolated. From 2009 onward, Yelloweye Rockfish have been counted in full for each skate. For model fitting, skates for which no Yelloweye Rockfish were retained were discarded from CPUE consideration under the assumption that they were set over halibut habitat unsuitable for rockfish. Catch-per-unit data were expressed as individual rockfish caught relative to hooks deployed.

**Commercial Fisheries**

Catch-per-effort data for the directed commercial fishery, expressed as total pounds of Yelloweye Rockfish retained relative to hooks deployed, were taken from logbook entries and fish tickets. Catch was determined sensitive to hook spacing, average depth fished, and the number of boats entered into the permitted fishery by year and management area. A generalized linear model assuming a Poisson error distribution was used to fit the pounds of Yelloweye Rockfish caught to hook spacing, average depth fished, and number of boats participating in the fishery, factored by year, management area, and specific vessel (to account for relative experience levels).

CPUE for both the directed fishery and the IPHC survey was initially calculated as the ratio of catch to standardized effort for each reported set for a given vessel, for each management area in a given year. The results were not normally distributed and were problematic to model fitting. Following Quinn and Deriso (1999), catch for the commercial fishery and bycatch from the IPHC survey were transformed by implementation of the Box-Cox transformation

$$\mathrm{T(U)} = \frac{\mathrm{U}^{\mathrm{a}} - 1}{\alpha}$$

to describe an underlying normal distribution where *U* = the untransformed catch values, *T* = the transformed values, and = the transformation parameter. For the commercial fishery, was set to 0.33 for all management areas to obtain a cube root transform. For the IPHC longline survey, it was necessary to assign different values to each area to obtain normality (CSEO = 0.33; EYKT = 0.2; SSEO = 0.5). Median catch *C* for each year *y* and management area *a* was calculated and back transformed as

$$\mathrm{C_{y,a}} = \mathrm{S(T)} = (\alpha\hat{\mu} + 1)^{1/\alpha}$$

where $\hat{\mu}$ is the median of the transformed values.

## Model Years and Management Areas

The model covers the years from 1985 – 2013.

| *Data set* | *Years available* |
|---|---|
| Directed DSR total annual fishery catch: | |
| | 1985-2004, 2012, 2013 |
| CSEO | 1985- 2004, 2008 – 2012, 2013 |
| | 1985, 1987-2001, 2004-2005, 2008-2009, 2012, |
| SSEO | 2013, 2014 |
| | |
| EYKT | |
| Directed DSR fishery age composition: | |
| CSEO | 1988, 1992 – 2004, 2012, 2013 |
| SSEO | 1991 – 2005, 2009 – 2013 |
| | 1992 – 2001, 2004 – 2005, 2008 – 2009, 2012, 2013 |
| EYKT | |
| Halibut longline fishery total annual bycatch | 1985 – 2014 for all management areas |
| Halibut bycatch fishery age composition: | |
| | 2008 - 2011 |
| CSEO | None |
| | 2010 - 2011 |
| SSEO | |
| | |
| EYKT | |
| Directed DSR fishery CPUE | As for total annual catch |
| IPHC survey CPUE | 1998 – 2014 for all management areas |
| Sport fishery total annual catch | 2006 - 2013 |
| Submarine/ROV survey density: | |
| | 1995, 1997, 2003, 2007, 2012 |
| CSEO | 1999, 2005, 2013 |
| | 1995,1997, 1999, 2003, 2009 |
| SSEO | |
| | |
| EYKT | |

Each management area (EYKT, CSEO, SSEO) was considered a distinct population, with recruitment, mortality, fishery removals, Pacific Halibut longline fishery incidental catch, survey density estimates, and estimates of suitable Yelloweye Rockfish habitat specific to each area. Length-weight-age keys and maturity-at-age were assumed the same for all areas, estimated external to the model, and input. Selectivity-at-age was estimated for each area. Males and females were not separated except in the calculation of female spawning biomass and female maturity-at-age.

# Analytic Approach

## Model Structure

Standard age-structured population dynamics equations (Quinn and Deriso 1999) were used to model Yelloweye Rockfish in SEO waters from 1985 – 2014 using AD Model Builder (Fournier et al. 2011) (BOX 1). Modeled age classes ran from 8 – 97, with 8 being the age of recruitment (the youngest age observed in commercial fisheries data), and 97 being a plus class. Recruitment was estimated from 1992 – 2014 as a vector of free parameters. Model estimates included spawning biomass, recruitment, abundance-at-age, commercial catch, incidental catch in the commercial longline halibut fishery, sport catch, CPUE for both the commercial fishery and the IPHC halibut longline survey, and density (number of individual per square kilometer) for each management area.

## Density

Although the line transect surveys count all observed Yelloweye Rockfish, density calculations were completed in DISTANCE 6.0 only for adults and sub-adults, omitting juveniles. The distinction between juvenile and sub-adult classification is based on assessment of changes in coloring and morphology that occur as a fish ages. The ROV surveys in 2012 and 2013 provided length-classification data, allowing for construction of a classification-at-age curve which was used to scale model estimates of total abundance to model estimates of adult and sub-adult density. Estimates of maturity-at-age and suitable rockfish habitat for each management area in square kilometers were assumed known without error.
As survey density scales model estimates of absolute abundance, catchability for the submarine and ROV line transects was set to 1.

## Catch-at-Age

Catch-at-age for each management area was a function of the Baranov catch equation, with fishing mortality-at-age *a* in year *y* $F_{y,a}$ the product of an asymptotically increasing selectivity-at-age $f_a$ and a full-recruitment fishing mortality term $F_y$ (BOX 1). Both the sport fishery and bycatch in the Pacific Halibut longline fishery were modeled as separate fisheries, but selectivity-at-age $f_a$ was assumed the same as for the yelloweye directed fishery.

## Spawning Biomass

For each management area, female spawning biomass for a given year *y* was estimated under the assumption of equal male/female proportions (BOX 2). Yelloweye Rockfish have internal fertilization and potentially extended periods of parturition; for convenience, it was assumed that parturition occurs in May, following O’Connell (1987).

## CPUE

For each year *y* and management area, mean catch *C* in the IPHC longline survey was modeled as

$$C_y = q_{iphc} E_y^{\propto+1} N_y^{\beta+1}$$

whereas for the directed fishery, mean catch *C* was modeled as

$$C_y = q E_y^{\propto+1} N_y^{\beta+1}$$

where *C* = median catch (pounds for the directed fishery, numbers for the IPHC survey), *q* = catchability for the commercial fishery, $q_{iphc}$ = catchability for the IPHC longline survey, *E* = median effort (total hooks), $N$ = abundance (millions of individuals), $B$ = biomass (metric tons), and and are model parameters defining the relationship between catch and abundance.

## Selectivity-at-Age

Within SSEO, selectivity-at-age $f_a$ is assumed the same for the directed Yelloweye Rockfish commercial longline fishery, the commercial halibut longline fishery, and the sport fishery. CSEO and EYKT contain age-composition data for halibut longline fishery bycatch, and a separate selectivity-at-age vector for bycatch was estimated. Selectivity vectors were estimated for each management area to potentially aid in identifying differences in age-structure. Selectivity-at-age was estimated as

$$f_a = \frac{1}{1 + e^{-slope(age - sel_{50\%})}}$$

for which $sel_{50\%}$ is the age at which 50% of the population is selected into the fishery, *slope* is the slope of the sigmoid curve at the $sel_{50\%}$ point.

## Parameter Estimation

Model parameters were estimated by minimizing a penalized negative log-likelihood objective function (BOX 3). Log-normal likelihoods were assumed for total annual catch, total annual halibut longline fishery incidental catch, sport catch, and density for each management area. Multinomial likelihoods were assumed for age composition data. Penalties were implemented in the objective function to facilitate scaling and parameter estimation. Full-recruitment fishing mortality F, catchability in the directed commercial fishery $q$, catchability in the IPHC longline survey $q_{iphc}$, the α and β parameters for CPUE in the IPHC longline survey, and recruitment variability were constrained by minimizing deviations from assumed log-normal prior probability distributions. Fishing mortality-at-age for both the commercial DSR fishery and incidental catch in the Pacific Halibut longline fishery was constrained by minimizing annual fluctuations (BOX 3). Irregularities in recruitment were also constrained (BOX 3).

*Priors, starting values, and assumed variances*

| Parameter | Prior value | Variance | Estimation phase |
|---|---|---|---|
| IPHC CPUE α | -0.5 | 0.25 | 4 |
| IPHC CPUE β | -1 | 0.25 | 4 |
| Mean *F* | 0.02 | 0.4 | 1 |
| Commercial catchability *q* | 1 | 0.5 | 1 |
| IPHC survey catchability *q* | 1 | 0.5 | 1 |

*Objective components and weights for each management area*

| Component | Weight | | |
|---|---|---|---|
| | CSEO | EYKT | SSEO |
| Density | 30 | 30 | 30 |
| Commercial annual catch | 70 | 70 | 70 |
| IFQ halibut annual bycatch | 50 | 50 | 50 |
| Total annual sport catch | 25 | 25 | 25 |

| | | | |
|---|---|---|---|
| Commercial catch-age composition | 5 | 5 | 5 |
| Halibut bycatch age-composition | 20 | 20 | n/a |
| Commercial CPUE | 1 | 1 | 1 |
| IPHC bycatch CPUE | 1 | 1 | 1 |
| *F* regularity | 0.01 | 0.01 | 0.01 |
| Recruitment deviations | 10 | 10 | 10 |
| **Priors** | | | |
| IPHC CPUE α | 1 | 1 | 1 |
| IPHC CPUE β | 1 | 1 | 1 |
| Mean *F* | 1 | 1 | 1 |
| Commercial catchability *q* | 1 | 1 | 1 |
| IPHC survey catchability *q* | 1 | 1 | 1 |

*Total estimated parameters for each management area*

| Parameter | Number |
|---|---|
| 1) mean recruitment | 1 |
| 2) annual recruitment deviations | 30 |
| 3) initial population, year 1 | 90 |
| 4) annual fishing mortality deviations for yelloweye fishery | 30 |
| 5) annual fishing mortality deviations for IFQ halibut bycatch | 30 |
| 6) annual fishing mortality deviations for sport catch | 8 |
| 8) recruitment variability | 1 |
| 9) Selectivity and CPUE parameters (CSEO, EYKT / SSEO)[1] | 10 / 8 |
| Total (CSEO, EYKT / SSEO) | 200 / 198 |

[1]As there are no Pacific Halibut bycatch age-composition data for SSEO, no selectivity-at-age curve is estimated for SSEO for that fishery.

**Externally Estimated Parameters**

Life history attributes were estimated externally from data collected through port sampling of commercial fisheries catches from 1992 - 2013. These were assumed constant over all areas and years, and include:

- Weight-at-age
- Maturity-at-age
- Age-error matrix

***Weight-at-Age (kg)***

Mean weight-at-age *W* was estimated by fitting observed weights-at-age to the equation

$$W_t = W_\infty[1 - e^{-k(t-t_0)}]$$

for which $W_t$ = weight at time $t$ (age), $W_\infty$ = asymptotic weight, $t_0$ = the time (age) at which an individual is considered to have weight 0, and $k$ = growth rate. Mean weight-at-age was assumed consistent across all management areas and equivalent between males and females (Fig. 4).

| $W_\infty$ | ***k*** | $\boldsymbol{t_0}$ |
|---|---|---|
| 6.027 | 0.039 | -10.13 |

***Maturity-at-Age***

Proportions mature-at-age $m_a$ were calculated for females only, fitting observed maturity-at-age to the equation:

$$m_a = \frac{mat_\infty}{1 + e^{-slope(age - mat_{50\%})}}$$

for which $mat_{50\%}$ is the age at which 50% of the population is reproductively mature, *slope* is the slope of the sigmoid curve at the $mat_{50\%}$, and $mat_\infty$ = asymptotic maturity.

| ***slope*** | $\boldsymbol{mat_{50\%}}$ |
|---|---|
| -0.341 | 17.634 |

***Age-Error Matrix***

An age-error matrix, defining the probability of correctly aging a fish based on otolith analysis, was constructed by Dana Hanselman (Auke Bay Lab, National Marine Fisheries Service) for earlier model work in 2010. This matrix is preserved in the current model iteration. The matrix is implemented in the calculation of predicted catch-at-age proportions for the directed Yelloweye Rockfish commercial fishery (BOX 1 & 2). This matrix, however, reflects the uncertainty of age readers for NMFS, not the age readers from the ADF&G Age Determination Unit. An age-error matrix was constructed from ADU data but improvements in the analysis of ADU data are needed before it is considered sufficiently robust for model integration.

## Model Results

All models with the exception of CSEO for which $M$ = 0.06 converged to parameter estimates with variances.

Model fits to DISTANCE 6.0 estimates of region-specific Yelloweye Rockfish per square kilometer are presented in Figs. 1 – 6, along with model fits from the 2014 stock assessment. EYKT showed the greatest change from last year's methods. Following Plan Team comments, these data points scale model estimates of abundance and provide general population trends, as opposed to requiring a precise fit to each point. Parameter point-estimates and variances from maximum likelihood methods (MLE), the parametric bootstrap (PB) and Monte Carlo methods (MCMC) for the $M$ = 0.02 structure were very similar (Figs. 2, 4, and 6).

Spawning biomass trends were highly dependent upon the implemented value for $M$ (Figs. 7 – 12). For $M$ = 0.02, trends were stable or slightly increasing.

Annual recruitment (Figs 13 – 18) showed increasing trends over all regions and $M$ values, with much less inter-annual variability in EYKT and SSEO relative to the 2104 assessment, although these trends are likely heavily influenced by falling at the end of the model time series, and therefore have little to no catch composition data to constrain them.

Fits to CPUE data, as in 2014, were variable (Figs. 19 – 24). Catchability values for commercial CPUE remained close to 1. Catchability for the IPHC longline survey showed less variability across regions than in the 2014 assessment, and also fell close to 1.

| | CSEO | EYKT | SSEO |
|---|---|---|---|
| Q (commercial fisheries) | 1.012 | 0.993 | 1.074 |
| Q (iphc survey) | 0.996 | 0.959 | 0.917 |

Values for $F_{40\%}$ relative to the input value for $M$ are given in Table 5. The Tier 4 assumption is that $F_{40\%}$ = 0.026 and that $M$ = 0.02. The values here are greater than 0.026 for the model $M$ = 0.02, but are much more in line with Tier 4 assumptions than the results of the 2014 stock assessment.

## Discussion

### Density

It can be seen in Figs. 1, 3 and 5 that while density data scale model estimates of absolute abundance, fitting to individual estimates was often poor. As discussed above, model estimates of density are not fitted directly to observed survey data, but to estimates of density derived from survey data by the DISTANCE software package (Thomas et al. 2006) as

$$\hat{D}_{distance} = \frac{nf(0)}{L}$$

for which $n$ = number of adult and sub-adult Yelloweye Rockfish observed, *f(0)* probability of detection as a function of distance from the transect line, and $L$ = total line length (meters). The probability detection function assumes that detection on the line = 1 (Burnham et al. 1980).

Model estimates of density assume the following:

- Estimates of Yelloweye Rockfish habitat ($km^2$) are without error;
- Estimates of density and variance from DISTANCE 6.0 are correct, including the assumption that detection on the line = 1.

If either of these assumptions were relaxed, the model would likely require extremely tight constraints on parameter estimation to allow model convergence.

## Natural Mortality

While improved model stability and parameter estimation result from fixing *M*, determining the most accurate and realistic value for *M* remains problematic. Running a series of retrospective analyses on these models might provide additional information on which input value of *M* produced the best predictive results.

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# Tables

Table 1. Total annual directed commercial Yelloweye Rockfish catch (t) for each management district for all modeled years

| Year | CSEO | SSEO | EYKT | Total |
|---|---|---|---|---|
| 1985 | 215.38 | 26.85 | 5.15 | 247.38 |
| 1986 | 204.82 | 77.74 | 0.00 | 282.56 |
| 1987 | 171.75 | 288.66 | 64.79 | 525.20 |
| 1988 | 127.19 | 211.13 | 39.17 | 377.49 |
| 1989 | 118.65 | 112.16 | 35.56 | 266.37 |
| 1990 | 70.22 | 86.02 | 15.69 | 171.93 |
| 1991 | 76.61 | 87.31 | 173.08 | 337.00 |
| 1992 | 101.11 | 131.41 | 46.92 | 279.44 |
| 1993 | 122.17 | 62.72 | 87.48 | 272.37 |
| 1994 | 128.32 | 72.57 | 110.38 | 311.27 |
| 1995 | 73.61 | 22.69 | 46.12 | 142.42 |
| 1996 | 162.25 | 62.94 | 95.86 | 321.05 |
| 1997 | 136.15 | 49.62 | 63.51 | 249.28 |
| 1998 | 110.44 | 50.17 | 64.44 | 225.05 |
| 1999 | 97.78 | 57.46 | 72.55 | 227.79 |
| 2000 | 58.74 | 58.94 | 55.59 | 173.27 |
| 2001 | 58.94 | 56.52 | 48.91 | 164.37 |
| 2002 | 70.89 | 57.02 | 0.00 | 127.91 |
| 2003 | 57.99 | 36.33 | 0.00 | 94.32 |
| 2004 | 55.51 | 23.71 | 86.88 | 166.10 |
| 2005 | 0.00 | 0.00 | 41.90 | 41.90 |
| 2006 | 0.00 | 0.00 | 0.00 | 0 |
| 2007 | 0.00 | 0.00 | 0.00 | 0 |
| 2008 | 0.00 | 19.70 | 21.72 | 41.42 |
| 2009 | 0.00 | 29.28 | 44.40 | 73.68 |
| 2010 | 0.00 | 28.49 | 0.00 | 28.49 |
| 2011 | 0.00 | 21.39 | 0.00 | 21.39 |
| 2012 | 31.05 | 31.99 | 35.99 | 99.03 |
| 2013 | 35.69 | 5.27 | 36.64 | 77.60 |
| 2014 | 0 | 0 | 32.50 | 32.50 |

Table 2. Total annual Yelloweye Rockfish incidental catch (t) in the commercial longline Pacific Halibut fishery for each management district for all modeled years

| Year | CSEO | SSEO | EYKT | Total |
|---|---|---|---|---|
| 1985 | 7.61 | 0.67 | 1.49 | 9.77 |
| 1986 | 4.28 | 0.92 | 0.27 | 5.47 |
| 1987 | 4.52 | 2.14 | 1.33 | 7.99 |
| 1988 | 1.57 | 3.09 | 0.11 | 4.77 |
| 1989 | 22.65 | 23.59 | 5.73 | 51.97 |
| 1990 | 13.01 | 29.97 | 5.08 | 48.06 |
| 1991 | 24.65 | 11.97 | 17.59 | 54.21 |
| 1992 | 43.81 | 22.30 | 16.48 | 82.59 |
| 1993 | 73.91 | 36.19 | 11.21 | 121.31 |
| 1994 | 103.13 | 44.80 | 14.61 | 162.54 |
| 1995 | 34.32 | 6.68 | 11.03 | 52.03 |
| 1996 | 28.18 | 8.63 | 14.09 | 50.9 |
| 1997 | 45.95 | 6.86 | 22.79 | 75.6 |
| 1998 | 49.54 | 10.20 | 35.26 | 95 |
| 1999 | 44.97 | 13.97 | 33.40 | 92.34 |
| 2000 | 40.20 | 14.37 | 24.61 | 79.18 |
| 2001 | 55.73 | 23.92 | 34.00 | 113.65 |
| 2002 | 56.06 | 23.10 | 34.97 | 114.13 |
| 2003 | 56.61 | 27.09 | 47.12 | 130.82 |
| 2004 | 47.17 | 32.72 | 45.76 | 125.65 |
| 2005 | 59.02 | 47.42 | 53.14 | 159.58 |
| 2006 | 67.03 | 54.17 | 39.16 | 160.36 |
| 2007 | 66.42 | 43.05 | 54.39 | 163.86 |
| 2008 | 48.61 | 26.08 | 46.73 | 121.42 |
| 2009 | 41.08 | 27.08 | 52.82 | 120.98 |
| 2010 | 32.54 | 23.32 | 57.02 | 112.88 |
| 2011 | 24.86 | 7.34 | 44.24 | 76.44 |
| 2012 | 20.18 | 9.96 | 33.69 | 63.83 |
| 2013 | 26.23 | 10.09 | 33.56 | 69.88 |
| 2014 | 22.40 | 6.30 | 19.70 | 48.40 |

Table 3. Total annual Yelloweye Rockfish sport and subsistence catch (t) for each management district for 2006 – present

| Year | CSEO | SSEO | EYKT | Total |
|---|---|---|---|---|
| 2006 | 36.973 | 21.859 | 0.804 | 59.636 |
| 2007 | 50.687 | 18.484 | 0.270 | 69.441 |
| 2008 | 34.829 | 12.313 | 0.399 | 47.541 |
| 2009 | 7.825 | 7.406 | 0.002 | 15.233 |
| 2010 | 28.605 | 9.666 | 0.004 | 38.275 |
| 2011 | 16.160 | 5.820 | 0.004 | 21.984 |
| 2012 | 20.665 | 7.707 | 0.011 | 28.383 |
| 2013 | 14.147 | 7.135 | 0.001 | 21.283 |

Table 4. Submersible (1995, 1997, 1999, 2003, 2005, 2007, 2009) and ROV (2012–2013) Yelloweye Rockfish density estimates with 95% confidence intervals (CI) and coefficient of variations (CV) by year and management area. The number of transects, Yelloweye Rockfish (YE), and meters surveyed included in each model are shown, along with the encounter rate of YE. Values in bold were used for this stock assessment. (Table adapted from Green at al. 2014)

| Area | Year | Area ($km^2$) | # YE[b] | Meters surveyed | Encounter rate (YE/m) | Density ($YE/km^2$) | Lower CI ($YE/km^2$) | Upper CI ($YE/km^2$) | CV |
|---|---|---|---|---|---|---|---|---|---|
| EYKT[a] | 1995 | 744 | 330 | 22,896 | 0.014 | 2711 | 1776 | 4141 | 0.20 |
| | 1997 | | 350 | 19,240 | 0.018 | 2576 | 1459 | 4549 | 0.28 |
| | 1999 | | 236 | 25,198 | 0.009 | 1584 | 1092 | 2298 | 0.18 |
| | 2003 | | 335 | 17,878 | 0.019 | 3825 | 2702 | 5415 | 0.17 |
| | **2009** | | **215** | **29,890** | **0.007** | **1930** | **1389** | **2682** | **0.17** |
| CSEO | 1995 | 1404 | 235 | 39,368 | 0.006 | 2929 | | | 0.19 |
| | 1997 | | 260 | 29,273 | 0.009 | 1631 | 1224 | 2173 | 0.14 |
| | 2003 | | 726 | 91,285 | 0.008 | 1853 | 1516 | 2264 | 0.10 |
| | 2007 | | 301 | 55,640 | 0.005 | 1050 | 830 | 1327 | 0.12 |
| | **2012** | | **118** | **38,590** | **0.003** | **752** | **586** | **966** | **0.13** |
| SSEO | 1999 | 732 | 360 | 41,333 | 0.009 | 2376 | 1615 | 3494 | 0.20 |
| | 2005 | | 276 | 28,931 | 0.010 | 2357 | 1634 | 3401 | 0.18 |
| | 2013 | | 118 | 30,439 | 0.004 | 986 | 641 | 1517 | 0.22 |

[a] Estimates for EYKT management area include only the Fairweather grounds, which is composed of a west and an east bank. In 1997, only 2 of 20 transects and in 1999, no transects were performed on the east bank that were used in the model. In other years, transects performed on both the east and west bank were used in the model.

[b] Subadult and adult Yelloweye Rockfish were included in the analyses to estimate density. A few small subadult Yelloweye Rockfish were excluded from the 2012 model based on size; length data were only available for the ROV surveys. Data were truncated at large distances for some models; as a consequence, the number of Yelloweye Rockfish included in the model does not necessarily equal the total number of Yelloweye Rockfish observed on the transects.

Table 5. Estimates of $F_{40\%}$ across each region relative to the input value of natural mortality *M*.

| | CSEO | EYKT | SSEO |
|---|---|---|---|
| M = 0.01 | 0.025 | 0.026 | 0.025 |
| M = 0.02 | 0.030 | 0.032 | 0.031 |
| M = 0.03 | 0.036 | 0.040 | 0.038 |
| M = 0.04 | 0.045 | 0.050 | 0.047 |
| M = 0.05 | 0.056 | 0.064 | 0.060 |
| M = 0.06 | Did not converge | 0.082 | 0.075 |

# Figures

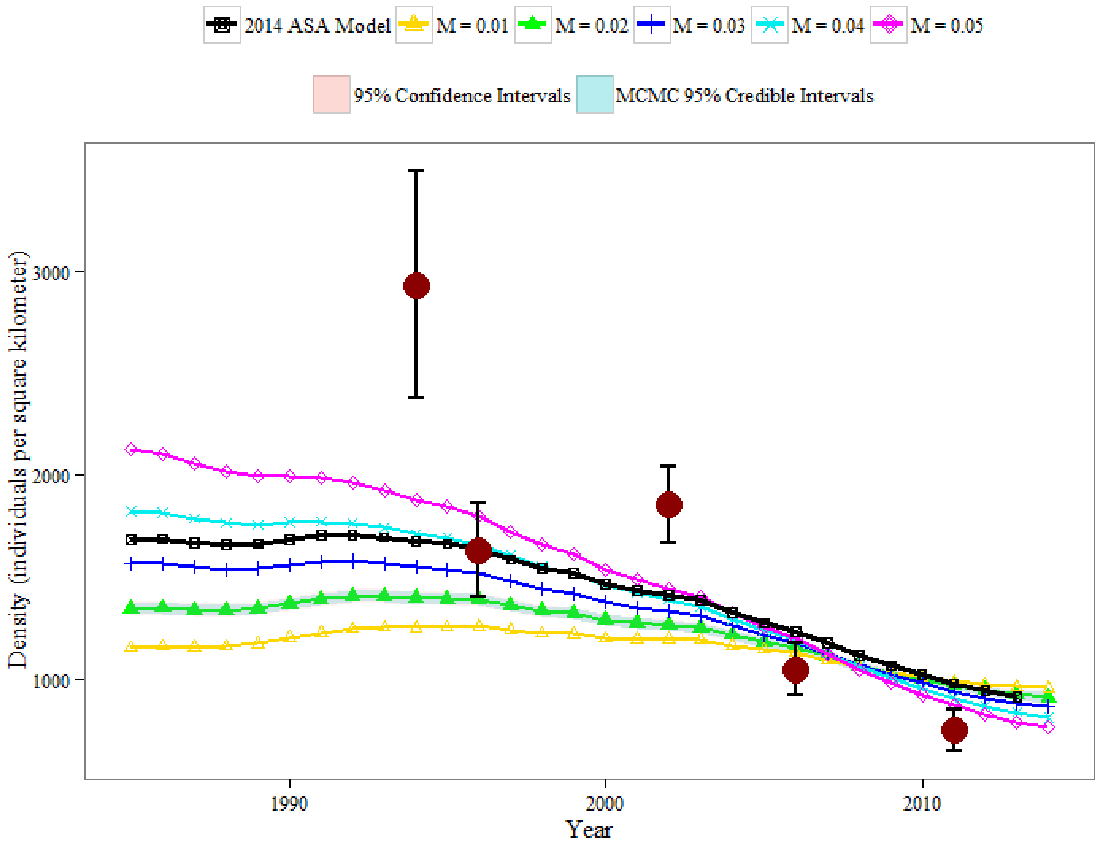


Figure 1. Model estimates of Yelloweye Rockfish adult and subadult density in CSEO over a suite of natural mortality values from 0.01 to 0.05, relative to ADF&G submarine/ROV surveys +/- two standard deviations (red points plus error bars) and compared with the 2014 stock assessment estimates of density, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that *M* = 0.02 (green line).

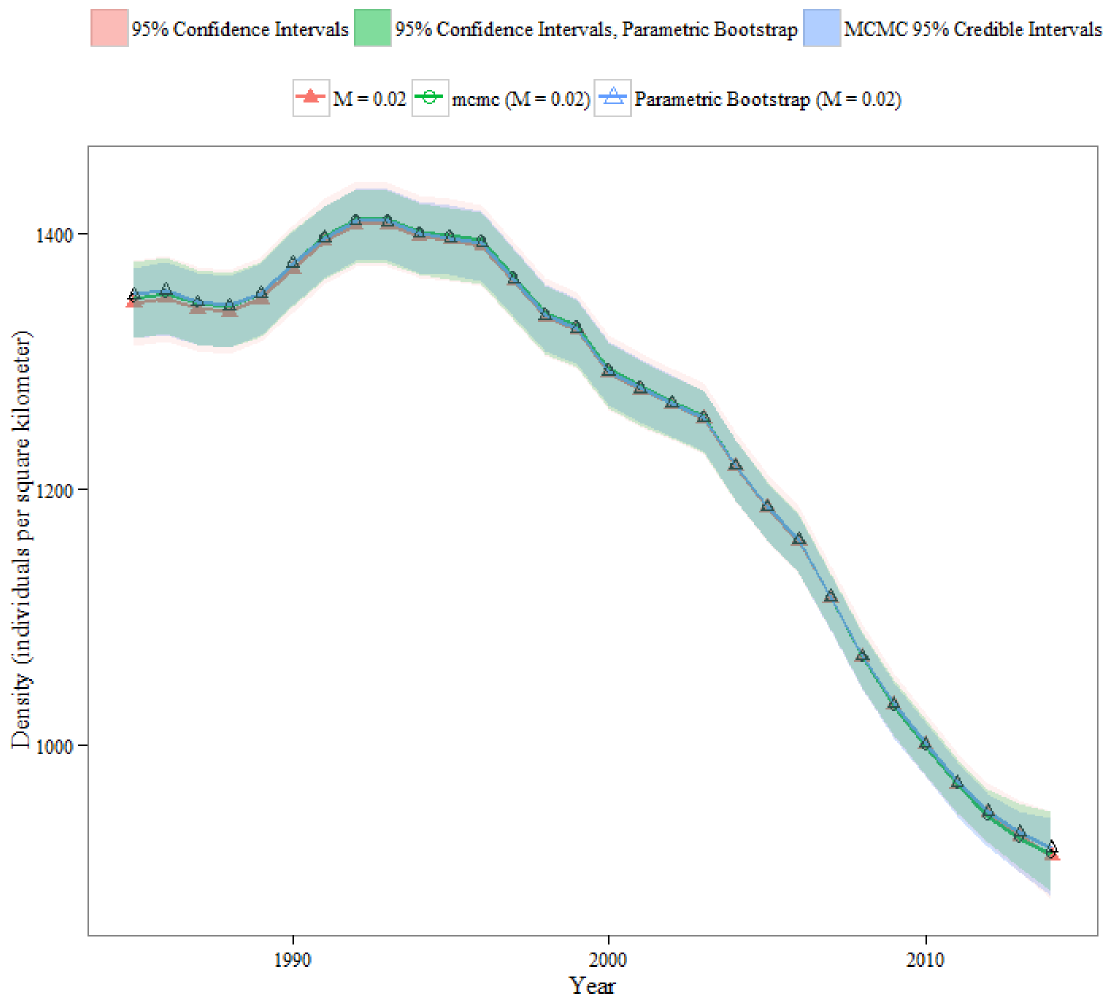


Figure 2. Subset of Figure 3 above: model point-estimates and associated variances of Yelloweye Rockfish adult and subadult density in CSEO using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 iterations) under the Tier 4 assumption that *M* = 0.02.

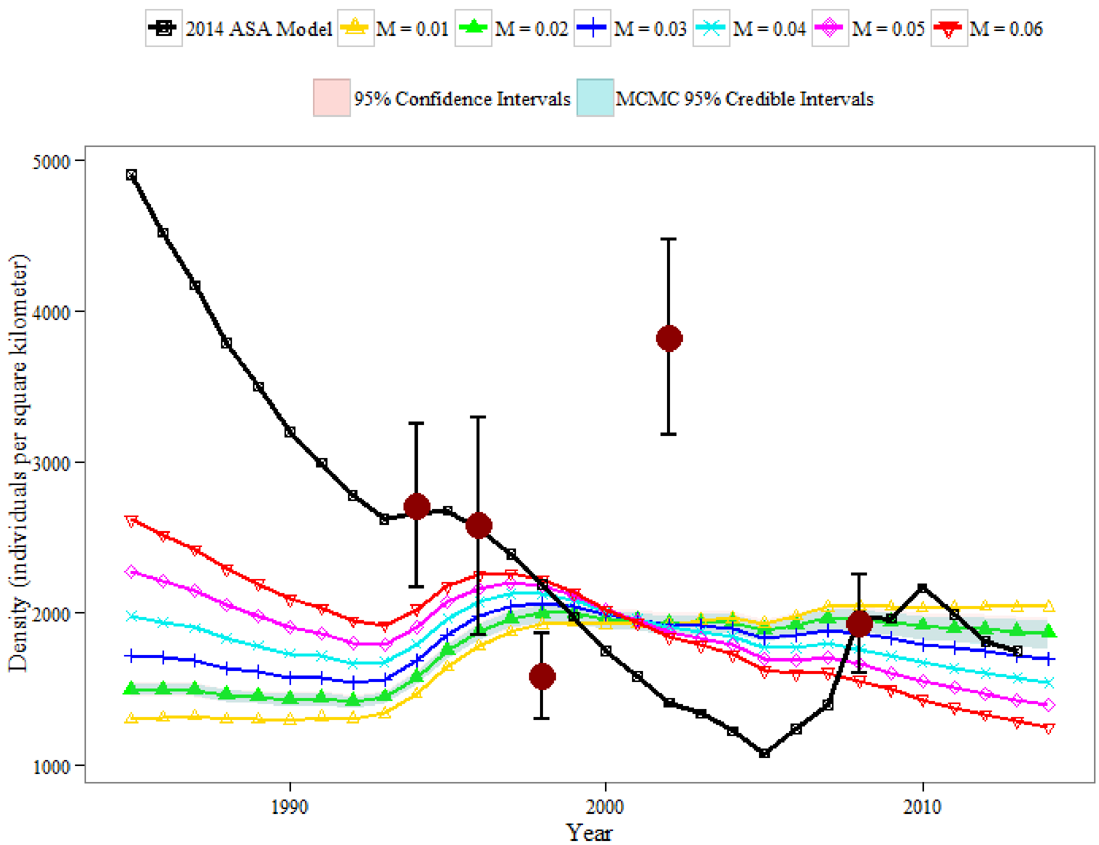


Figure 3. Model estimates of Yelloweye Rockfish adult and subadult density in EYKT over a suite of natural mortality values from 0.01 to 0.05, relative to ADF&G submarine/ROV surveys +/- two standard deviations (red points plus error bars) and compared with the 2014 stock assessment estimates of density, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that $M = 0.02$ (green line).

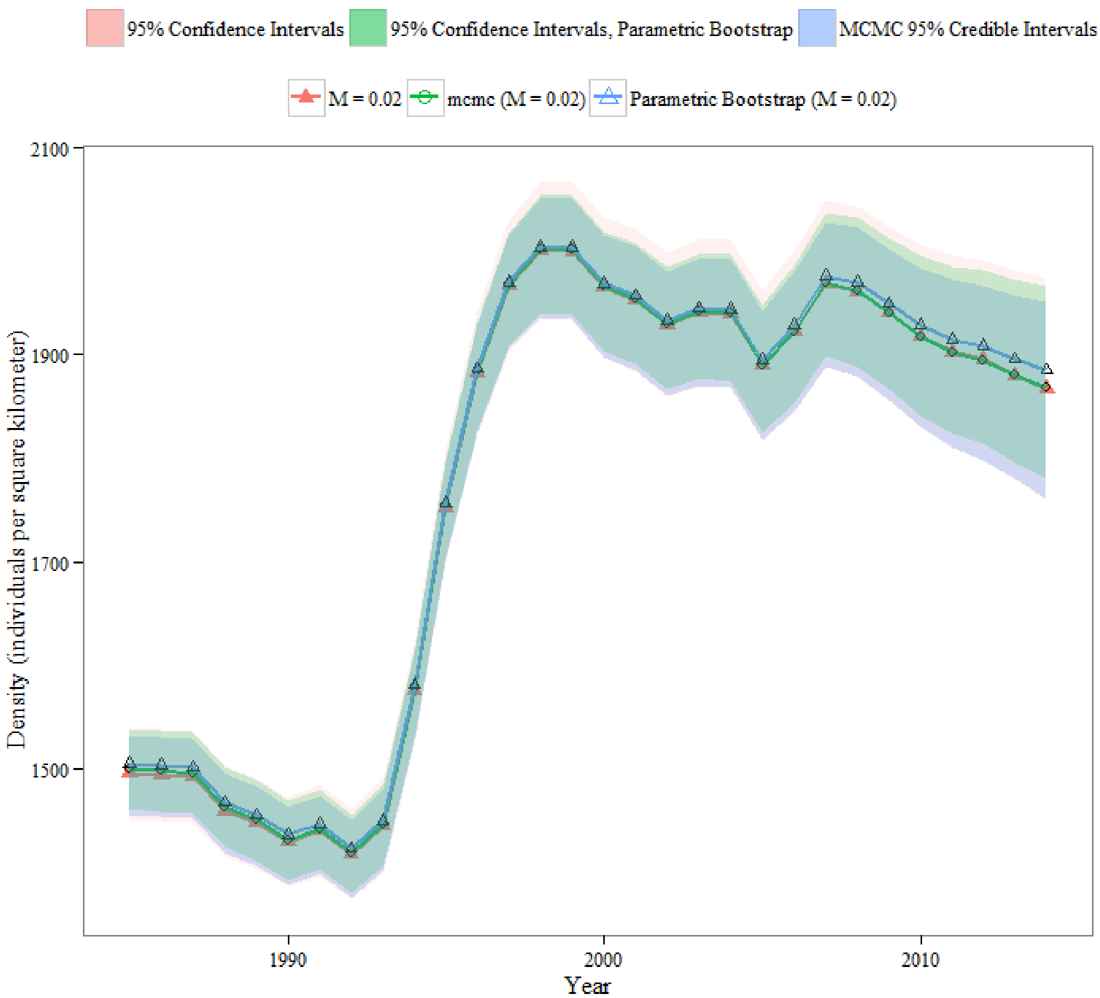


Figure 4. Subset of Figure 3 above: model point-estimates and associated variances of Yelloweye Rockfish adult and subadult density in EYKT using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 iterations) under the Tier 4 assumption that $M$ = 0.02.

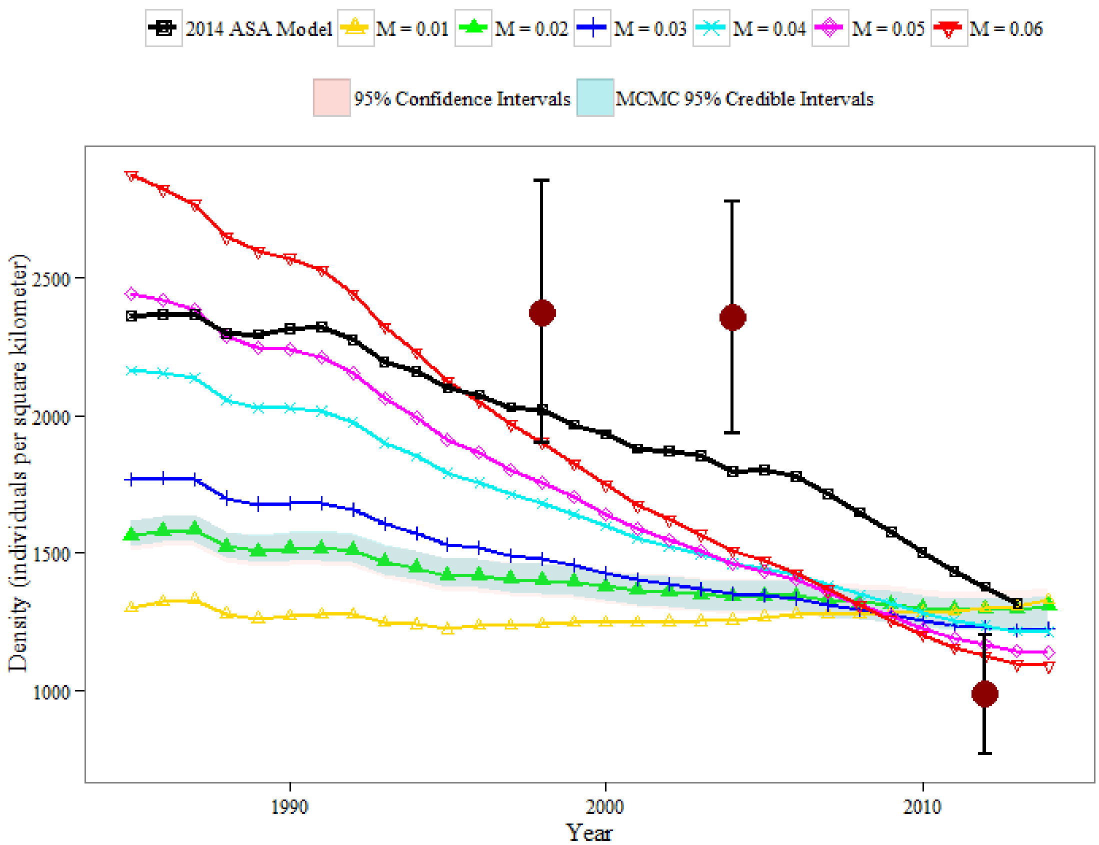


Figure 5. Model estimates of Yelloweye Rockfish adult and subadult density in SSEO over a suite of natural mortality values from 0.01 to 0.05, relative to ADF&G submarine/ROV surveys +/- two standard deviations (red points plus error bars) and compared with the 2014 stock assessment estimates of density, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that $M$ = 0.02 (green line).

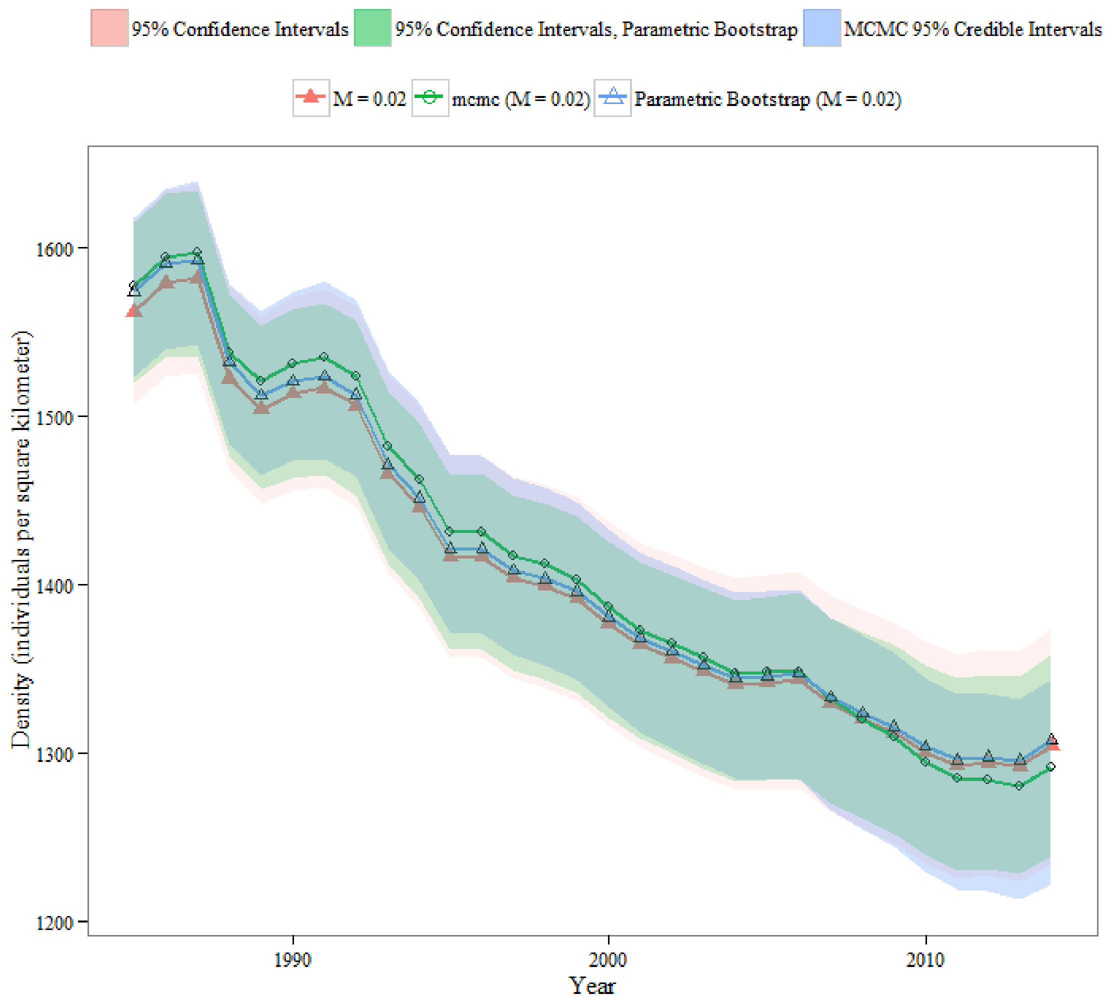


Figure 6. Subset of Figure 5 above: model point-estimates and associated variances of Yelloweye Rockfish adult and subadult density in SSEO using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 iterations) under the Tier 4 assumption that *M* = 0.02.

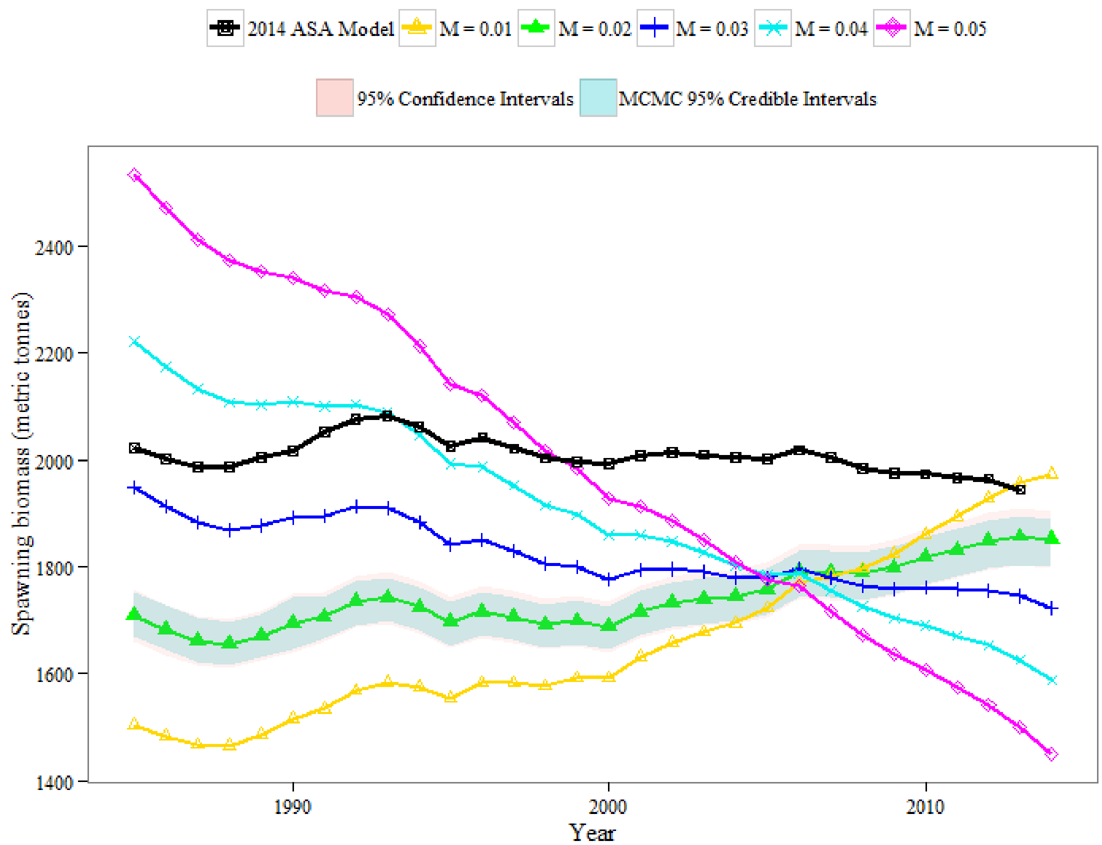


Figure 7. Estimates of Yelloweye Rockfish spawning biomass in CSEO over a suite of natural mortality values from 0.01 to 0.06, compared with the 2014 estimates of spawning biomass, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that $M$ = 0.02.

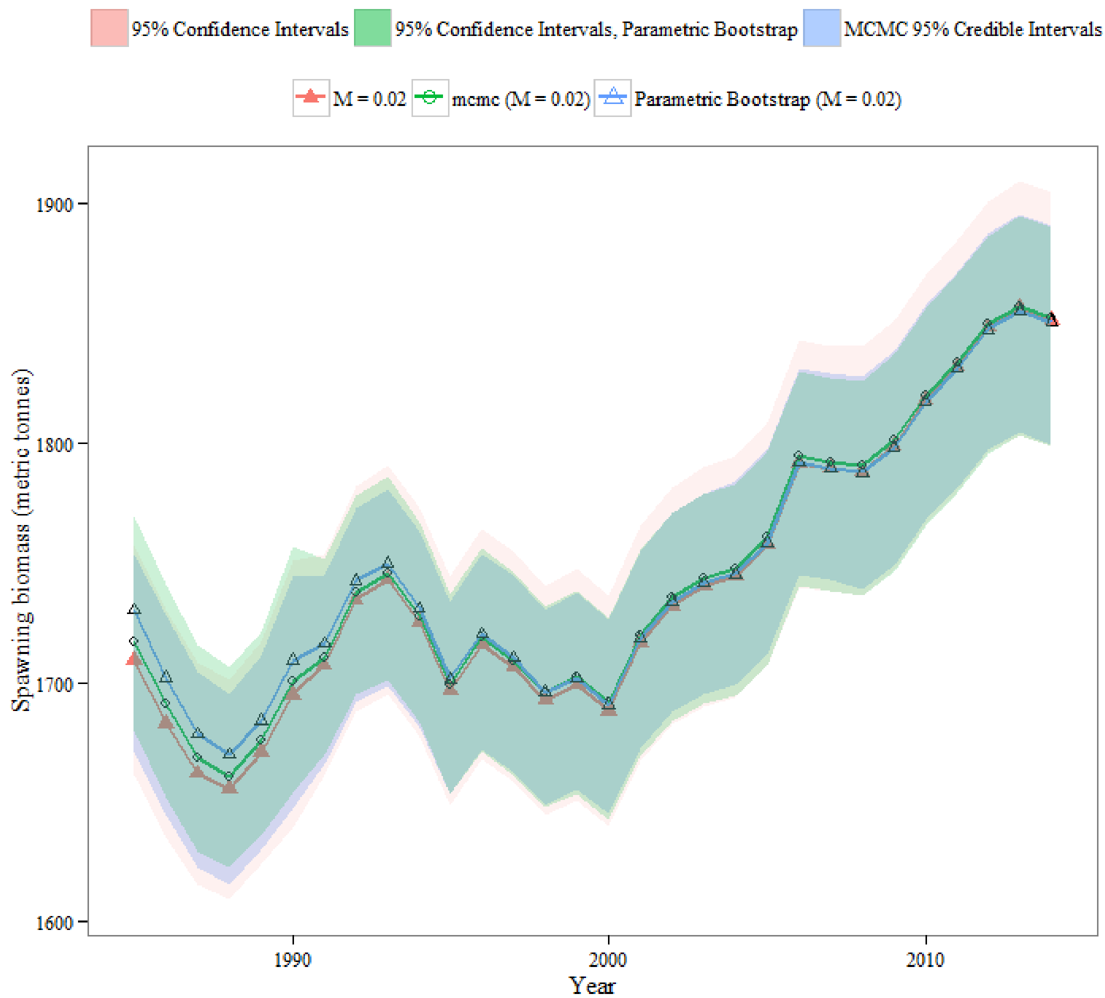


Figure 8. Subset of figure 7 above: Model point-estimates and associated variances of Yelloweye Rockfish spawning biomass in CSEO using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 interactions) under the Tier 4 assumption of *M*=0.02.

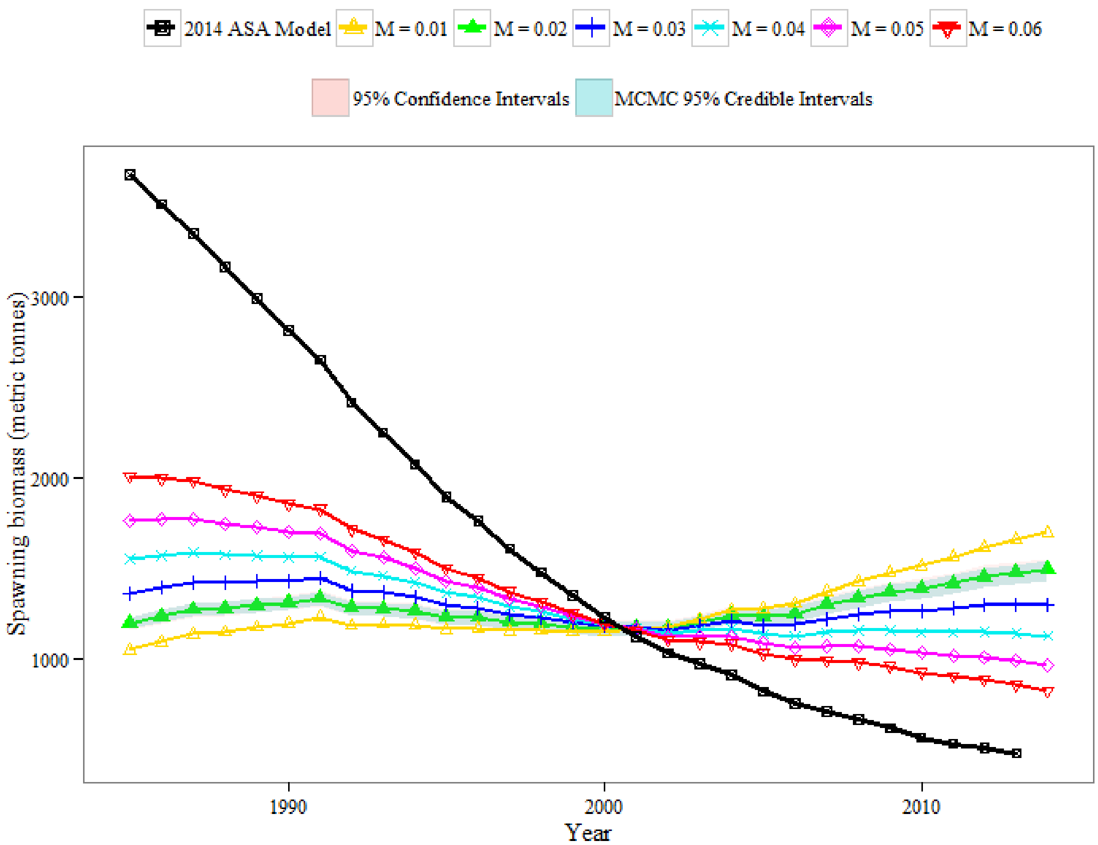


Figure 9. Estimates of Yelloweye Rockfish spawning biomass in EYKT over a suite of natural mortality values from 0.01 to 0.06, compared with the 2014 estimates of spawning biomass, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that *M* = 0.02.

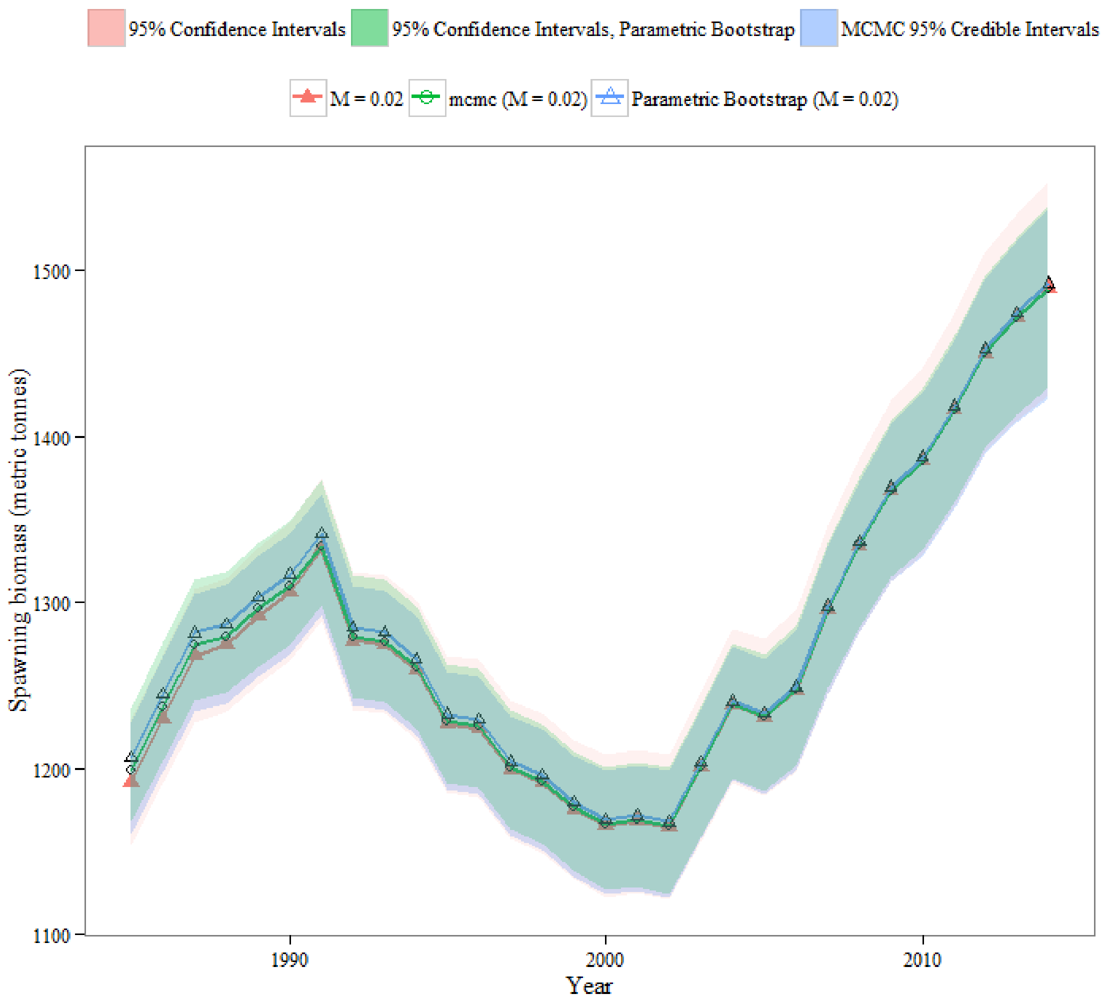


Figure 10. Subset of Figure 9 above: model point-estimates and associated variances of Yelloweye Rockfish spawning biomass in EYKT using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 iterations) under the Tier 4 assumption that $M$ = 0.02.

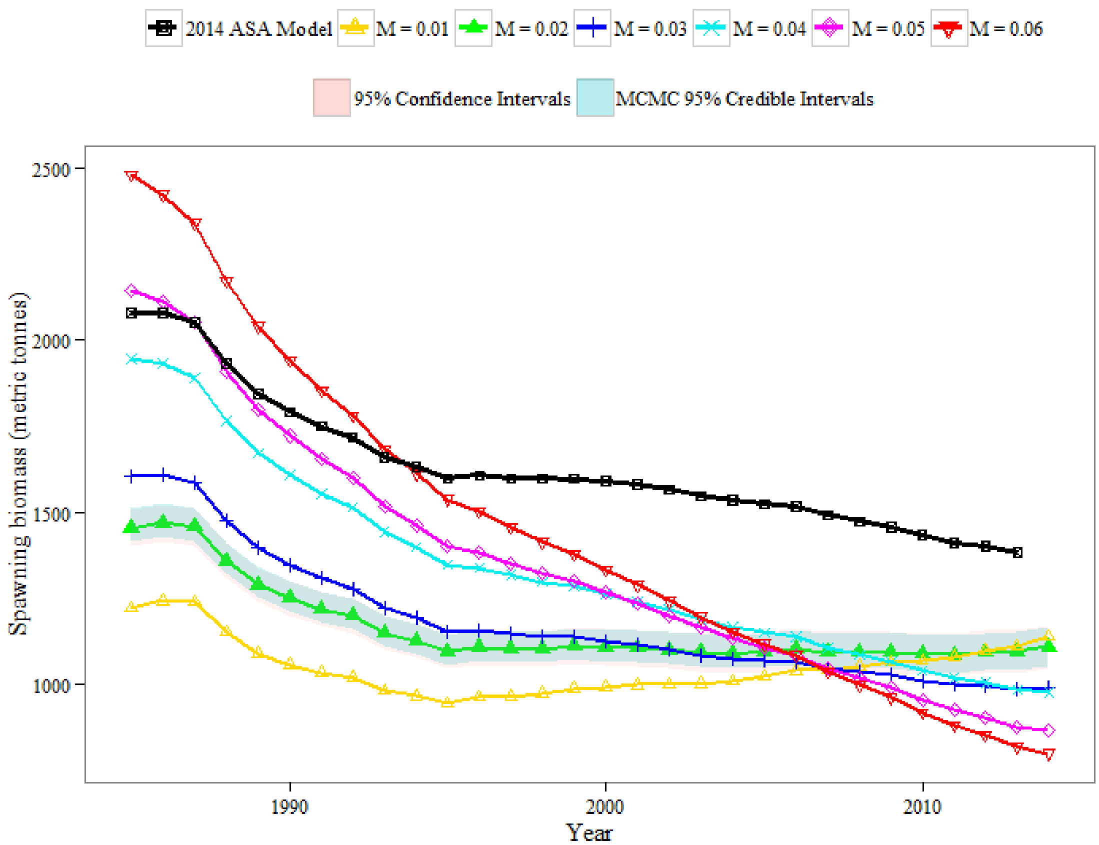


Figure 11. Estimates of Yelloweye Rockfish spawning biomass in SSEO over a suite of natural mortality values from 0.01 to 0.06, compared with the 2014 estimates of spawning biomass, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that *M* = 0.02.

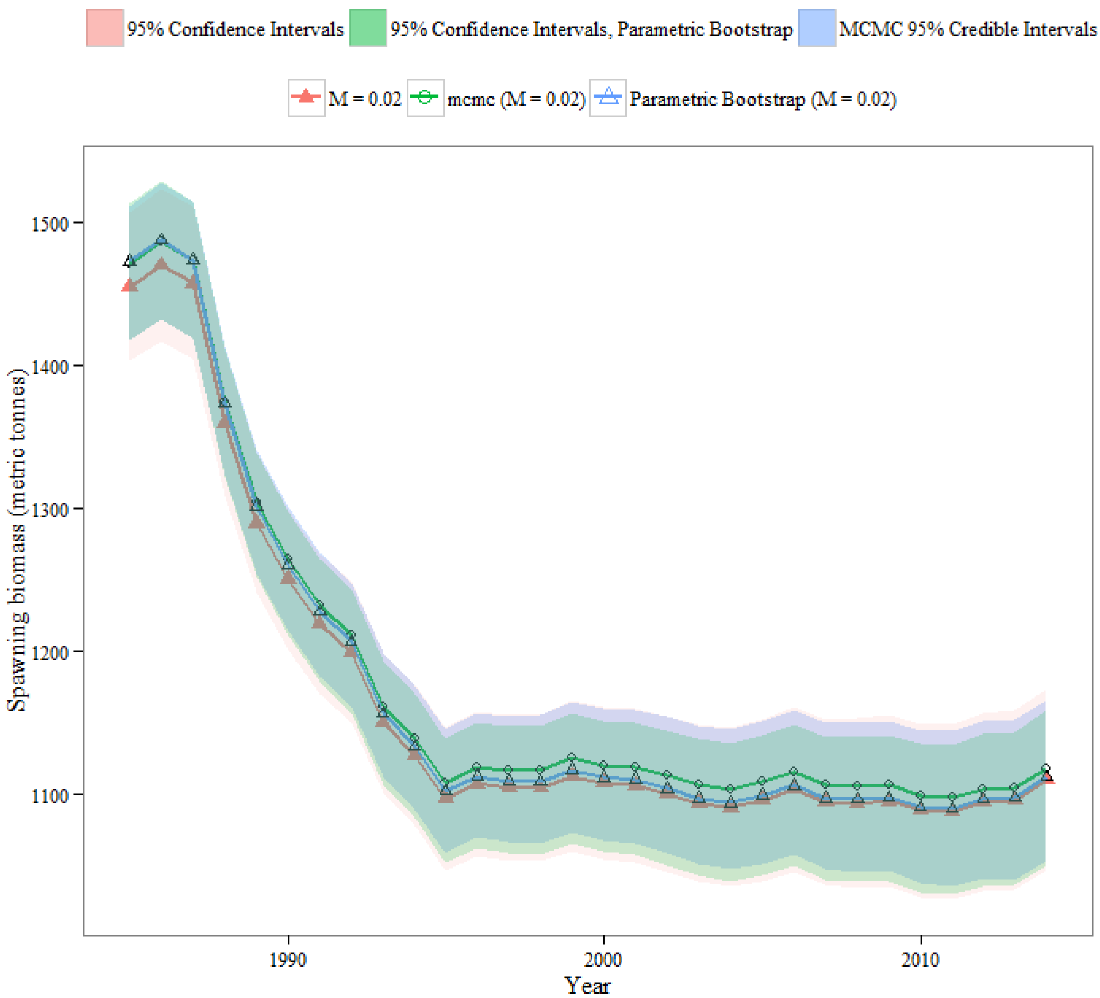


Figure 12. Subset of Figure 11 above: model point-estimates and associated variances of Yelloweye Rockfish spawning biomass in SSEO using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 iterations) under the Tier 4 assumption that $M$ = 0.02.

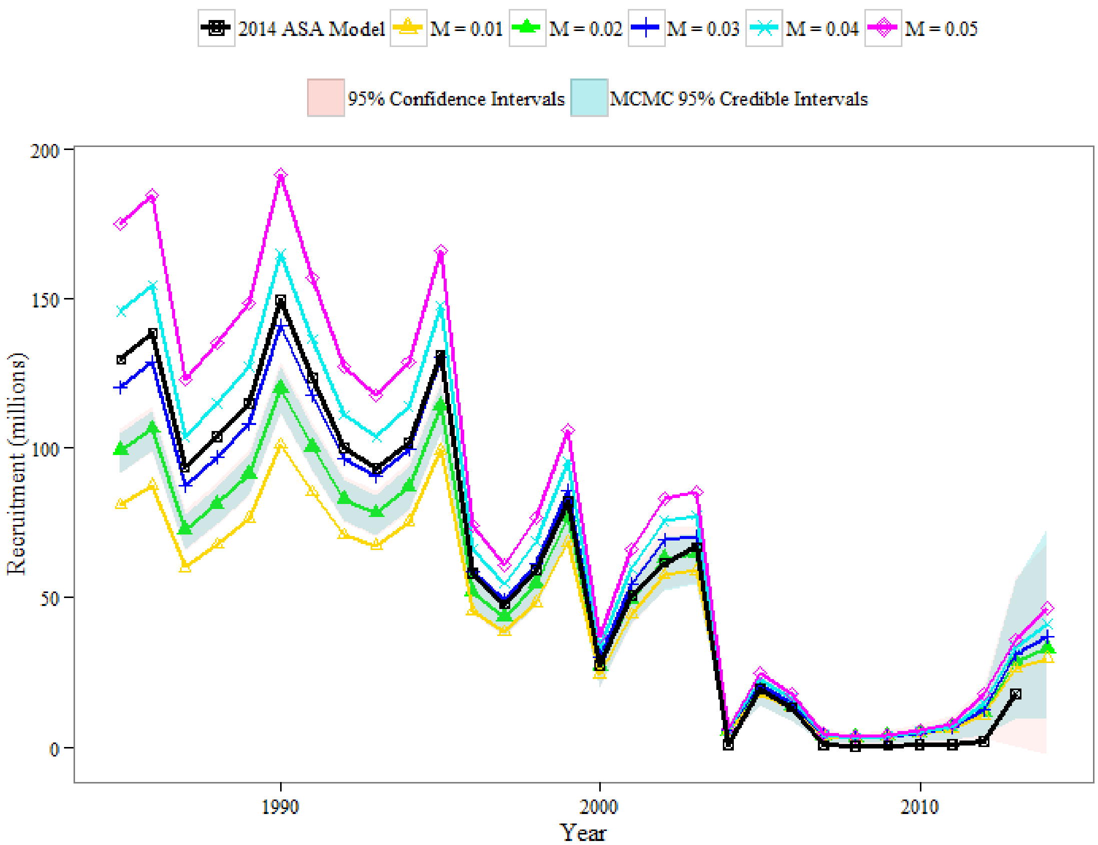


Figure 13. Estimates of Yelloweye Rockfish age-3 recruitment in CSEO over a suite of natural mortality values from 0.01 to 0.06 compared with the 2014 estimates of recruitment, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that *M* = 0.02.

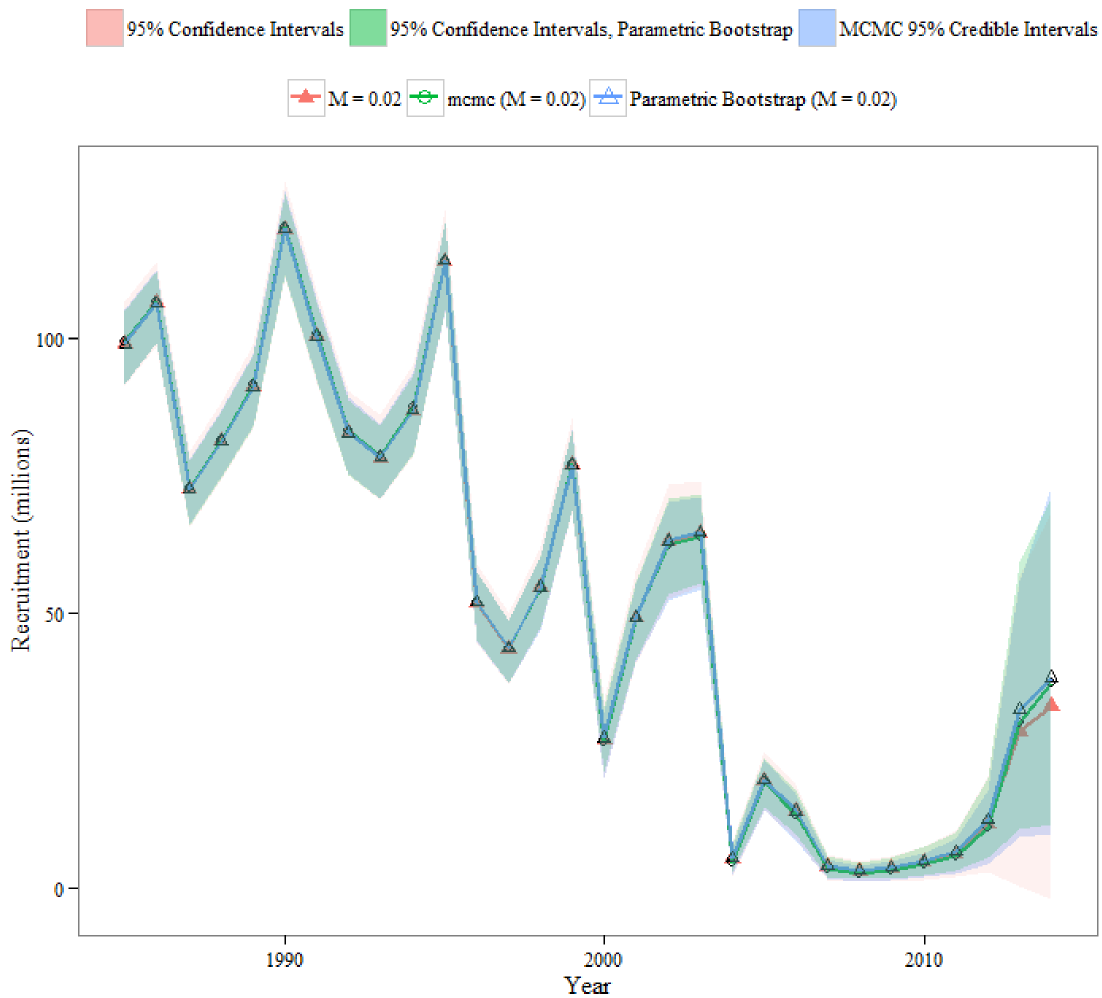


Figure 14. Subset of Figure 13 above: model point-estimates and associated variances of yelloweye age-3 recruitment in CSEO using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 iterations) under the Tier 4 assumption that M = 0.02.

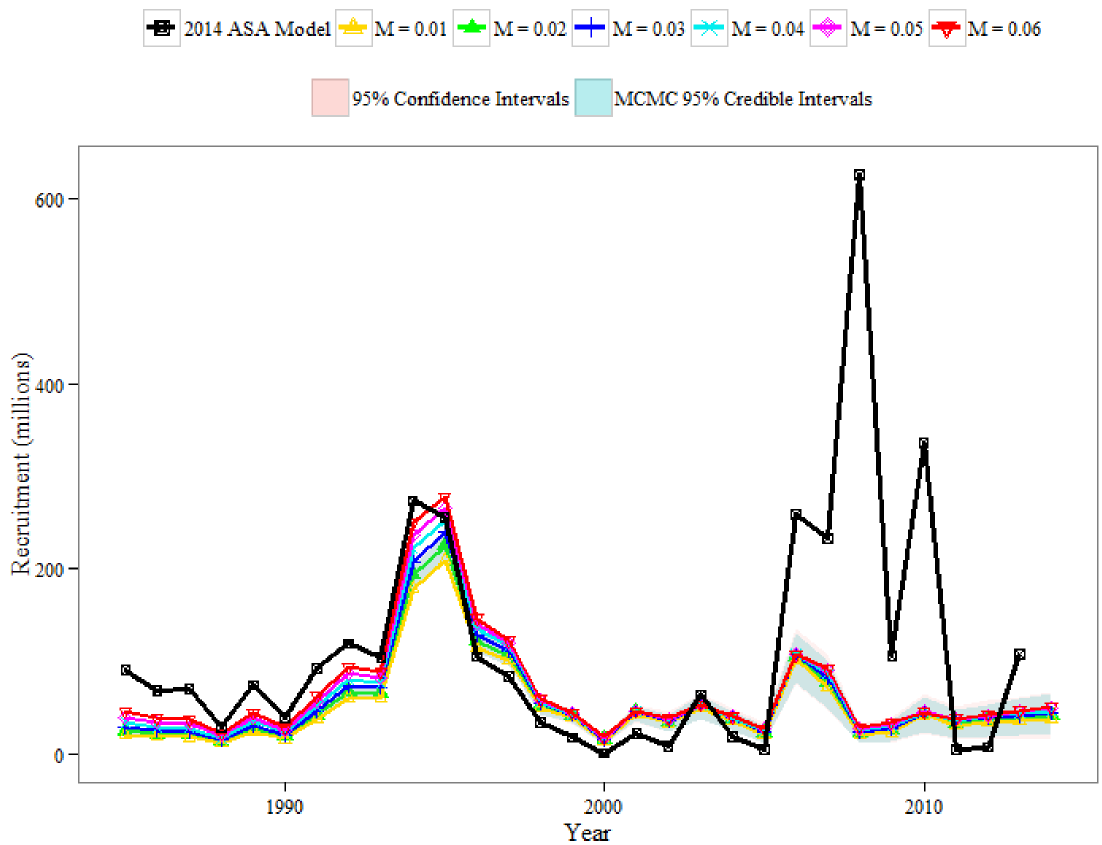


Figure 15. Estimates of Yelloweye Rockfish age-3 recruitment in EYKT over a suite of natural mortality values from 0.01 to 0.06 compared with the 2014 estimates of recruitment, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that $M$ = 0.02.

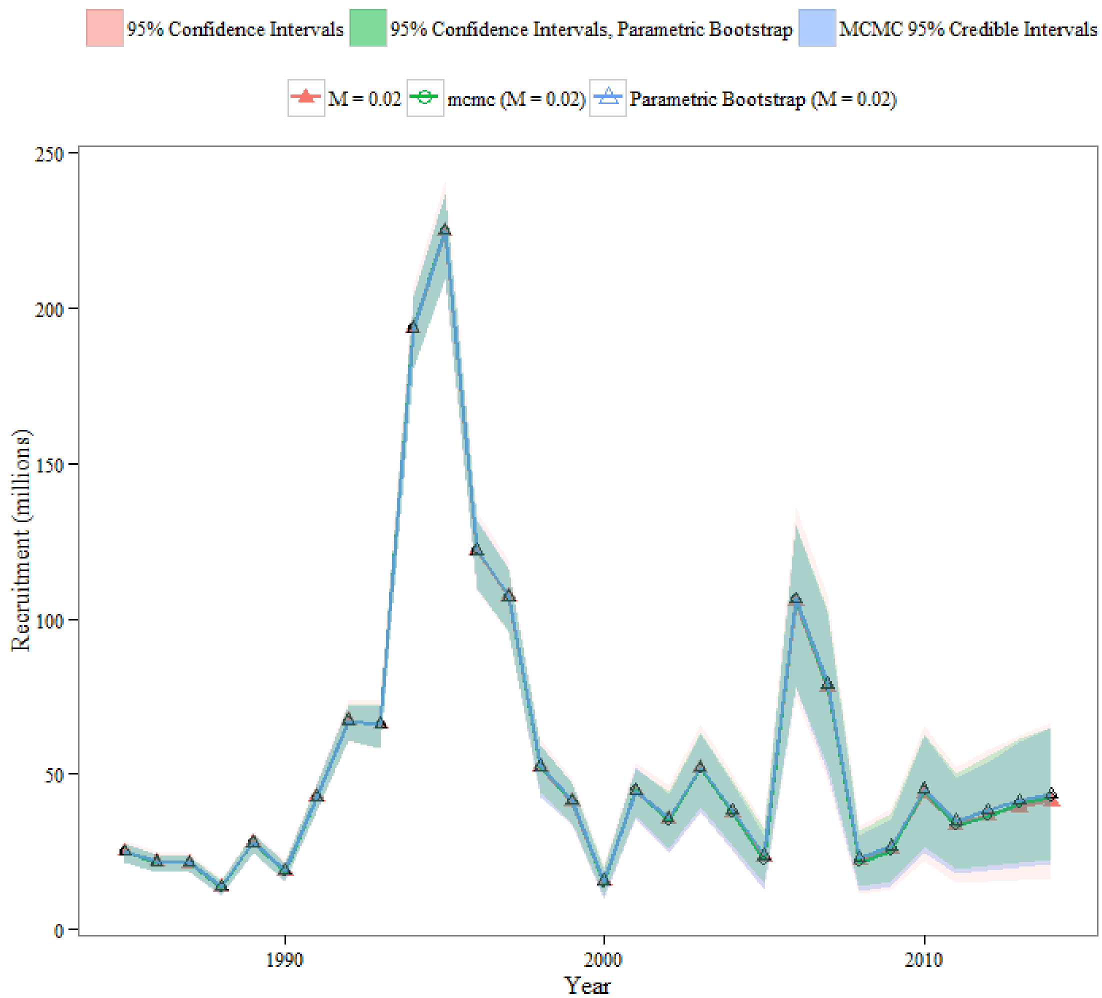


Figure 16. Subset of Figure 15 above: model point-estimates and associated variances of Yelloweye Rockfish age-3 recruitment in EYKT using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 iterations) under the Tier 4 assumption that *M* = 0.02.

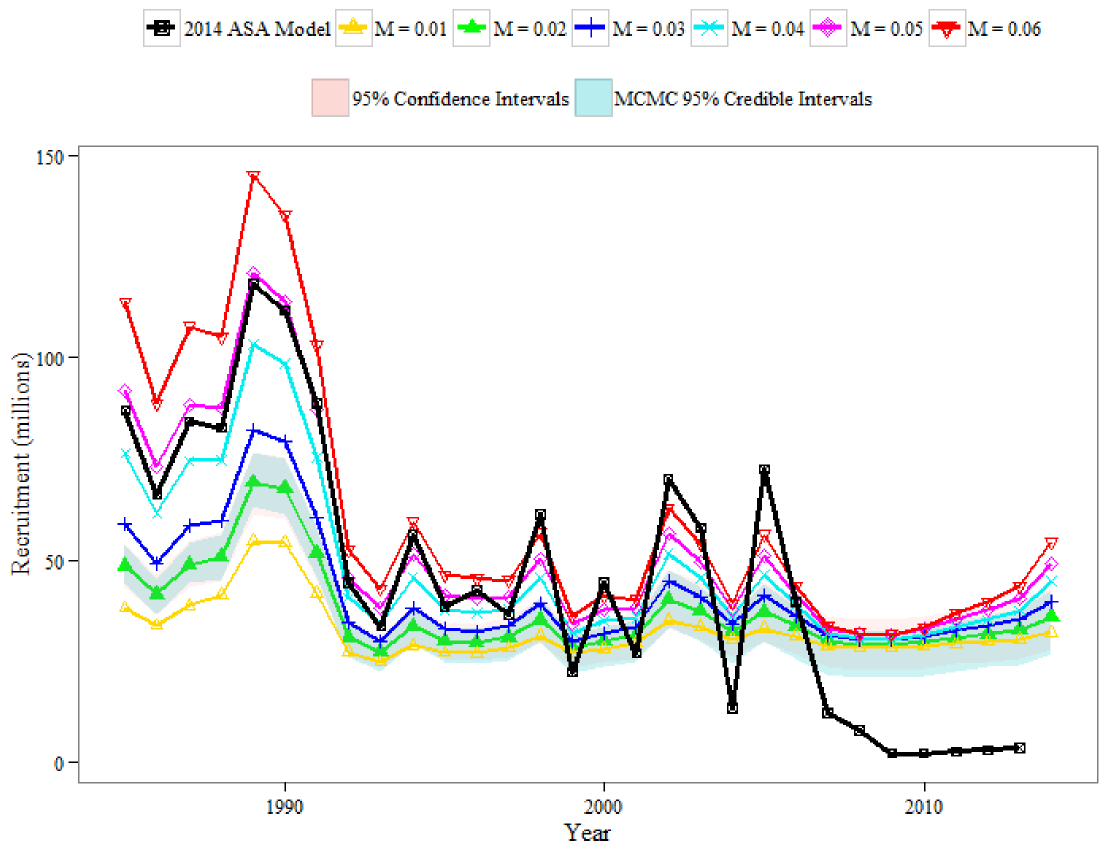


Figure 17. Estimates of Yelloweye Rockfish age-3 recruitment in SSEO over a suite of natural mortality values from 0.01 to 0.06 compared with the 2014 estimates of recruitment, with 95% credible intervals from 1,000,000 MCMC iterations and 95% confidence levels for the model incorporating the Tier 4 assumption that *M* = 0.02.

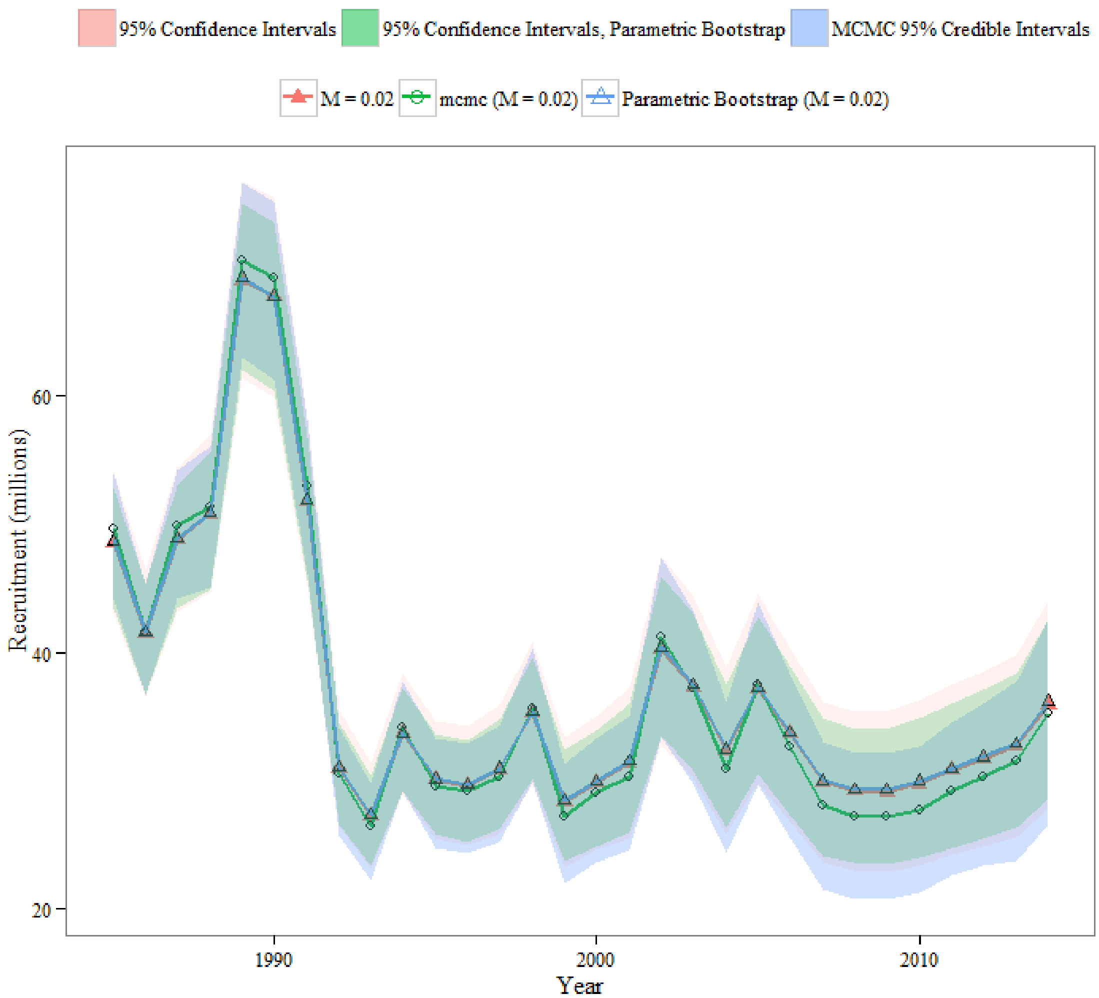


Figure 18. Subset of Figure 17 above: model point-estimates and associated variances of Yelloweye Rockfish age-3 recruitment in SSEO using maximum likelihood methods, the parametric bootstrap (10,000 iterations) and an MCMC (1,000,000 iterations) under the Tier 4 assumption that $M$ = 0.02.

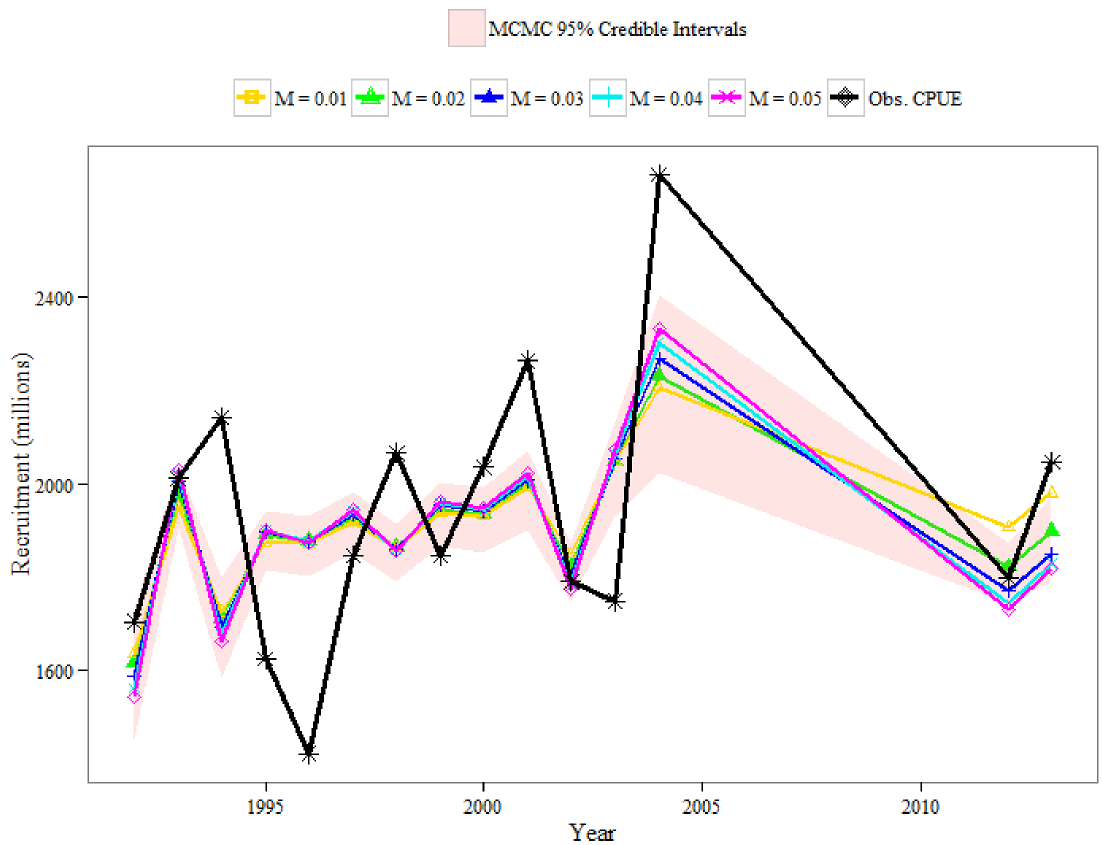


Figure 19. Estimates of Yelloweye Rockfish CPUE from the directed commercial fishery in CSEO over a suite of natural mortality values from 0.01 to 0.05 compared with observed CPUE values, with 95% credible intervals from 1,000,000 MCMC iterations for the model incorporating the Tier 4 assumption that $M$ = 0.02.

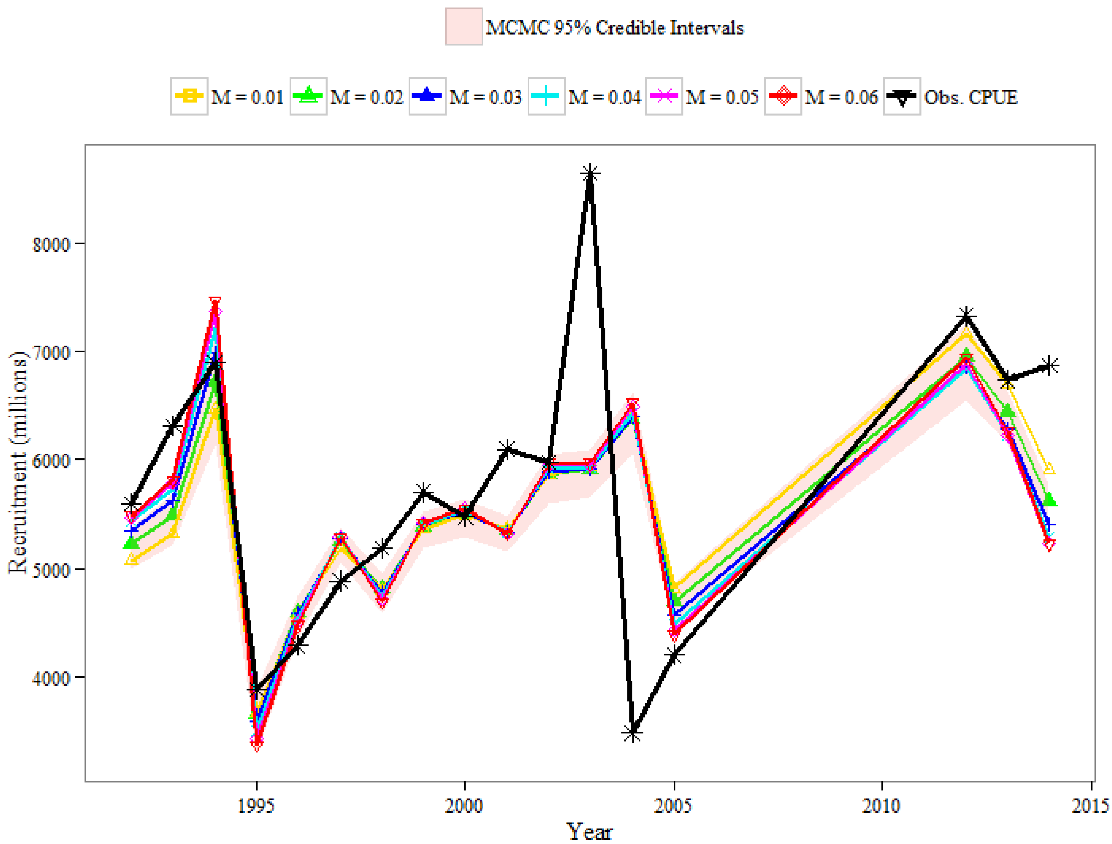


Figure 20. Estimates of Yelloweye Rockfish CPUE from the directed commercial fishery in EYKT over a suite of natural mortality values from 0.01 to 0.06 compared with observed CPUE values, with 95% credible intervals from 1,000,000 MCMC iterations for the model incorporating the Tier 4 assumption that *M* = 0.02.

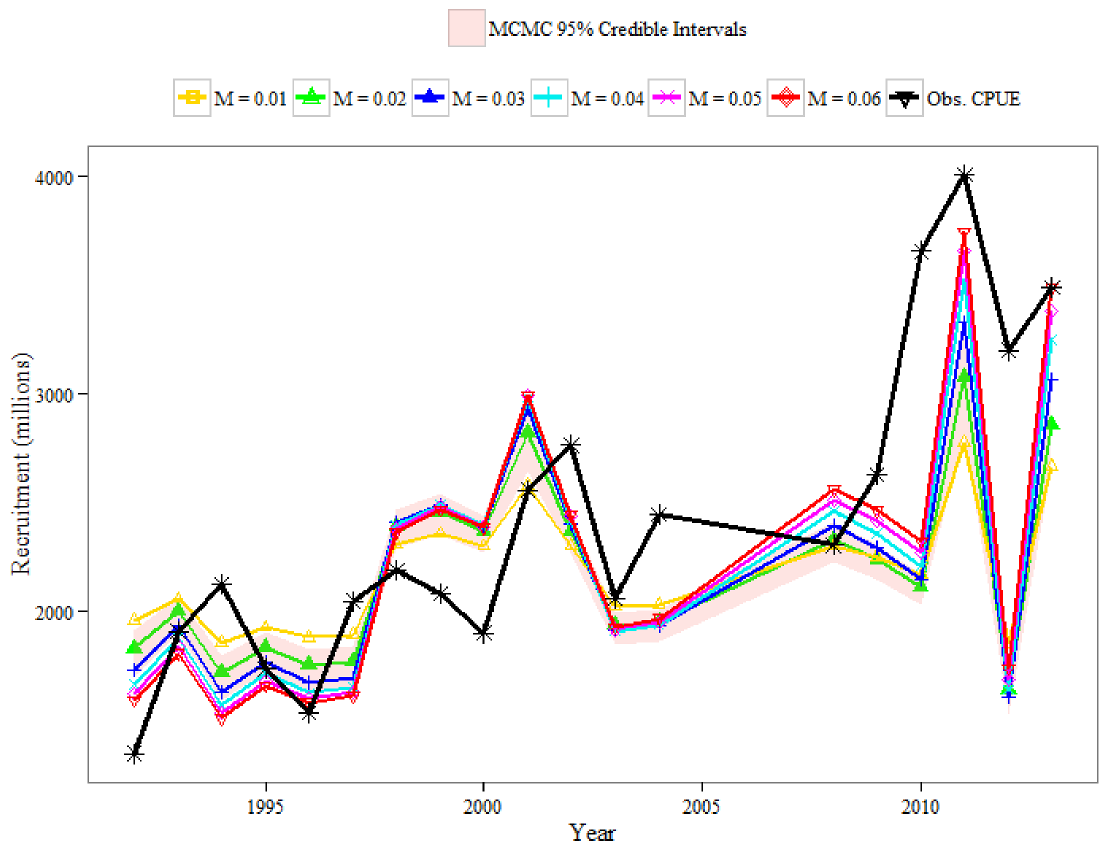


Figure 21. Estimates of Yelloweye Rockfish CPUE from the directed commercial fishery in SSEO over a suite of natural mortality values from 0.01 to 0.06 compared with observed CPUE values, with 95% credible intervals from 1,000,000 MCMC iterations for the model incorporating the Tier 4 assumption that *M* = 0.02.

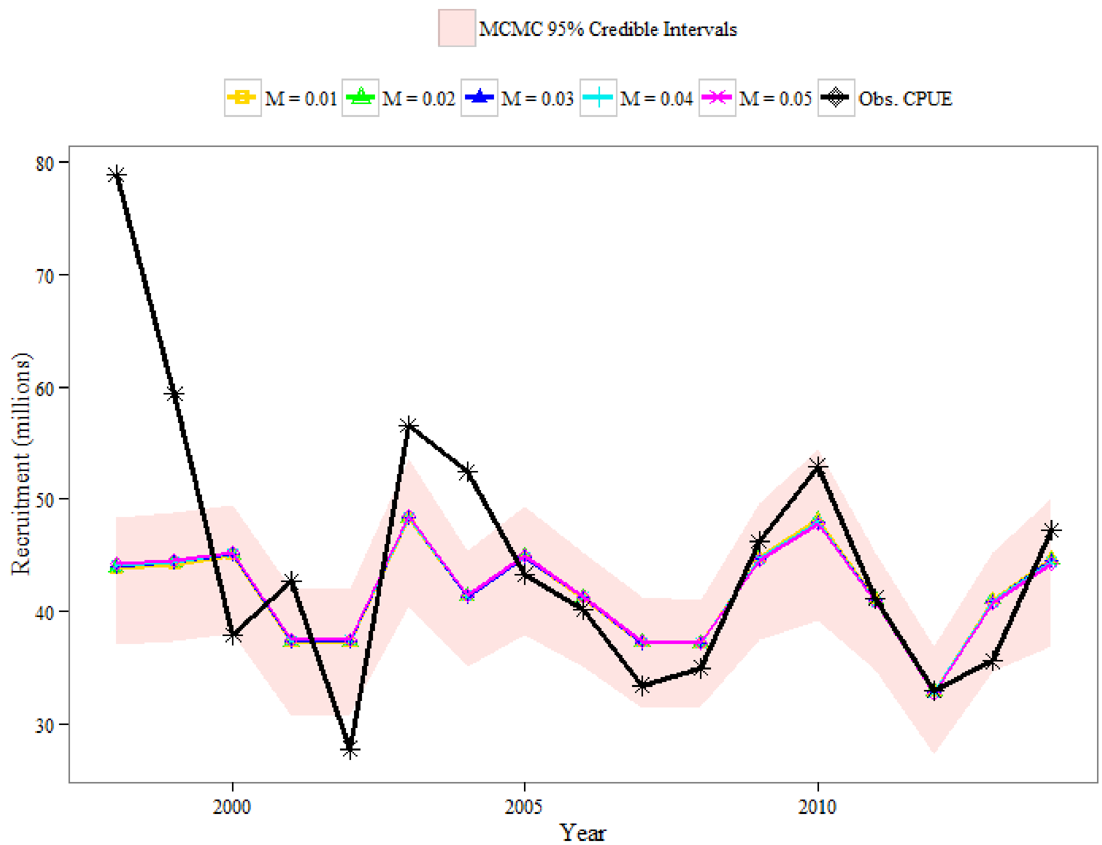


Figure 22. Estimates of Yelloweye Rockfish CPUE from the IPHC halibut longline survey in CSEO over a suite of natural mortality values from 0.01 to 0.05 compared with observed CPUE values, with 95% credible intervals from 1,000,000 MCMC iterations for the model incorporating the Tier 4 assumption that $M = 0.02$.

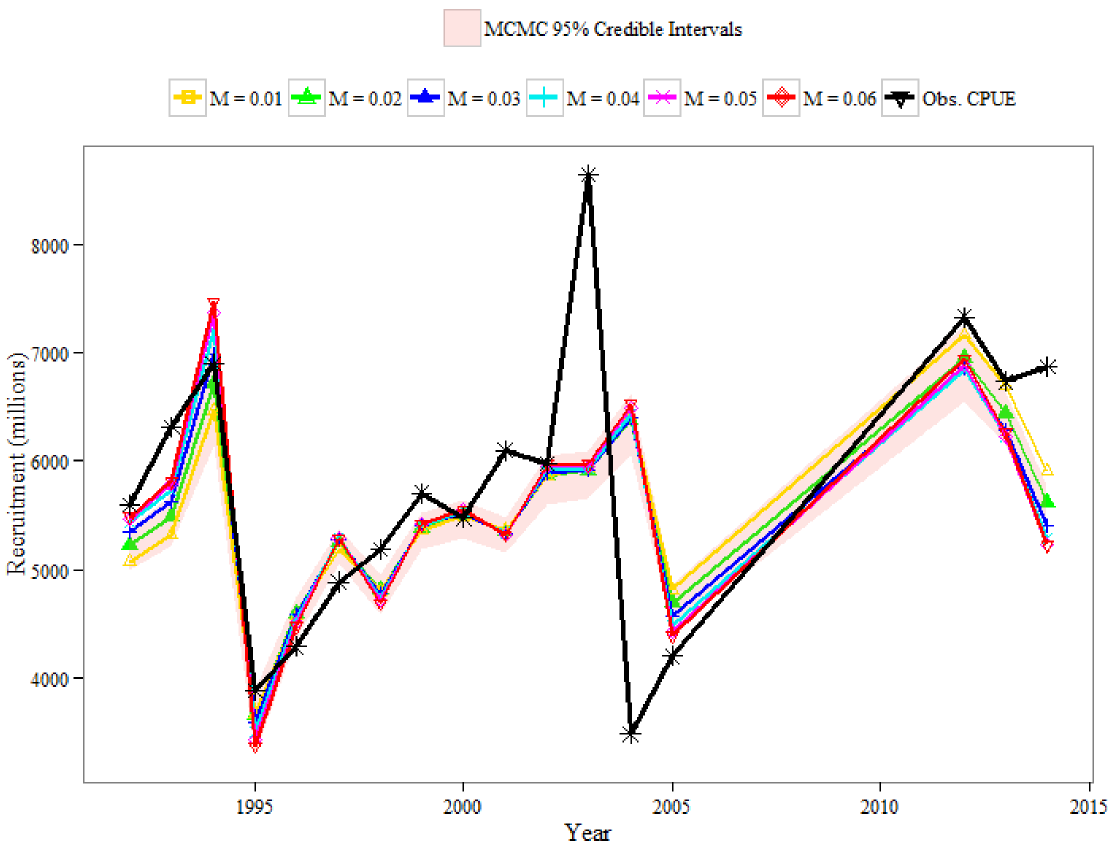


Figure 23. Estimates of Yelloweye Rockfish CPUE from the IPHC halibut longline survey in EKYT over a suite of natural mortality values from 0.01 to 0.06 compared with observed CPUE values, with 95% credible intervals from 1,000,000 MCMC iterations for the model incorporating the Tier 4 assumption that *M* = 0.02.

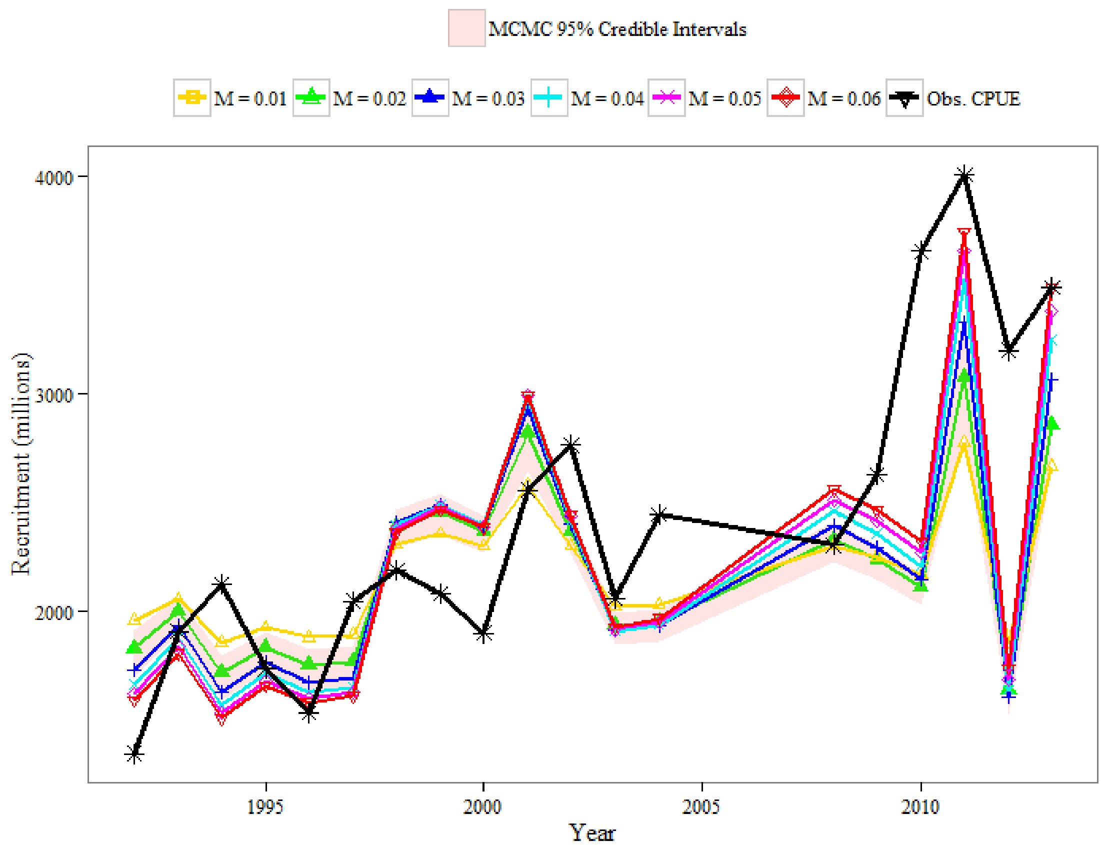


Figure 24. Estimates of Yelloweye Rockfish CPUE from the IPHC halibut longline survey in SSEO over a suite of natural mortality values from 0.01 to 0.05 compared with observed CPUE values, with 95% credible intervals from 1,000,000 MCMC iterations for the model incorporating the Tier 4 assumption that $M$ = 0.02.

**BOX 1: Model parameters and quantities**

| | |
|---|---|
| $y$ | Year |
| $a$ | Age classes |
| $w_a$ | Vector of estimated weight-at-age, $a_{0\ ->}\ a_{+;}$ model input |
| $mat_a$ | Vector of estimated maturity-at-age, $a_{0\ ->}\ a_{+;}$ model input |
| $a_0$ | Age at model recruitment (8) |
| $a_+$ | Plus class (ages 97+) |
| $\mu_r$ | Mean annual recruitment |
| $\mu_f$ | Mean annual full-recruitment fishing mortality (log) |
| $\phi f_y$ | Annual fishing mortality deviation for directed DSR fishery |
| $\phi b_y$ | Annual fishing mortality deviation for commercial halibut incidental catch |
| $\phi s_y$ | Annual fishing mortality deviation for sport removals |
| $\tau_y$ | Annual recruitment deviation ~ (0, $\sigma_r$) |
| $\sigma_r$ | Recruitment standard deviation |
| $fs_a$ | Vector of selectivities-at-age for all fishery removals, $a_{0\ ->}\ a_{+;}$ |
| $M_a$ | Natural mortality (1896 – 1984) |
| $M_b$ | Natural mortality (1985 - 2013) |
| $F_{y,a}$ | Fishing mortality by year $y$ and age $a$ $F_{y,a} = fs_a e^{(\mu_f + \phi f_y + \phi b_y + \phi s_y)}$ |
| $Z_{y,a}$ | Total mortality by year $y$ and age $a$ ($Z_{y,a} = F_{y,a} + M$) |
| $S_{y,a}^{m\_s}$ | Survival by year and age at the month $m\_s$ of the submarine/ROV survey |
| $S_{y,a}^{m\_sp}$ | Survival by year and age at the spawning month $m\_sp$ |
| $T_{a,a'}$ | Aging-error matrix |
| $Z_{1prior}$ | Prior mean for total mortality 1896 - 1984 |
| $Z_{2prior}$ | Prior mean for total mortality 1985 - 2013 |
| $\mu_{f\ prior}$ | Prior mean for mean annual full-recruitment fishing mortality |
| $\sigma_{r(prior)}$ | Prior mean for recruitment variance |
| $q_{(prior)}$ | Prior mean for directed fishery catchability |
| $q_{iphc(prior)}$ | Prior mean for IPHC longline survey catchability |
| $\sigma^2_{Z1}$ | Prior CV for total mortality 1896 - 1984 |
| $\sigma^2_{Z2}$ | Prior CV for total mortality 1985 - 2013 |
| $\sigma^2_r$ | Prior CV recruitment deviations |
| $\sigma^2_f$ | Prior CV for fishing mortality |
| $\sigma^2_q$ | Prior CV for directed fishery catchability |
| $\sigma^2_{q\_iphc}$ | Prior CV for IPHC longline survey catchability |

**BOX 2: Population Dynamics**

| | |
|---|---|
| $\hat{C}_y = \sum_a \frac{N_{y,a} * F_{y,a} * (1 - e^{-Z_{y,a}})}{Z_{y,a}} * w_a$ | Catch equation (directed DSR fishery, commercial longline halibut incidental catch, and sport removals) |
| $\hat{D}_y = \sum_a \frac{N_{y,a} * s_{t,a}^{m\_s} * mat_a}{km^2}$ | Survey density (numbers of adults and sub-adults per $km^2$) |
| $\hat{P}_{y,a} = \sum_a \left( \frac{\hat{C}_{y,a}}{\sum_a \hat{C}_{y,a}} \right) * T_{a,a'}$ | Fishery age composition |
| $C_y = qE_y^{\alpha+1} N_y^{\beta+1}$ | CPUE for the directed DSR fishery, where C = median catch over all sets |
| $C_{ipch\_y} = q_{iphc} E_{iphc\_y}^{\alpha+1} N_y^{\beta+1}$ | CPUE for the IPHC longline survey, where C = median catch over all sets |

Start year

$$N_a = \begin{cases} e^{(\mu_r + \tau_{styr})}, & a = a_0 \\ e^{(\mu_r + \tau_{styr + a_0 - a})} e^{-(a - a_0)M}, & a_0 < a < a_+ \\ \frac{e^{\mu_r} e^{-(a-a_0)M}}{1 - e^{-M}}, & a = a_+ \end{cases}$$

Number at age of recruitment (8)
Number at ages between recruitment and plus class
Number in plus class (97+)

Subsequent years

$$N_a = \begin{cases} e^{(\mu_r + \tau_y)}, & a = a_0 \\ N_{y-1,a-1} * e^{-Z_{y-1,a-1}}, & a_0 < a < a_+ \\ N_{y-1,a-1} * e^{-Z_{y-1,a-1}} + N_{y-1,a} * e^{-Z_{y-1,a}} & a = a_+ \end{cases}$$

Number at age of recruitment (8)
Number at ages between recruitment and plus class
Number in plus class (97+)

$$SB_y = \sum_{a=a_0}^{a+} N_{y,a} s_{y,a}^{m\_sp} mat_a w_a / 2$$

Annual female spawning biomass

**BOX 3: Likelihood components**

| | |
|---|---|
| $L_1 = \lambda_1 \sum_y \left(\ln(C_y + 0.00001) - \ln(\hat{C}_y + 0.0001)\right)^2$ | Commercial catch |
| $L_2 = \lambda_2 \sum_y \left(\ln(C_y + 0.00001) - \ln(\hat{C}_y + 0.0001)\right)^2$ | IPHC bycatch |
| $L_3 = \lambda_3 \sum_y \left(\ln(C_y + 0.00001) - \ln(\hat{C}_y + 0.0001)\right)^2$ | Sport catch |
| $L_4 = \lambda_4 \sum_y \frac{\left(\ln(D_y) - \ln\left(\hat{D}_y\right)\right)^2}{2 * \sigma^2(D_y)}$ | Density |
| $L_5 = \lambda_5 \sum_y \frac{\left(\ln(C_y) - \ln\left(\hat{C}_y\right)\right)^2}{2 * \sigma^2(C_y)}$ | Commercial CPUE, where $\hat{C}$ = mean catch over all sets |
| $L_6 = \lambda_6 \sum_y \frac{\left(\ln(C_y) - \ln\left(\hat{C}_y\right)\right)^2}{2 * \sigma^2(C_y)}$ | IPHC longline survey CPUE, where $\hat{C}$ = mean catch over all sets |
| $L_7 = \lambda_7 \sum_{styr}^{endyr} - n_y \sum_{a_0}^{a+} \left(P_{y,a} + 0.0001\right) * \ln\left(\hat{P}_{y,a} + 0.0001\right)$ | Fishery age composition ($n_y$ = sample size) |
| $L_8 = \frac{1}{2\sigma_\alpha^2} \left(\ln\left(\alpha / \alpha_{prior}\right)\right)^2$ | Penalty on deviation from log-normal prior probability distribution of α in the IPHC survey CPUE |
| $L_9 = \frac{1}{2\sigma_\beta^2} \left(\ln\left(\beta / \beta_{prior}\right)\right)^2$ | Penalty on deviation from log-normal prior probability distribution of β in the IPHC survey CPUE |
| $L_{10} = \frac{1}{2\sigma_q^2} \left(\ln\left(q / q_{prior}\right)\right)^2$ | Penalty on deviation from log-normal prior probability distribution of recruitment deviations |
| $L_{11} = \frac{1}{2\sigma_{q_{iphc}}^2} \left(\ln\left(q_{iphc} / q_{iphc_{prior}}\right)\right)^2$ | Penalty on deviation from log-normal prior probability distribution of recruitment deviations |
| $L_{12} = \frac{1}{2\sigma_F^2} \left(\ln\left(F / F_{prior}\right)\right)^2$ | Penalty on deviation from log-normal prior probability distribution of full-recruitment fishing mortality *F* |
| $L_{13} = \lambda_{13} \sum_y \varepsilon_y^2$ | Penalty on recruitment deviations |
| $L_{14} = \lambda_{12} \sum_y \varepsilon_y^2$ | Fishing mortality regularity penalty |
| $L_{total} = \sum_{i=1}^{13} L_i$ | Total objective function value |