14: ASSESSMENT OF THE DEMERSAL SHELF ROCKFISH STOCK COMPLEX IN THE SOUTHEAST OUTSIDE DISTRICT OF THE GULF OF ALASKA

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Executive Summary

The demersal shelf rockfish (DSR) complex (yelloweye, quillback, copper, rosethorn, canary, China, and tiger rockfish) is assessed on a biennial cycle, with a full stock assessment typically conducted in odd calendar years. Prior to 2010 yelloweye rockfish density was estimated using a manned submersible (*Delta*) and since 2012 density has been estimated using a remotely operated vehicle (ROV). No surveys were completed in 2010 or 2011. Yelloweye rockfish biomass is estimated as the product of density, mean fish weight, and area of rocky habitat for each management district. The recommended DSR acceptable biological catch (ABC) and overfishing level (OFL) for this year's SAFE are based on the most recent yelloweye rockfish biomass estimates plus the Tier 6 calculation of the non-yelloweye rockfish DSR component. In addition, the results of a preliminary statistical age-structured assessment model, which incorporates submersible and ROV yelloweye rockfish density estimates, commercial, recreational, and subsistence fishery data, and International Pacific Halibut Commission (IPHC) survey data, are presented in Appendix A.

Summary of Changes in Assessment Inputs

Changes in the input data:

Catch information and average weights for yelloweye rockfish catch from the commercial fishery were updated for 2016. Average weight of yelloweye rockfish changed from 3.96 kg to 3.93 kg in East Yakutat (EYKT), from 3.47 kg to 3.52 kg in Central Southeast Outside (CSEO), 3.95 to 3.67 kg in Northern Southeast Outside (NSEO), and in Southern Southeast Outside (SSEO) from 3.53 kg (2013 data) to 3.32 kg.

Changes in the assessment methodology:

The only change to the status quo assessment methodology is the non-yelloweye DSR component is calculated using Tier 6 calculations based on catch data from 2010 to 2014 for recreational, commercial and subsistence data. This time period was the only range when all three catch data sets overlapped. The Tier 6 option is used because it is consistent with other stock assessments that do not have reliable biomass estimates and is based on historical catch rather than an expansion of yelloweye rockfish biomass.

Summary of Results

DSR are managed under Tier 4 of North Pacific Fishery Management Council (NPFMC) harvest rules, where maximum allowable $F_{ABC} \leq F_{40\%}$ and $F_{OFL}=F_{35\%}$. The maximum allowable ABC for 2017 is 289 t (269 t yelloweye + 20 t non-yelloweye DSR Tier 6) based on Tier 4 status for the DSR complex. DSR are particularly vulnerable to overfishing given their longevity, late maturation, and habitat-specific residency. As in previous years, we recommend a harvest rate lower than the maximum allowed under Tier 4; $F=M=0.02$. This results in an author's recommended ABC of 227 t (207 t yelloweye + 20 t non-yelloweye DSR Tier 6) for 2017. The overfishing level (OFL) is set using $F_{35\%}$=0.032; which is 357 t for 2017. Tier 6 calculations for non-yelloweye DSR is based on historical catch rather than a 3% expansion of yelloweye rockfish biomass that has been used in previous years.

Per the 2009 Board of Fisheries (BOF) decision, subsistence DSR removals are deducted from the ABC prior to the allocation of the total allowable catch (TAC) to the commercial and recreational fisheries. In the current assessment 7 t was deducted from the ABC for DSR caught in the subsistence fisheries for a TAC of 220 t. In 2006 the BOF allocated the Southeast Outside District DSR TAC as: 84% to the commercial fishery and 16% to the recreational fishery. Thus, 185 t is allocated to commercial fisheries, and 35 t is allocated to recreational fisheries for 2017.

Reference values for DSR are summarized in the following table, with the recommended ABC and OFL values in bold. The stock was not subjected to overfishing last year.

	As estimated or *specified last* year for:		As estimated or *recommended this* year for:	
Quantity	2016	2017	2017	2018
M (natural mortality rate)	0.02	0.02	0.02	0.02
Tier	4	4	4	4
Yelloweye Biomass (t)	10,559		10,347	
Specified/recommended F_{ABC}	0.020	0.020	**0.020**	**0.020**
$F_{OFL}=F_{35\%}$	0.032	0.032	0.032	0.032
$maxF_{ABC}$	0.026	0.026	0.026	0.026
Recommended DSR ABC (t)	231[1]	231[1]	**227[1]**	**227[1]**
DSR OFL (t)	364[1]	364[1]	357[1]	357[1]
DSR max ABC (t)	295[1]	295[1]	289[1]	289[1]
Status	As determined last year for:		As determined this year for:	
	2014	2015	2015	2016
Is the stock being subjected to overfishing?	No	n/a	No	n/a

[1]For 2016 and 2017 the non-yelloweye DSR ABCs and OFL are calculated using Tier 6 methodology. Non-yelloweye Tier 6 ABCs and OFL are added to Tier 4 yelloweye ABCs and OFL for total DSR values. .

Quantity (Tier 6 for other DSR only)	As estimated or *specified last* year and *recommended this* year for:	
	2016	**2017**
OFL (t)	**26**	**26**
ABC (t)	**20**	**20**

Updated catch data (t) for DSR in the eastern Gulf of Alaska (EGOA) as of October 17, 2016 (NMFS Alaska Regional Office Catch Accounting System via the Alaska Fisheries Information Network (AKFIN) database, http://www.akfin.org are summarized in the following table.

Year	EGOA Catch Total[1]	EGOA ABC	EGOA TAC[1]
2014	98	274	267
2015	102	225	217
2016	100[2]	218	211

[1] TAC and Catch are for the commercial fishery only. The recreational harvest (retained harvest plus estimated discard) for the SEO was 40 t in 2014, 49 t in 2015, and 43 t in 2016.

[2]Updated commercial catch data (t) for demersal shelf rockfish in the Southern Outside District as of October 17, 2016.

Area Apportionment

The ABC and OFL for DSR are for the SEO Subdistrict. The State of Alaska manages DSR in the Eastern regulatory area with Council oversight and any further apportionment within the SEO Subdistrict is at the discretion of the State.

Summaries for Plan Team

Species	**Year**	**Biomass**	**OFL**	**ABC**	**TAC[1]**	**Catch[2]**
	2014	13,274	438	274	267	98
	2015	10,933	361	225	217	102
	2016	10,559	364	218	211	103[2]
	2017	10,347	357	227		

[1]TAC and Catch are for the commercial fishery only (directed and incidental catch). The TAC is calculated after the subsistence projected catch is deducted from the ABC. The recreational harvest (retained harvest plus estimated discard) for the SEO was 34 t in 2013, 40 t in 2014, 49 t in 2015, and 43 t in 2016.

[2]Updated commercial catch data (t) for demersal shelf rockfish in the Southern Outside District as of October 17, 2016.

Responses to SSC and Plan Team Comments Specific to this Assessment

The Team recommends using direct habitat measures (e.g., depth strata) rather than yelloweye rockfish presence as a means for screening data to be used for evaluating changes in yelloweye population density (CPUE index).

The commercial fishery CPUE indices have been replaced with simple pounds-per-hook calculations for each region, and skates with zero yelloweye have not been removed. The CPUE indices for the IPHC longline survey also use this methodology for calculating CPUE. Both sonar data and yelloweye rockfish presence were used as screening criteria. These datasets will be re-examined for the 2017 assessment to explore the impact of the data screening process on yelloweye rockfish abundance estimates.

The Team recommended that a high priority be placed on combining areas and indices so that a region-wide assessment of yelloweye rockfish can be evaluated. The SSC agrees with the PT recommendation that a high priority be placed on combining areas and indices so that a region-wide assessment of yelloweye rockfish can be evaluated.

The EGOA consists of 4 management areas: EYKT, NSEO, CSEO, and SSEO that are typically surveyed every 4th year due to funding and logistics. Current funding allows for a survey to be conducted once a year in a given management area with density estimates remaining static until a new survey has been conducted for a given area. A region-wide assessment and indices are being explored using a yelloweye age structure global model and will be addressed in future assessments.

The Team recommends investigating the use of geostatistical modeling (GSTAT) and incorporating density into depth stratification for yelloweye to provide appropriate weighting for density and biomass estimates due to large data gaps among survey areas and years.

Current survey methods place random ROV dive locations within yelloweye rockfish habitat less than 180 m depth which was delineated from sidescan and multibeam sonar data and from the directed commercial fishery logbooks. Management areas are surveyed every year with an area being revisited typically every 4th year. Due the spatial scale of the EGOA and with a limited extent of these areas being mapped additional mapping surveys would need to be conducted to appropriately identify suitable yelloweye rockfish habitat. Post-stratification of density data by depth could be investigated, but would need to be focused on a particular area of interest in EYKT, NSEO, CSEO, or SSEO to develop methods that could then be expanded to the remaining management areas. The use of GSTAT will be examined for future assessments.

The Team recommends using a fixed M for the global yelloweye age structure model.

We agree that the use of a fixed M is more appropriate and will be used in future age structure model assessments.

The Team recommends to iteratively reweighting the variance on the surveys.

This will be explored and addressed in future assessments.

The Team recommends examining abundance bubble plots to determine if there has been any indication of recent strong recruitment. Recruitment was present in EYKT, but was not evident region-wide.

The directed commercial fishery for DSR has only been open in EYKT for the past few years (2014, 2015, and 2016) with the remaining management areas being closed and incidental catch primarily occurring in EYKT and CSEO.

The SSC is concerned about the determination of effective sample size in the age structure model for yelloweye using deviance information criterion (DIC) which resulted in unrealistic negative values and recommends further investigation and provide additional explanation or correction.

This was further investigated and determined that the large negative values may be influenced by the underestimation of survey density variance, uninformative data, and/or the inability of the Markov Chain Monte Carlo (MCMC) to converge onto a set of parameter estimates.

Appendix. An age-structured stock assessment for yelloweye rockfish (*Sebastes rubberimus*) in Southeast Alaska Outside Waters

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Executive Summary

This appendix to the 2016 Demersal Shelf Rockfish SAFE represents the current status of an age-structured assessment (ASA) model for yelloweye rockfish *(Sebastes rubberimus)* in Southeast Alaska outside waters (SEO) (Figure 1). This assessment is in response to previous commentary from both the Gulf of Alaska Plan Team and the Scientific and Statistical Committee. Only three of the management districts within Southeast Alaska Outside waters are included in this assessment (CSEO, SSEO, and EYKT). A fourth management district (NSEO) has only a single survey point available to scale abundance, and has been omitted from this assessment. A new survey within NSEO as well as CSEO was undertaken in 2016, and it is anticipated that these data will be included in the 2017 assessment.

Summary of Changes in Assessment from September meeting

Changes in input data

No data changes

Changes in methodology

1. A coding error in the density likelihood was corrected. A recurring issue during model development has been overly precise model fits to Remote Operated Vehicle survey density inputs. A variety of solutions to this have been proposed and examined. Correction of this error, however, appears to negate the need for these proposed solutions;
2. The results from two model structures are presented that include the density likelihood correction: the corrected global model in which natural mortality is estimated ('Corrected Global model'), and the corrected global model in which natural mortality is fixed at the Tier 4 assumption of M = 0.026 ('Fixed M'). Results from the uncorrected global model are presented for comparison;
3. Age composition sample sizes were iteratively reweighted following examination of the standard deviation of normalized residuals (SDNR).

Summary of Results

1. The Corrected Global model estimated natural mortality M to be 0.032. As the Tier 4 assumption is that M = 0.026, estimates of parameters and derived quantities from the Corrected Global and Fixed M models were very similar;
2. Model outputs continue to be highly sensitive to density and age-composition data;
3. Although fixing M stabilizes retrospective model performance, the author recommends use of the Corrected Global model in assessing population dynamics and setting harvest levels. There are sufficient density data available to condition M to biologically reasonable values, and fixing M potentially loses information contained within the age composition data;
4. Projections of spawning biomass show continued declines under a variety of harvest levels, supporting a continued conservative management approach;
5. Should the preferred model be accepted for purposes of management advice, the author recommends setting harvest levels to $F_{65} = 0.022$ and using the lower 90% confidence

interval of the model-estimated allowable biological catch (ABC), which produces an ABC for 2016 of 150 metric tons.

Quantity	Current assessment	Preferred ASA model
	2016	2016
M	0.02	0.032
Tier	4	
Biomass (t)	10,559	10,490
Spawning biomass (t)		4,574
F_{OFL}	$F_{35\%}$ = 0.032	$F_{55\%}$ = 0.031
Max F_{ABC}	$F_{40\%}$ = 0.026	$F_{60\%}$ = 0.026
F_{ABC}	$F_{45\%}$ = 0.02	$F_{65\%}$ = 0.022
OFL (t)	**338**[1]	**217**[2]
maxABC (t)	**275**[1]	**181**[2]
ABC (t)	**211**[1]	**150**[2]

[1] ABC for yelloweye rockfish only. Final ABC contains projected catch of other rockfish species

[2] Lower 90% confidence interval of model-estimated biomass

Responses to SSC and Plan Team Comments Specific to this Assessment

1. *It was recommended to examine a model in which natural mortality M was fixed to the Tier 4 assumption of 0.026.*
2. *Application of standard deviation of normalized residuals (SDNR) to survey density was proposed as a potential solution to overly precise model fitting to those data*
3. *Plots of abundance at age were requested to discern whether evidence for recruitment was present in both data and model outputs*
4. *Comparisons of likelihood components for the regional and global model were requested as an aid to understanding changes in model function relative to combined data sources*
5. *The SSC requested additional explanation or correction of the unrealistic negative values in the effective number of parameters when using the Deviance Information Criterion (DIC) as a metric for model comparison.*

Author's response

1. The Fixed M model is presented.
2. Reweighting the variance of survey density estimates using an iterative progression of SDNR values was explored but discarded, as natural mortality declined to unreasonable levels and density input became increasingly uninformative. Correcton of the density likelihood error has also accomplished the goal of this suggestion.
3. Observed catch-age plots are presented. Although a small recruitment event appears to have occurred in the mid 2000s and is replicated in both data and assessment outputs, correction of

the density likelihood has removed the appearance of recruitment occurring in the last three model years that had been needed to precisely fit density inputs;

4. Time contraints did not allow implementation of the corrected density likelihood across regional models. Should the Plan Team request it, those comparisons can be included in the next model iteration;
5. The Deviance Information Criterion was applied to the models examined in the previous iteration from a set of MCMC draws. Following Spiegelhalter et al. (2002), the DIC for each model structure was calculated as

$$DIC = D(\bar{\theta}) + 2p_D$$

where

$$D(\theta) = -2logL(data|\theta)$$

$$p_D = \bar{D} - D(\bar{\theta})$$

$\bar{D}$ is defined as the posterior mean of the objective function value, and $D(\bar{\theta})$ as the value of the objective function evaluated at the posterior parameter means. While Spiegelhalter et al. (2002) state that P_D values can be negative, they suggest that their existence implies a substantial conflict between prior and data, or an instance in which the posterior mean of a series of MCMC draws is an inadequate estimator of the parameter mean, indicated by likelihoods whose surfaces are non-log-concave. In the current context, the presence of negative values for the effective number of parameters likely indicates a parameter or set of parameter the estimation of which is poorly informed by the available data.

The definition of $D(\bar{\theta})$ assumes that the MCMC run has converged to a solution set, and that the posterior parameter means obtained at its conclusion are indicative of the true parameter values.

In the Uncorrected Global model, the large negative values may have been due to the influence of three drivers:

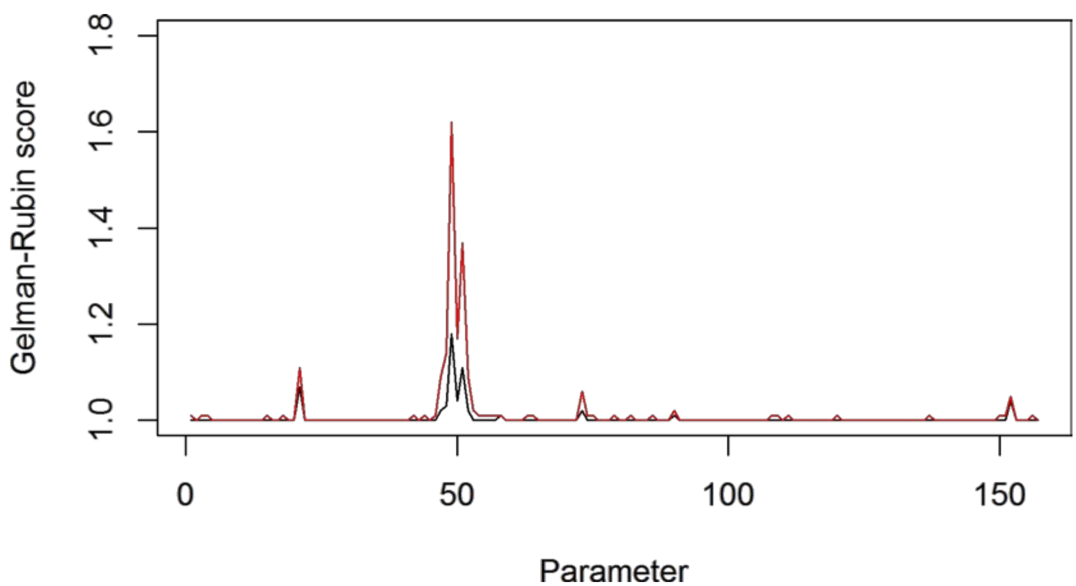
1. the underestimation of survey density variance, subsequently preventing the model from fully exploring the actual parameter space;
2. the inability of the MCMC to successfully converge to a set of parameter estimates;
3. uninformative data resulting in poorly defined parameter likelihood surfaces (including parameter correlation);

Two sets of 10,000,000 MCMC draws each for the Corrected Global model were run to test for convergence. Each set used different starting points for the MCMC chain. Each chain was thinned by retaining every 500th draw, and the first 25% of the saved draws discarded as burn-in. The resulting estimates of DIC values and effective number of parameters were sufficiently different to suggest non-convergence even after 10,000,000 draws. Effective numbers of parameters were still negative, although much smaller than when applied to the Uncorrected Global Model.

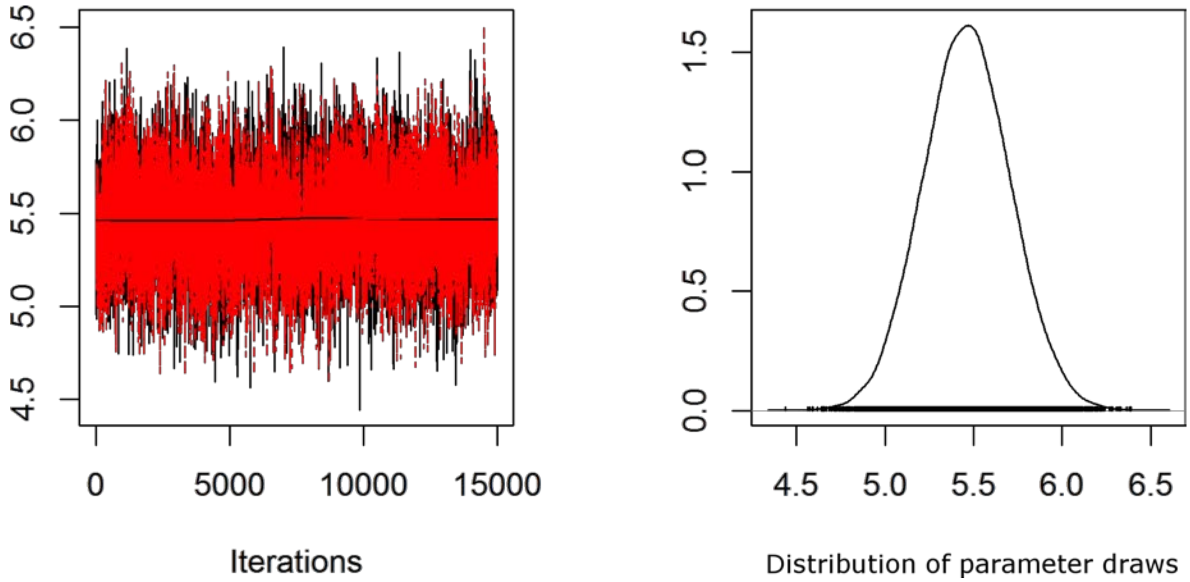
DIC values for models from 10,000,000 MCMC iterations, saving every 500th			
	Corrected – Chain 1	Corrected – Chain 2	Uncorrected*
Expectation of log-likelihood	1825	1824	9743
Expectation of theta	1832	1927	10274
Effective number of parameters	**-7**	**-103**	**-632**
DIC	1818	1722	9111

*The Uncorrected model was from the previous MCMC run, using 2,000,000 iterations and preserving every 100th

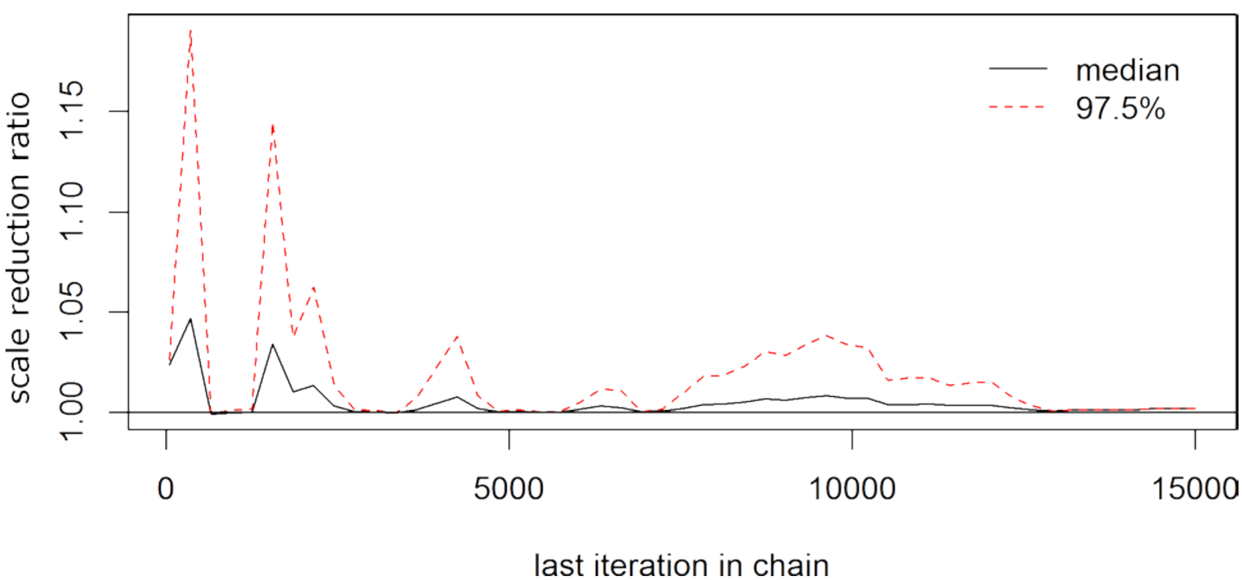
Examination of Gelman & Rubin's convergence diagnostic (Gelman and Rubin, 1992) and MCMC chain densities pointed to lack of convergence in a number of parameters, most notably Year 1 abundances at ages 16 - 18, which had poor Gelman-Rubin scores (greater than 1.1).



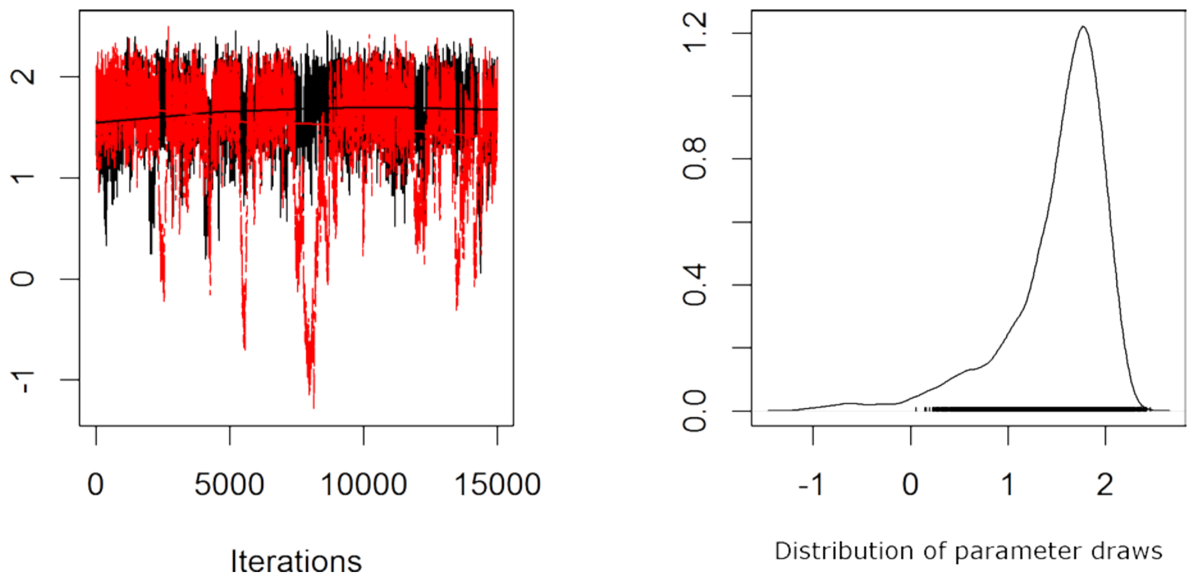
Summary of Gelman-Rubin diagnotic scores for each parameter from two MCMC chains (black line = point estimate of diagnostic, red line = upper 97.5% confidence interval) of 10,000,000 draws each, preserving every 500th draw and discarding the initial 25% as burn-in, with different starting values, showing large scores for parameters 49 – 51, (initial Year 1 abundances for ages 16 – 18).



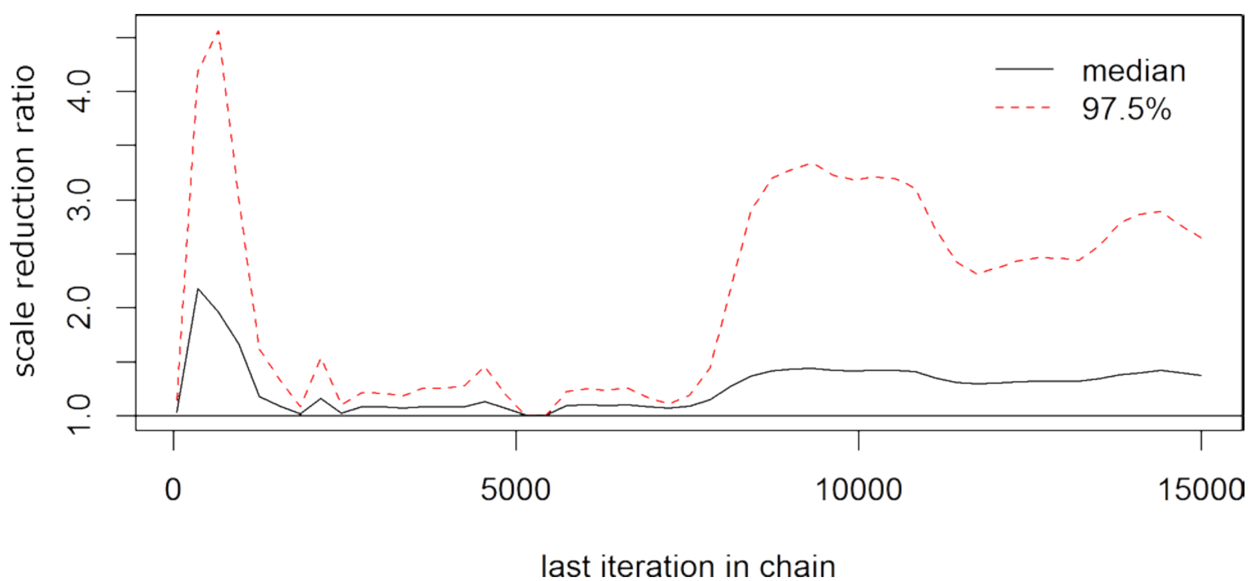
Converged posterior chain draws for a well-defined parameter (mean recruitment, parameter 2) from two MCMC chains of 10,000,000 draws each, preserving every 500th draw and discarding the initial 25% as burn-in, with different starting values.



Gelman diagnostics for mean recruitment (parameter 2) from two MCMC chains of 10,000,000 draws each, preserving every 500th draw and discarding the initial 25% as burn-in, with different starting values, showing convergence.



Unconverged posterior chain draws for a poorly-defined parameter (Year 1 abundance at age 16, parameter 49) from two MCMC chains of 10,000,000 draws each,, preserving everything 500th draw and discarding the initial 25% as burn-in, with different starting values.



Gelman diagnostics for Year 1 abundance age 16 (parameter 49) from two MCMC chains of 10,000,000 draws each, preserving every 500th draw and discarding the initial 25% as burn-in, with different starting values, showing lack of convergence.

Although this analysis was necessarily brief due to time constraints, it suggests that the negative effective number of parameters presented in the Uncorrected Global model was not truly indicative of model performance. Application of DIC as a metric of model comparison may be incorrect at the present time because the MCMC process does not converge, even in the Corrected Global and Fixed M models in which the density likelihood error has been corrected. Model convergence may be facilitated in the future by revisions to model structures or data, or it may be that the observed parameter distributions are unavoidable given the available data.

Should the SSC or Plan Team request it, the author would be happy to explore this dynamic further.

Data

The following data were used in the assessment

Source	Data	Region	Years
Directed commercial fishery, bycatch in Pacific halibut directed fishery	Total Annual Catch	CSEO	1985 - 2004, 2012, 2013
		SSEO	1985 - 2004, 2008 – 2012, 2013
		EYKT	1985, 1987-2001, 2004 - 2005, 2008 - 2009, 2012, 2014
	Age Composition	CSEO	1988, 1992 – 2004, 2012, 2013
		SSEO	1991 – 2005, 2009 – 2013
		EYKT	1992 – 2001, 2004 – 2005, 2008 – 2009, 2012, 2013, 2015
Recreational fishery	Total Annual Catch		2006 – 2015 for all management areas
ADFG Submersible /ROV survey CSEO	Density	CSEO	1995, 1997, 2003, 2007, 2012
		SSEO	1999, 2005, 2013
		EYKT	1995,1997, 1999, 2003, 2009, 2015

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 directed commercial fishery for yelloweye rockfish was implemented in the three management areas. Fisheries data from the early 1990s 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).

In contrast to the directed commercial fishery for yelloweye rockfish, which has not been opened in every management area for every year included in the assessment model, 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 Pacific halibut longline fishery were taken from 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 1).

Fisheries removals from the commercial longline fishery and bycatch in the commercial Pacific halibut longline fishery were combined into a single global vector of removals across all regions.

Sport Harvest

Sport (recreational) harvest refers to total removals from recreational efforts, with an assumption of 100% mortality for any fish released. Total metric 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 onward (Table 2). 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 rockfish density from 1990 - 2009. Survey locations were selected randomly but constrained to fall within rocky habitat considered appropriate for yelloweye rockfish (a detailed description of ADF&G submersible and ROV survey methods is found in Green et al. 2014). After 2009, the submersible was replaced by a ROV controlled directly from the survey ship. Surveys utilizing the ROV were conducted from 2012 onward (no surveys were undertaken in 2010 or 2011). 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 submersible and ROV surveys along with estimates of variance (Table 3). For the purposes of the ASA model, density and variance estimates from the submersible and ROV were 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 Pacific 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. Global age-composition was estimated from the merged catches across all regions. Years in which sample size was less than 50 were omitted.

Commercial fisheries CPUE

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, hook size, depth, and the number of boats entered into the permitted fishery by year and management area. A generalized addtive model (GAM) was used to fit the pounds of yelloweye rockfish to those drivers, factored by year and specific vessel (to account for relative experience levels).

IPHC survey CPUE

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

$$effskt = noskt * 1.52 * (1 - e^{-0.05*hkspc}) * nohk/100 * hkadjs$$

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. Only IPHC survey stations falling over yelloweye rockfish habitat were considered.

Analytic approach

Model structure

Standard age-structured population dynamics equations (Quinn and Deriso 1999) were used to model yelloweye rockfish in Southeast Alaska OUtside waters from 1985 - 2015 using AD Model Builder (Fournier et al. 2011) (Box 1). Modeled age classes ran from 8 - 75+, with 8 being the age of recruitment (the youngest age observed in commercial fisheries data), and 75 being a plus class. Model estimates included spawning biomass, recruitment, natural mortality, abundance-at-age, commercial catch, incidental catch in the commercial Pacific longline halibut fishery, sport catch, CPUE for both the directed commercial fishery and the IPHC Pacific halibut longline survey, and density (number of individual per square kilometer). Parameter estimation was through maximum likelihood methods; uncertainties were evaluated through both maximum likelihood and Bayesian methods.

Males and females were not separated except in the calculation of female spawning biomass and female maturity-at-age. Regionally distinct ROV and submersible density surveys were averaged for years in which two regions had survey data.

Parameters estimated outside the assessment model

Life history attributes were estimated externally from data collected through port sampling of commercial fisheries catches and bycatch in the commercial halibut fishery from 1992 - 2015.

Weight-at-age (kilograms)

Weight-at-age was estimated by fitting a von Bertalanffy growth curve to fish sampled from the commercial fishery and halibut longline fishery bycatch. The parameter t_0 was set to -4 to provide a better visual fit of the resulting curves to younger ages for which sample size was smaller.

Maturity-at-age

Maturity at age was calculated for females only, using a general linear model with a logit transformation. Age at 50% maturity was calculated as 17.63 years.

Parameters estimated inside the assessment model

The basic model structure estimated 149 parameters conditioned on available data and model structural assumptions. Ten parameters governed mean recruitment, mean year 1 abundance, natural mortality, mean fishing mortalities, selectivity and catchability parameters, and variability of annual recruitment deviations. The other 140 parameters were implemented as deviation vectors from mean values to quantify annual recruitment, abundance at age for year 1, and annual fishing mortalities. As models 1, 2, and 3 shared mean recruitment, mean year 1 abundance, and mean fishing mortality parameters for coding efficiency, but preserved distinct estimates of derived quantities, the total number of estimated parameters sums to less than three times the number of parameters estimated by the global model.

Estimated parameters	
1) mean recruitment	1
2) mean year 1 initial abundance	1
3) variance of recruitment deviations	1
4) natural mortality	1
5) Selectivity, catchability, and mean fishing mortalities	6
6) annual fishing mortality deviations for the combined directed fishery and Pacific halibut fishery incidental catch	31
7) age-specific year 1 deviations	67
8) annual fishing mortality deviations for recreational catch	10
9) annual recruitment deviations	31
Total	149

Density

Although the line transect surveys count all observed yelloweye rockfish, density calculations are 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 yelloweye rockfish habitat for each management area in square kilometers were assumed known without error.

Catch-at-age

Catch-at-age 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 (Appendix B1). Both the sport harvest and bycatch in the halibut longline fishery were modeled as separate fisheries, but selectivity-at-age f_a was assumed the same as for the yelloweye rockfish 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).

Selectivity-at-age

Asymptotic selectivity-at-age f_a 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, sport catch, IPHC survey CPUE, and density. Normal likelihoods were implemented for commercial fishery CPUE. Multinomial likelihoods were assumed for age composition data. Penalties were implemented to facilitate scaling and parameter estimation for full-recruitment fishing mortality, year 1 abundance-at-age, recruitment, and natural mortality.

Likelihood component	*Statistical model for error*	*Variance assumption*
Fishery total catch	Log-normal	CV = 0.05
Fishery age comp.	Multinomial	Year-specific sample size
Recreational Catch	Log-normal	CV = 0.1
Density	Log-normal	DISTANCE-estimated variance
Fishery CPUE	Normal	GAM variance
IPHC survey CPUE	Log-normal	Year-specific variance of CPUE
Annual recruitment deviations	Normal	$\sigma_R = 1.0$
Year 1 abundance deviations	Normal	σ_Y = estimated
Natural mortality	Log-normal	$\sigma = 0.2$ Last phase: $\sigma = 2$
Mean *F*	Normal	$\sigma = 1$ Last phase: $\sigma = 2$
Mean sport *F*	Normal	$\sigma = 1$ Last phase: $\sigma = 2$
Mean recruitment	Normal	$\sigma = 1$ Last phase: $\sigma = 2$
Mean year 1 abundance	Normal	$\sigma = 1$ Last phase: $\sigma = 2$

Rescaling age-composition sample size (SDNR)

The variances of the residuals in the age-composition data were compared to the assumed input sample sizes by assessing the standard deviation of normalized residuals (Breen at el. 2003). Under the assumption that the normalized residuals are normally distributed, the author followed the example of Francis (2011) in defining an acceptable SDNR value for a given year as

$$max(sdnr) < [\chi^2_{0.95}/(m-1)]^{0.5}$$

for which m = the number of years in the age-composition data set. If the SNDR for any given year exceeded this limit, the input age composition sample size vector was divided by the SDNR vector, and the model re-run with the revised sample sizes. The process was iteratively repeated until the target maximum SDNR value was reached.

Results

Model evaluation

Changes in parameter space for mean recruitment, natural mortality, mean Year 1 abundance, Year 1 abundance variance, fishing mortalities, and catchabilities are presented in Figure 2 from 10,000,000 MCMC draws, saving every 500th draw. The width of the distribution for *M* in the

Uncorrected model is extremely narrow compared with the Corrected Global model, but the width of catchability in the IPHC survey CPUE is wider for the Corrected Global model.

Model estimates of density, spawning biomass, and recruitment were similar between the Corrected Global and Fixed M models (Figs. 3 – 5). Overall abundance was lower than in the Uncorrected model due to lower estimates of *M*. The additional penalties on recruitment for the last three model years in the Uncorrected model were unnecessary in either the Corrected Global or Fixed M models.

Fisheries selectivity was identical for the Corrected and Fixed M models (Fig. 6). Age at 50% selectivity was slightly younger for these models than in the Uncorrected model.

Annual full-recruitment fishing mortalities are shown in Figure 7.

Residuals for commercial catch composition for a given region were similar across all three model structures (Fig. 8).

The increased recruitment over the last three years seen in the Uncorrected model outputs of abundance at age were not replicated in either the Corrected Global (Fig. 9) or Fixed M models (Fig. 10). There is a small recruitment in the commercial fishery catch age data that was matched by a small model recruitment around 2005 – 2006.

Model fits to commercial CPUE were similar between the Corrected Global and FIxed M models, and roughly flat, whereas the Uncorrected model fitted the CPUE data by showing a decline (Fig. 11). Uncertainty for model estimates of IPHC survey CPUE (Fig. 12) was much larger in the Uncorrected model than either of the revised models, but the reason for this is unexplored at present.

The Corrected Global model estimated natural mortality to be 0.0237 prior to the iterative reweighting of the age composition data according to the SDNR analyses, after which M = 0.032. Both values fall well within values present in the literature, and close to the Tier 4 assumption that M = 0.026. 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 estimate from O'Connel and Brylinksy (2003) of Z = 0.056 was from commercial fisheries data in CSEO from 2000 to 2002.

Retrospective analysis

Retrospective analyses were run back to 2011 for both the Corrected Global and Fixed M models (Figs. 13 - 18). While each model had a number of retrospective model runs that did not converge, these were not the same between models. The improved stability of the Fixed M model can be seen in the consistent density and spawning biomass trends (Figs. 14, 16) as opposed to changing trends in the Corrected model (Figs. 13, 15). The results continue to emphasize the influence of the ROV survey density estimates, but this influence is diminished when natural mortality is fixed.

Model selection

Although fixing *M* stabilizes retrospective model performance, the author recommends use of the Corrected Global model in assessing population dynamics and setting harvest levels, as sufficient density data are available to condition *M* to biologically reasonable values, and fixing *M* potentially loses information contained within the age composition data;

Harvest comparisons and projections of total stock biomass

Output from the Corrected Global global model suggests that implemented fishing mortality has largely been below the target value of 0.02 in recent years (Fig. 7). Model output, however, places 0.02 at roughly F_{65}. This suggests that the replacement rate for yelloweye rockfish is below that which can be sustained under current fishing pressure.

Current stock assessment methods calculate the total allowable catch (TAC) as $F_{ABC} * B$ where F_{ABC} = 0.02 (F_{ABC} = F_{45}) and B = the lower 90% confidence interval of total estimated biomass over all regions, with a 3% adjustment added for non-yelloweye commercial catch. No selectivity is considered (i.e. selectivity is assumed to equal 1 for ages). Biomass is taken from the last survey implemented in each area. The lower 90% confidence interval for total biomass over all regions was estimated at 10,933 metric tons in the 2015 stock assessment, with the recommended TAC set to 225 metric tons.

The Corrected Global model estimated total biomass for 2016 to be 10,490 metric tons. The lower 90% confidence interval for that estimate is 8,392 metric tons. A set of potential fisheries removal levels are presented below; projections of spawning biomass are presented in Figure 19.

***F* level**	**Biomass** (metric tons)	**ABC** (metric tons)
F_{65} (0.022)	L 90% CI (8392)	150
F_{60} (0.026)	L 90% CI (8392)	181
F_{55} (0.031)	L 90% CI (8392)	217
CURRENT ABC (assumes no selectivity)		**218**

Recommendations and ABC for 2016

If the Corrected Global model were accepted for purposes of management advice, the author recommends setting harvest levels to F_{65} and using the lower 90% confidence interval of the model-estimated ABC to set catch levels, which produces a TAC level for 2016 of 150 metric tons, in constrast to the TAC of 211 metric tons under current management methods.

Data gaps and research priorities

The current global model used a simple average of ROV survey densities when two separate region estimates were available for a given year. Upon acceptance of the model structure, these data should be reanalyzed to produce a single estimate of density and uncertainty for each year;

Additional information on life history (natural mortality) and fisheries selectivity would improve those parameter estimates and possibly aid in the resolution between model outputs and Tier 4 assumptions regarding mortality;

The non-uniform distribution of suitable yelloweye rockfish habitat is a significant source of uncertainty, as is the distribution of yelloweye rockfish within each instance of habitat. Yelloweye rockfish density may be more accurately modeled by surveying fewer areas more thoroughly to obtain a density gradient running from the center of the habitable zone out to its termination. A revised global model structure could then be developed

References

Breen, P.A., Kim, S.W., and Andrew, N.L. 2003. A length-based Bayesian stock assessment model for the New Zealand abalone *Haliotis iris*. Mar. Freshw. Res. 54(5): 619–634.

Bull, B., Francis,Brylinksy, C., J. Stahl, D. Carlile, and M. Jaenicke. 2009. Assessment of the demersal shelf rockfish stock for 2010 in the southeast outside district of the Gulf of Alaska. In: Stock assessment and fishery evaluation report for the groundfish resources for the Gulf of Alaska, North Pacific Fisheries Management Council, Anchorage, Alaska pp. 1067 – 1110.

Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. 2011. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Taylor and Francis Online.

Gelman, A., and D.B. Rubin. 1992. "Inference from iterative simulation using multiple sequences." Statistical Science pp: 457-472.

Green, K.., K. Van Kirk, J. Stahl, M. Jaenicke, and S. Meyer. 2015. Assessment of the demersal shelf rockfish stock for 2010 in the southeast outside district of the Gulf of Alaska. In: Stock assessment and fishery evaluation report for the groundfish resources for the Gulf of Alaska, North Pacific Fisheries Management Council, Anchorage, Alaska pp. 751 – 838.

Methot, R.D., and I.G. Taylor. 2011. Adjusting for biass due to variability of estimated recruitments in fishery assessment models. Can. J, Fish. Sci. 68: 1744 - 1760

O'Connell and Brylinksy. 2003. The Southeast Alaska demersal shelf rockfish fishery with 2004 season outlook. Alaska Department of Fish and Game Regional Information Report No. 1J03-43

Spiegelhalter, D.J., Best, N.G., Carlin, B.P.,and A. van der Linde. 2002. Bayesian Measures of Model Complexity and Fit. Journal of the Royal Statistical Society, Series B, 64:4, pp. 583-639

Thomas, L., S.T. Buckland, E.A. Rexstad, J. L. Laake, S. Strindberg, S. L. Hedley, J. R.B. Bishop, T. A. Marques, and K. P. Burnham. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. Journal of Applied Ecology 47: 5-14.

Quinn, T.J. II and R.B. Deriso. 1999. Quantitative Fish Dynamics, Oxford, New York.

Table 1. Total annual directed commercial yelloweye catch (t) and total annual yelloweye incidental catch (t) in the commercial longline Pacific halibut fishery for each for each management district for all modeled years 1985-2015.

Year	CSEO	SSEO	EYKT	Total
1985	222.99	27.52	6.64	257.15
1986	209.1	78.66	0.27	288.03
1987	176.27	290.8	66.12	533.19
1988	128.76	214.22	39.28	382.26
1989	141.3	135.75	41.29	318.34
1990	83.23	115.99	20.77	219.99
1991	101.26	99.28	190.67	391.21
1992	144.92	153.71	63.4	362.03
1993	196.08	98.91	98.69	393.68
1994	231.45	117.37	124.99	473.81
1995	110.88	29.37	67.27	207.52
1996	190.73	71.58	115.74	378.05
1997	183.83	56.48	97.42	337.73
1998	159.98	60.37	99.7	320.05
1999	142.74	71.44	107.03	321.21
2000	98.94	73.31	84.9	257.15
2001	114.67	80.44	82.91	278.02
2002	126.95	80.12	34.97	242.04
2003	114.6	63.42	50.72	228.74
2004	102.68	56.42	132.63	291.73
2005	59.02	47.42	95.04	201.48
2006	67.03	54.17	39.16	160.36
2007	66.42	43.05	54.39	163.86
2008	48.61	45.78	68.45	162.84
2009	41.08	56.37	97.21	194.66
2010	32.54	51.81	57.02	141.37
2011	24.86	28.73	44.24	97.83
2012	51.23	41.95	69.68	162.86
2013	61.93	62.82	70.2	194.95
2014	22.81	7.65	52.14	82.6
2015	25.18	7.47	51.78	84.43

Table 2. Total annual yelloweye recreational and subsistence catch (t) for each management district for 2006 – 2013.

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
2014	17.97	6.64	0.008	24.61
2015	22.3	6.19	0.027	28.52

Table 3. Submersible (1995, 1997, 1999, 2003, 2005, 2007, 2009) and ROV (2012–2015) 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 yelloweye rockfish. Values in bold were used for this stock assessment. (Table adapted from Green at al. 2015).

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
	2015		251	22,896	0.008	1755	1065	2176	0.25
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.

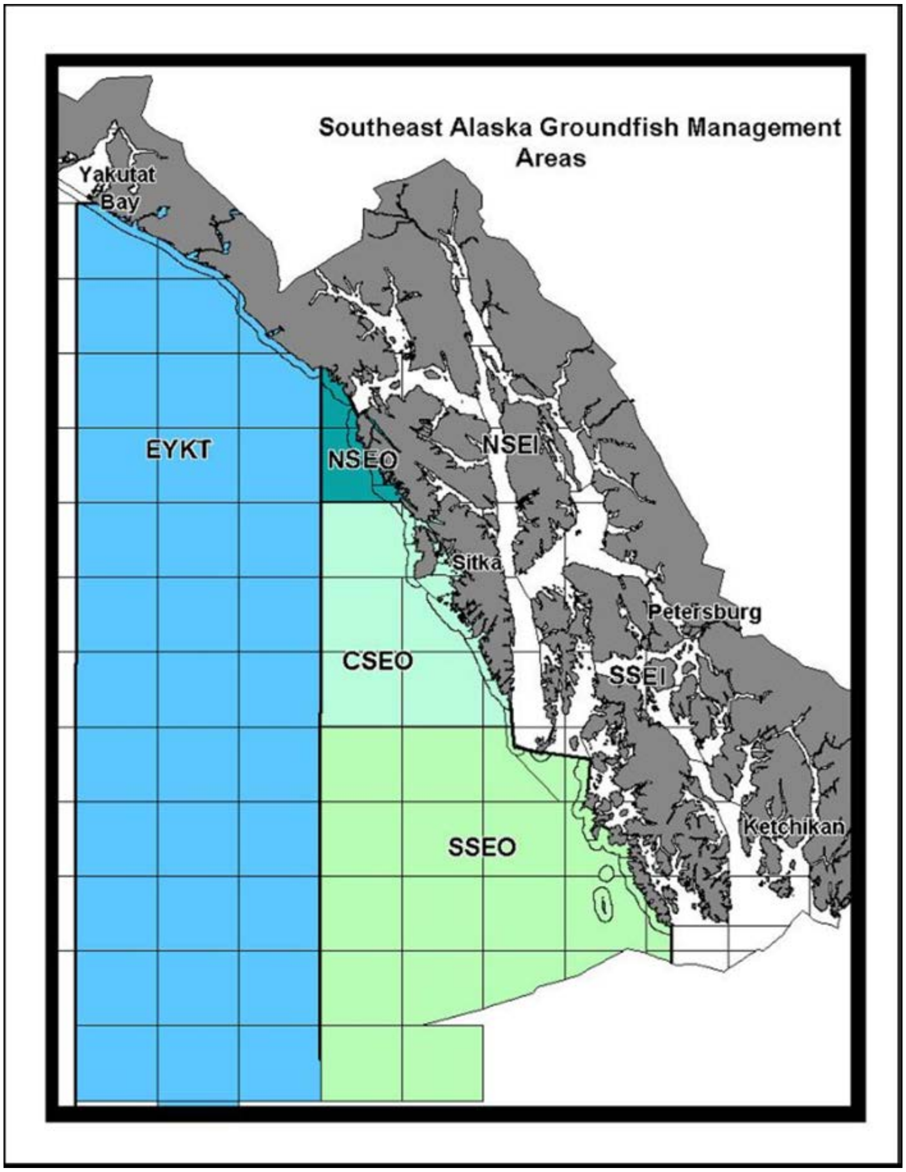


Figure 1. Southeast Alaska Outside Waters

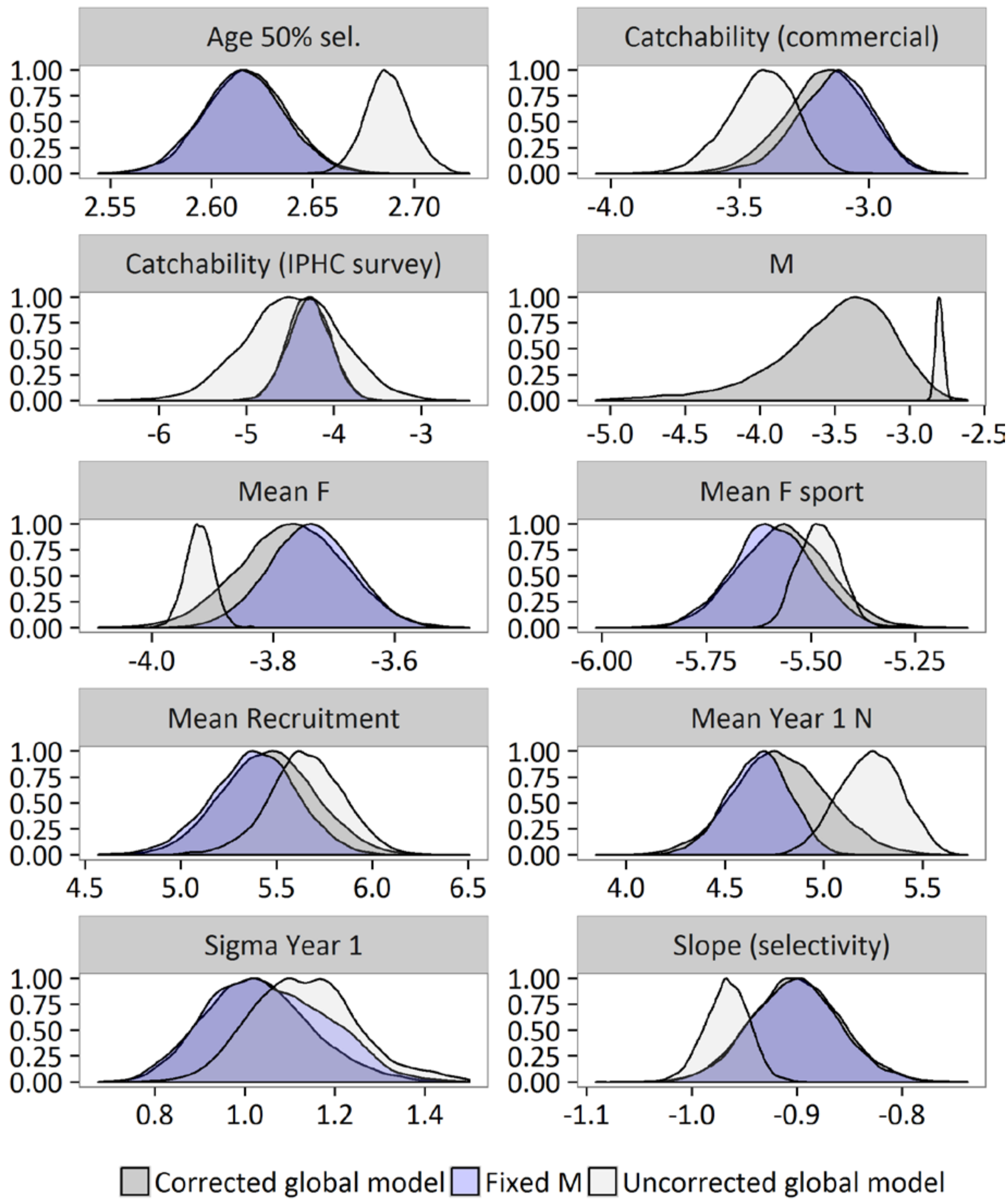


Figure 2. Parameter distributions from 10,000,000 MCMC draws with every 500th saved for the Corrected Global and Fixed M models, compared to 2,000,000 MCMC draws with every 100th saved for the Uncorrected Global model.

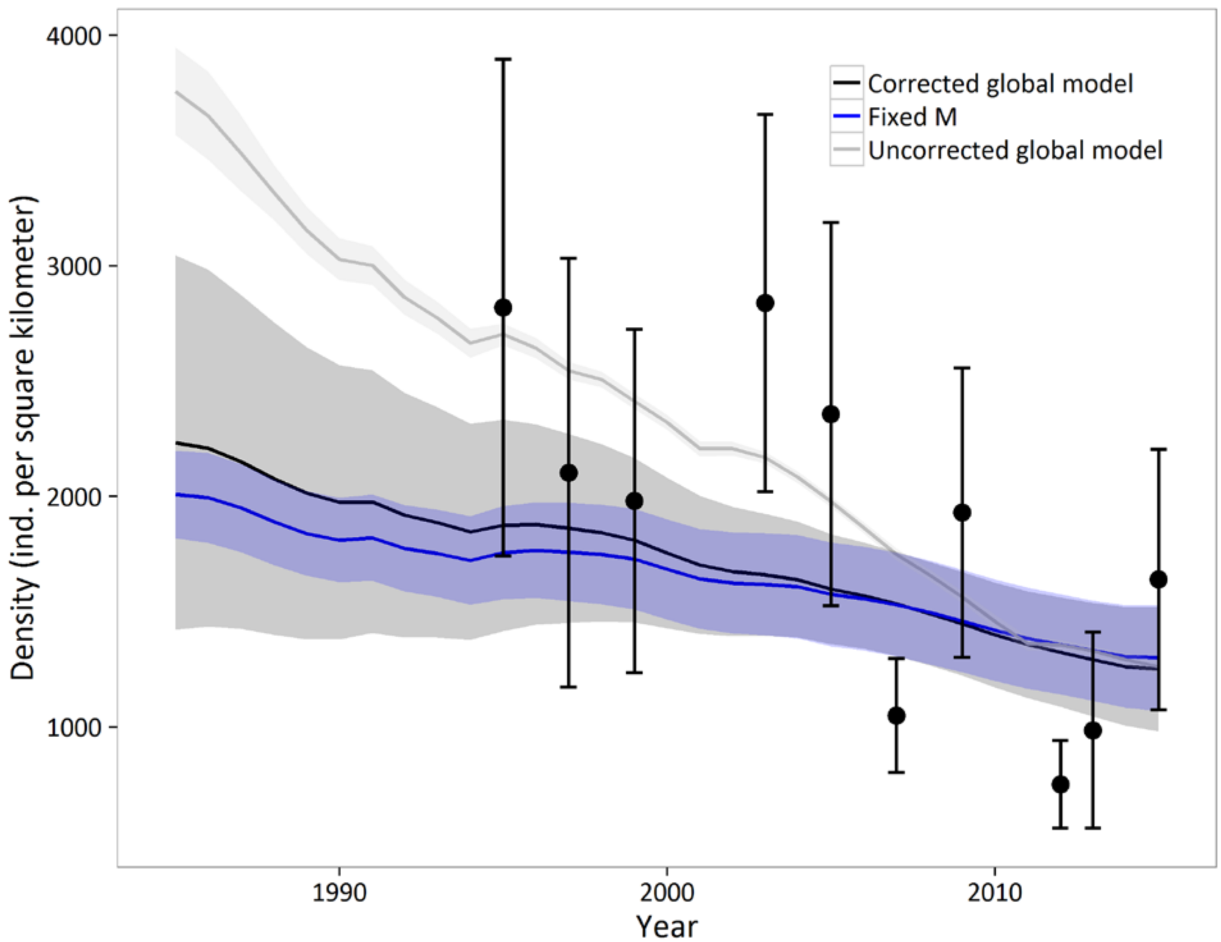


Figure 3. Model estimates of total density with +/- two standard deviations.

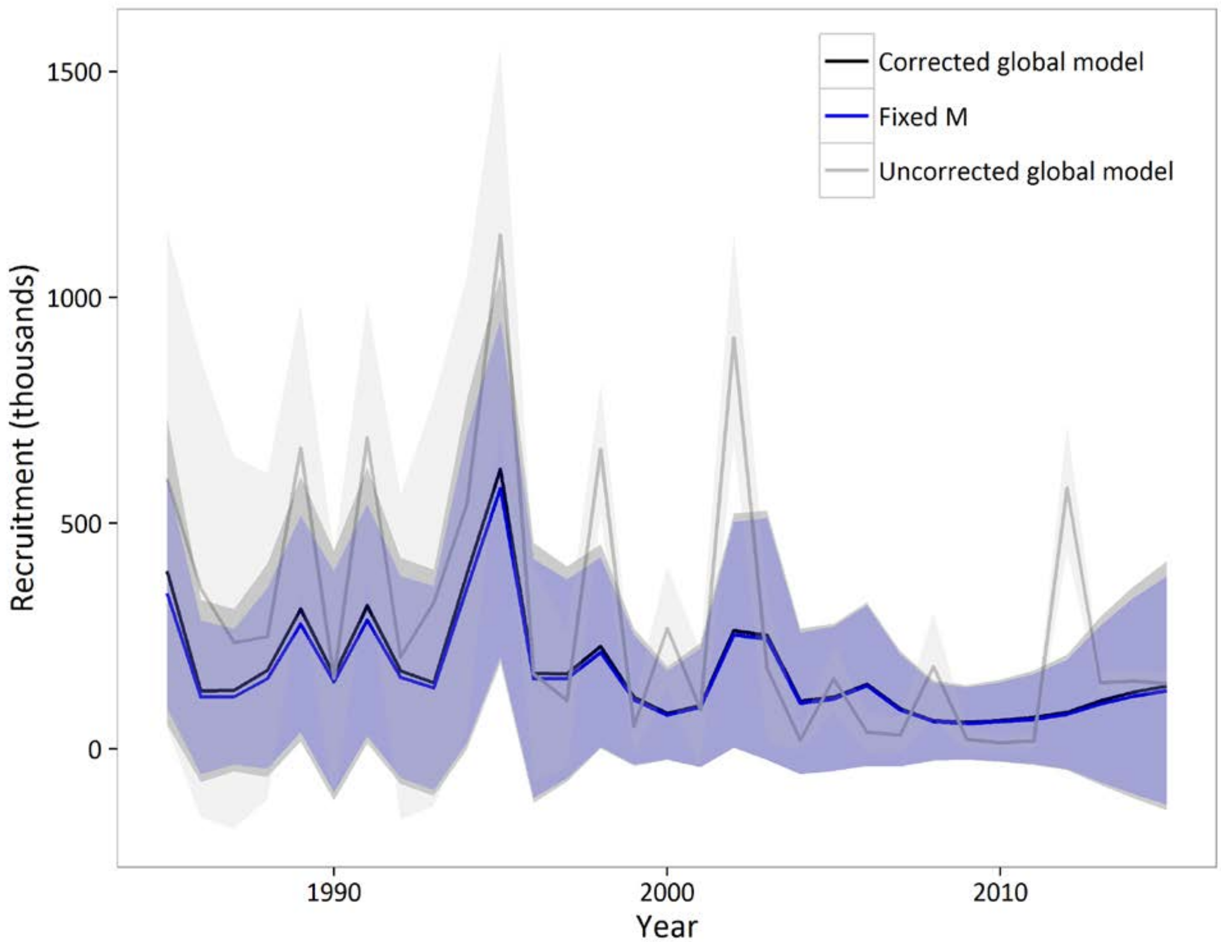


Figure 4. Model estimates of total recruitment (age 8) with +/- two standard deviations.

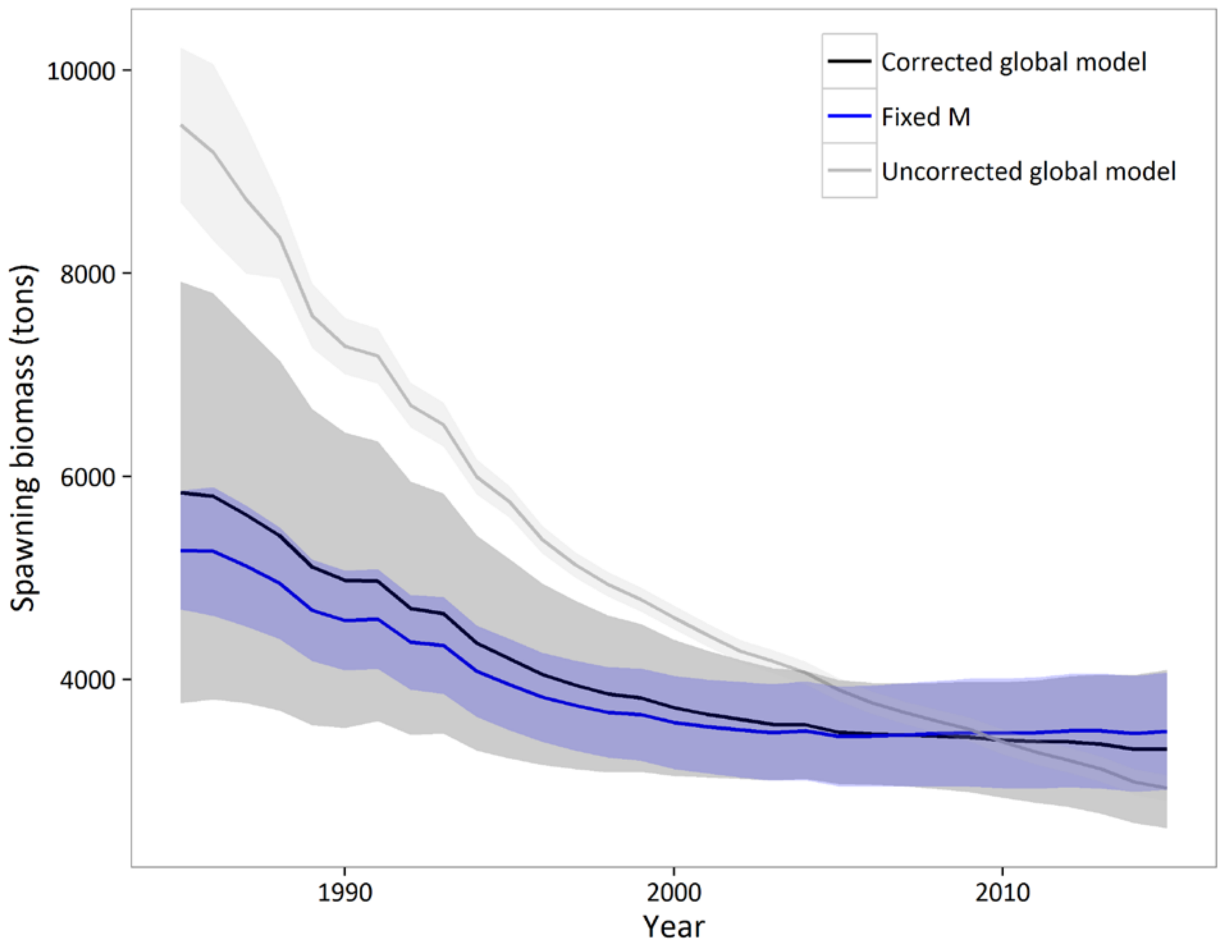


Figure 5. Model estimates of total spawning biomass with +/- two standard deviations.

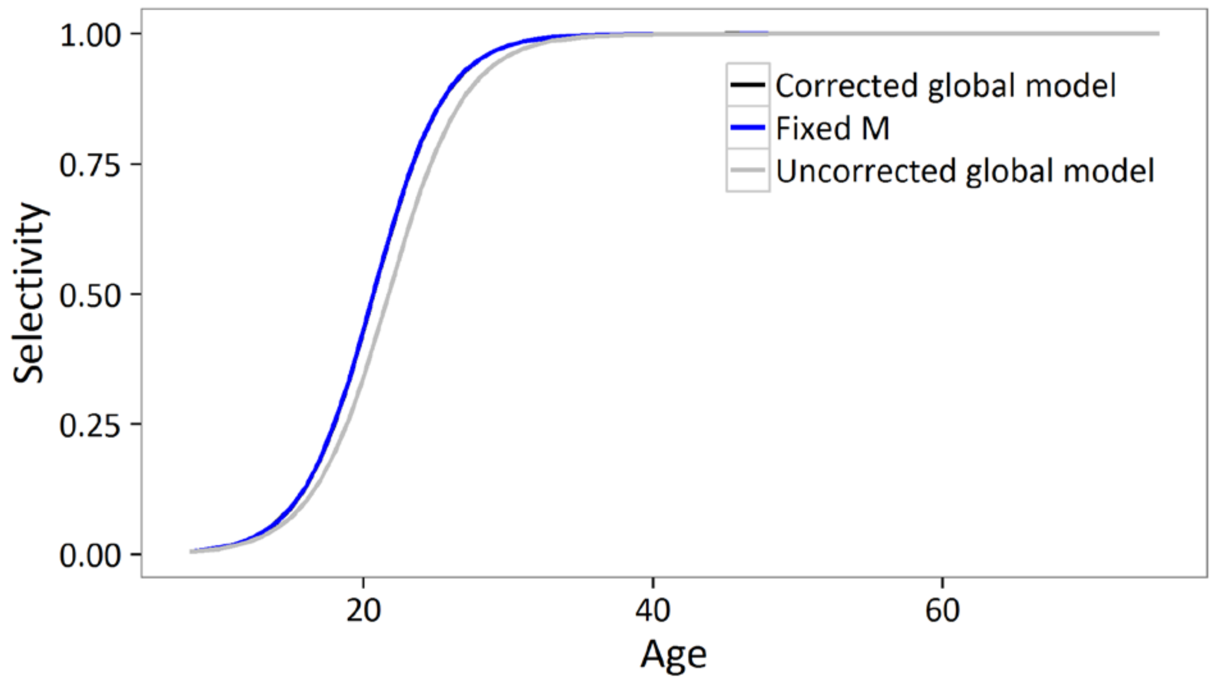


Figure 6. Directed commercial fishery selectivity curves

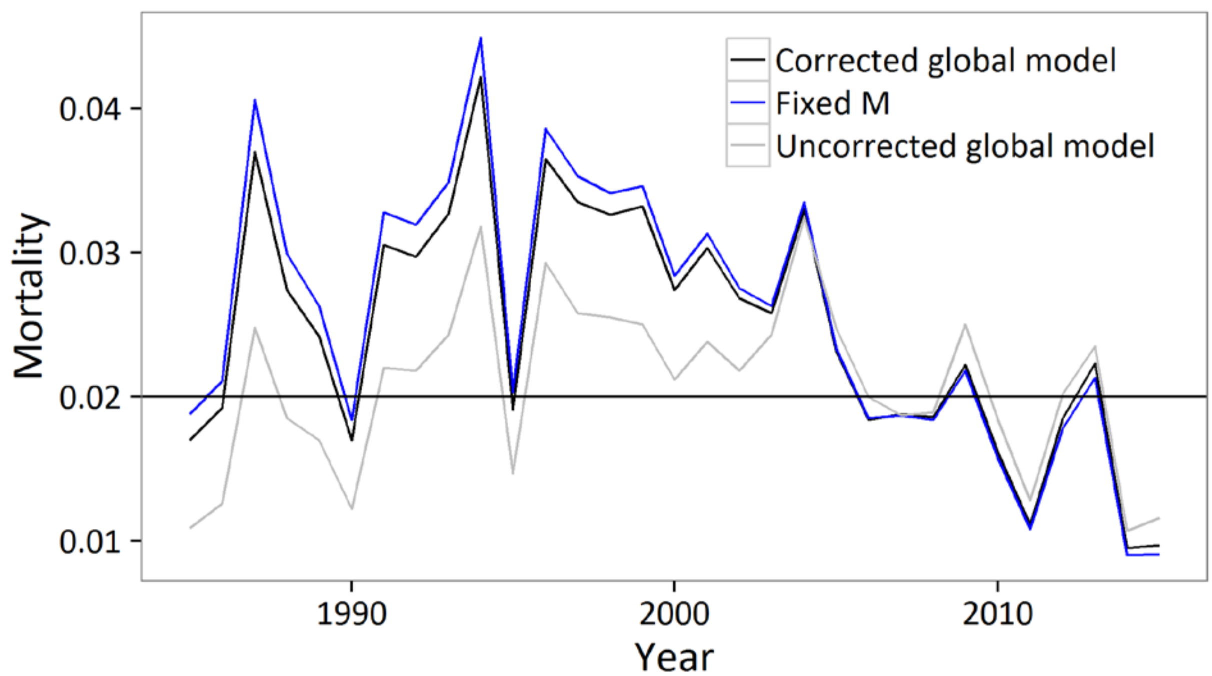


Figure 7. Full-recruitment fishing mortality with vertical line at currently implemented F = 0.02

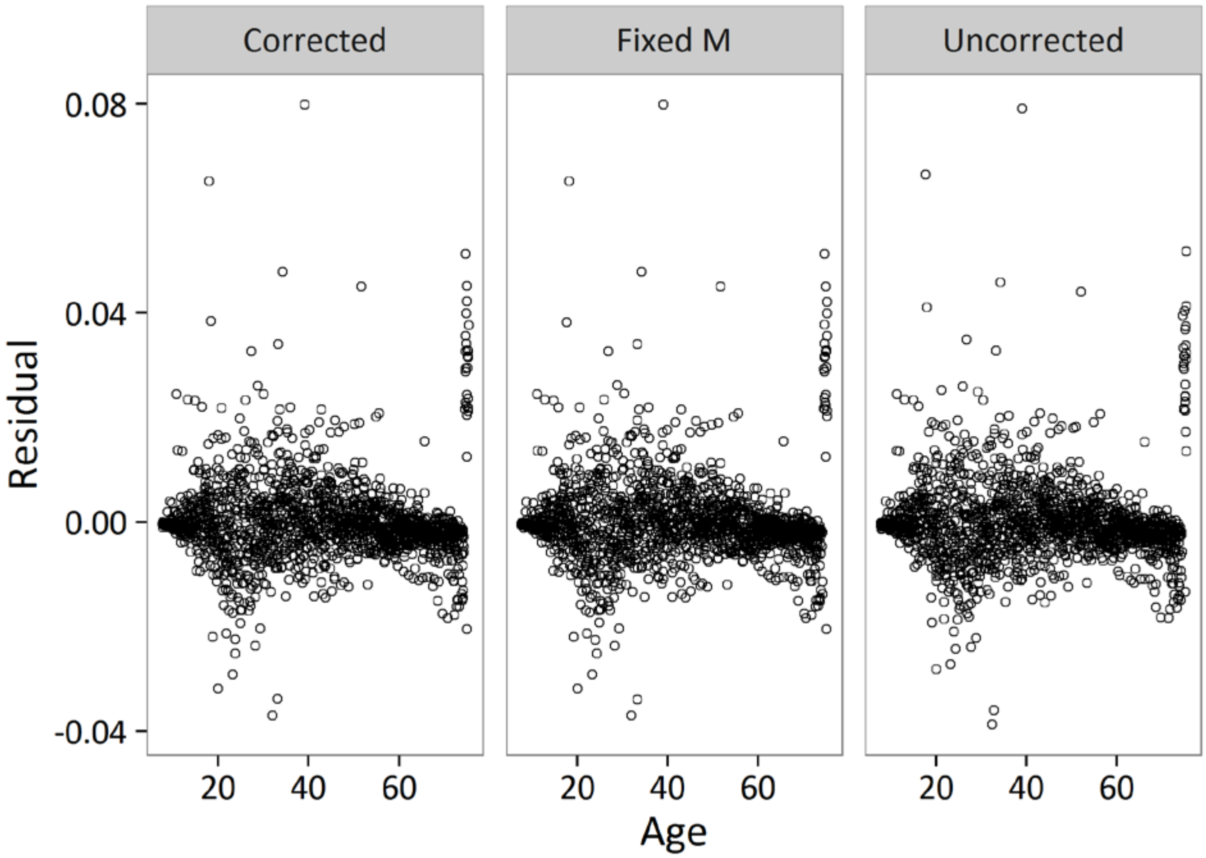
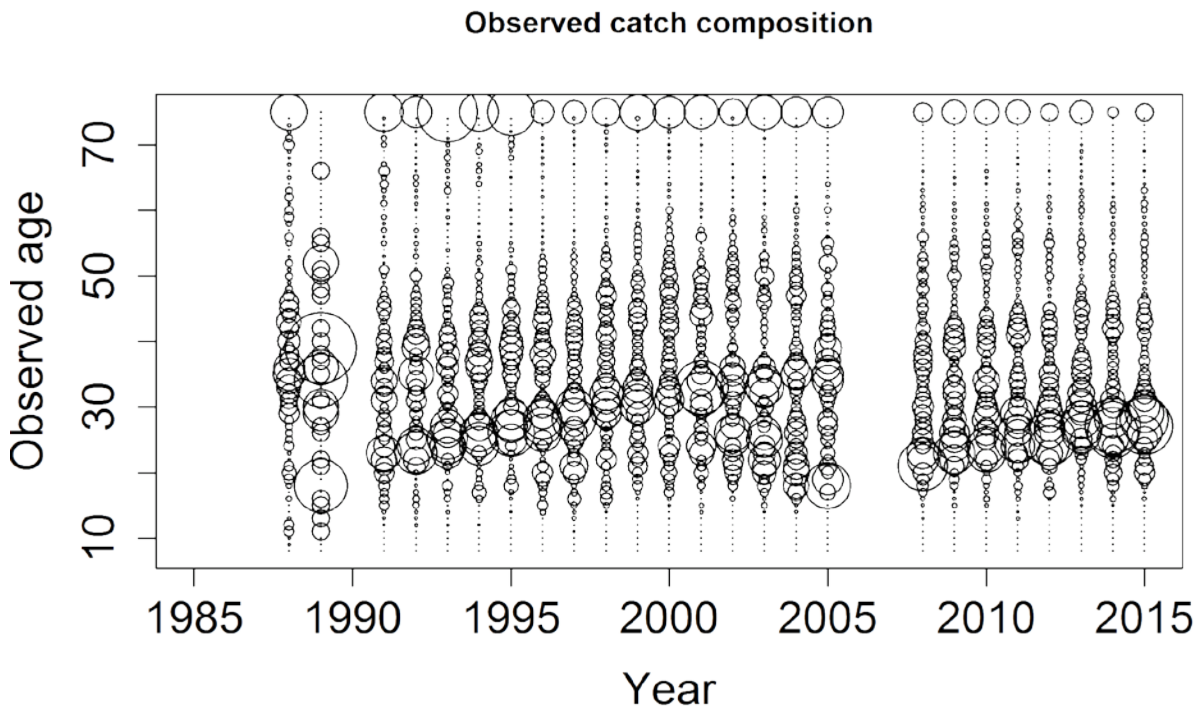


Figure 8. Commercial catch age composition residuals (observed - predicted).



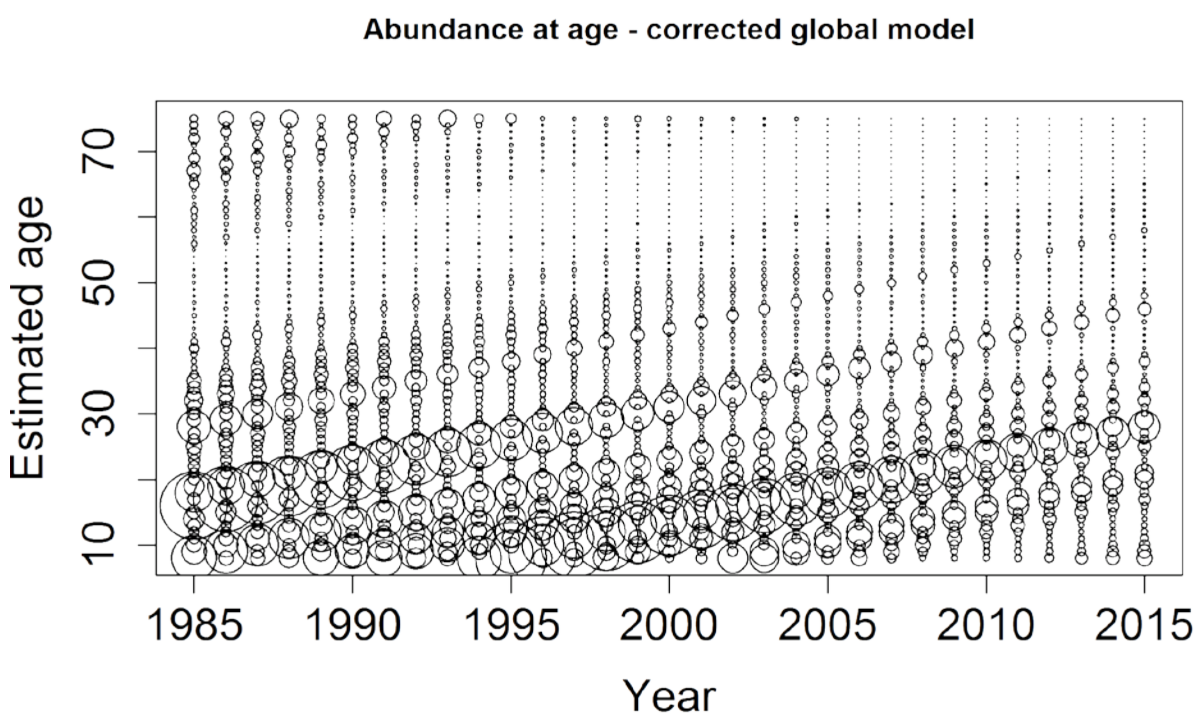
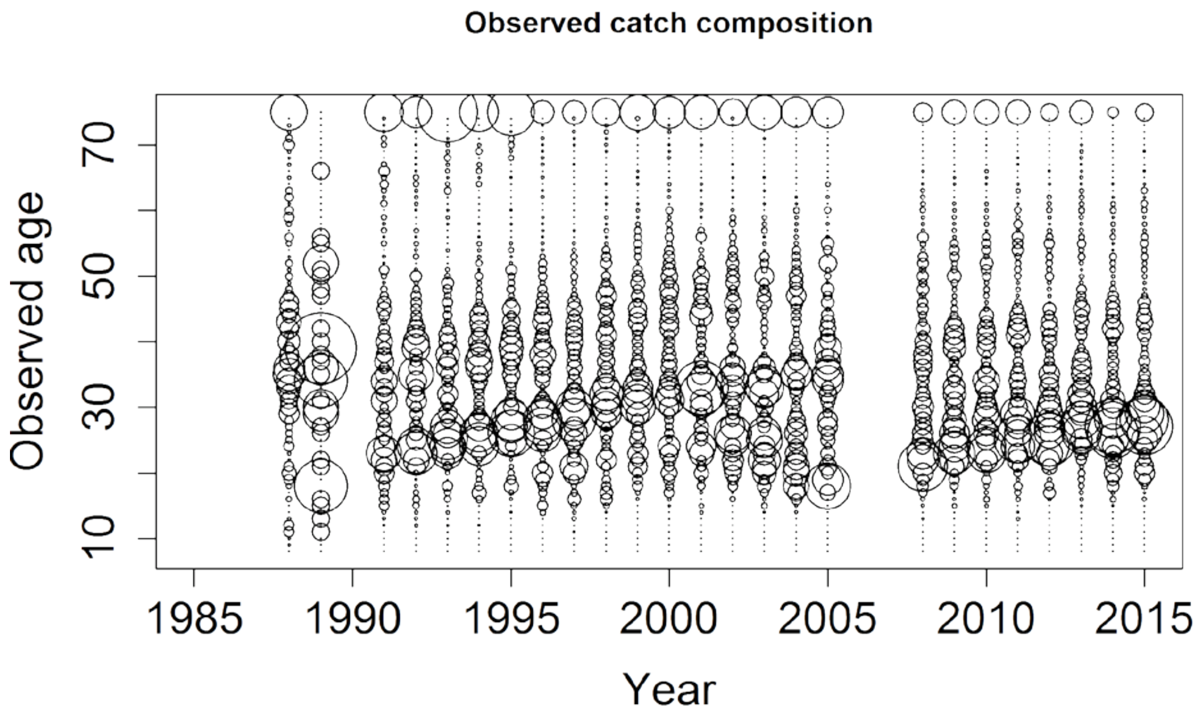


Figure 9. Abundance at age and observed catch at age for the Corrected Global Model.



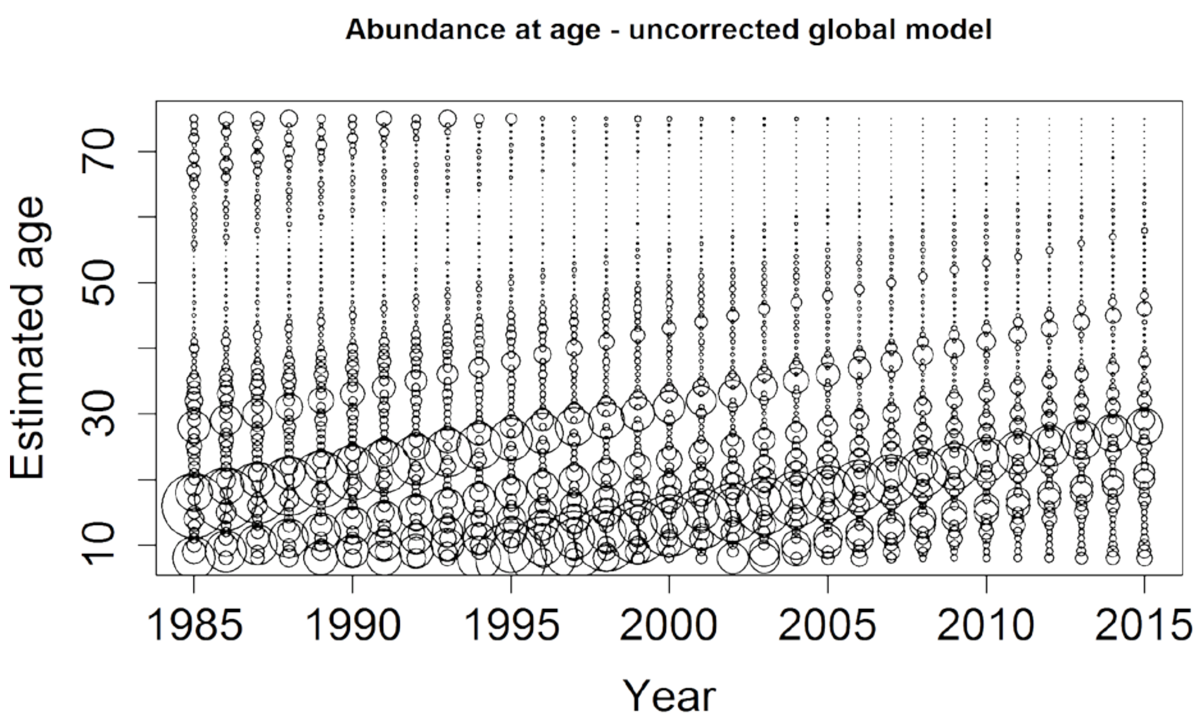


Figure 10. Abundance at age and observed catch at age for the Fixed M model.

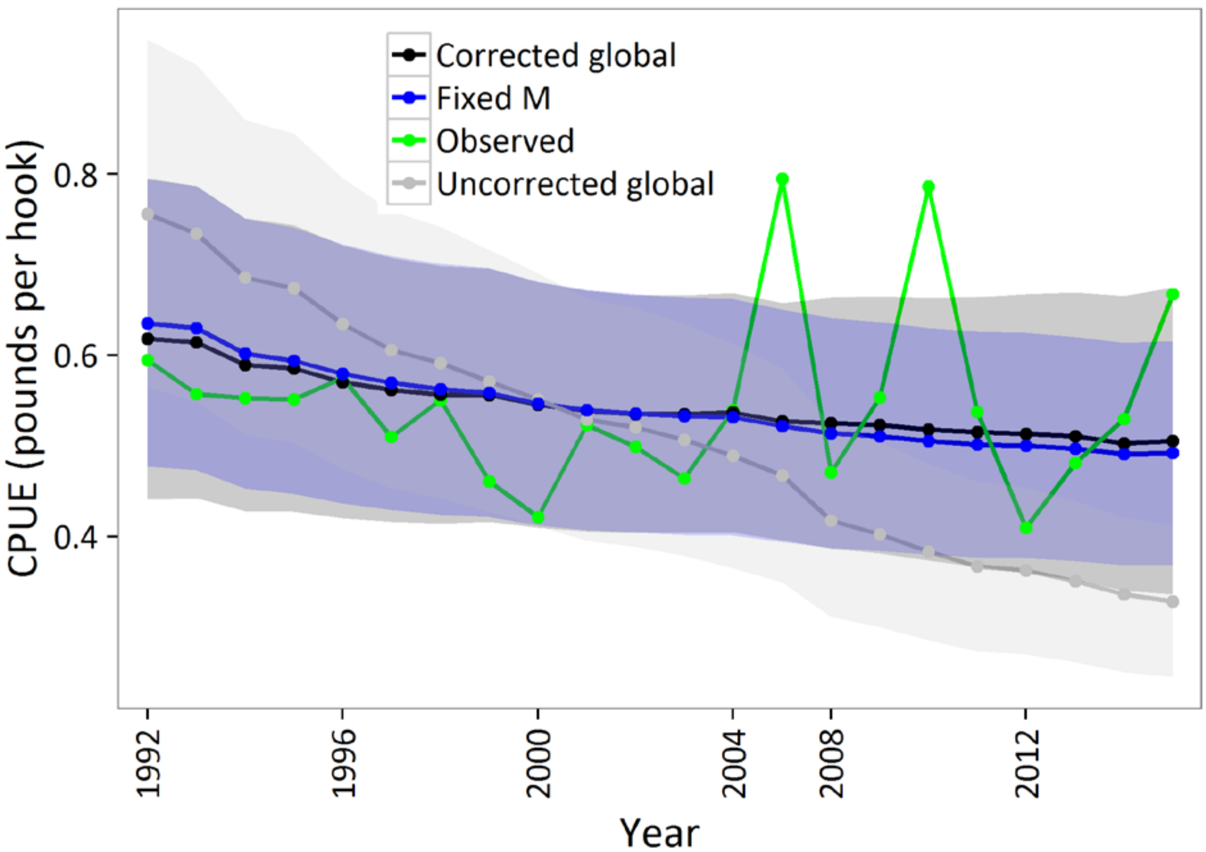


Figure 11. Model fits to commercial fishery CPUE with 95% confidence intervals.

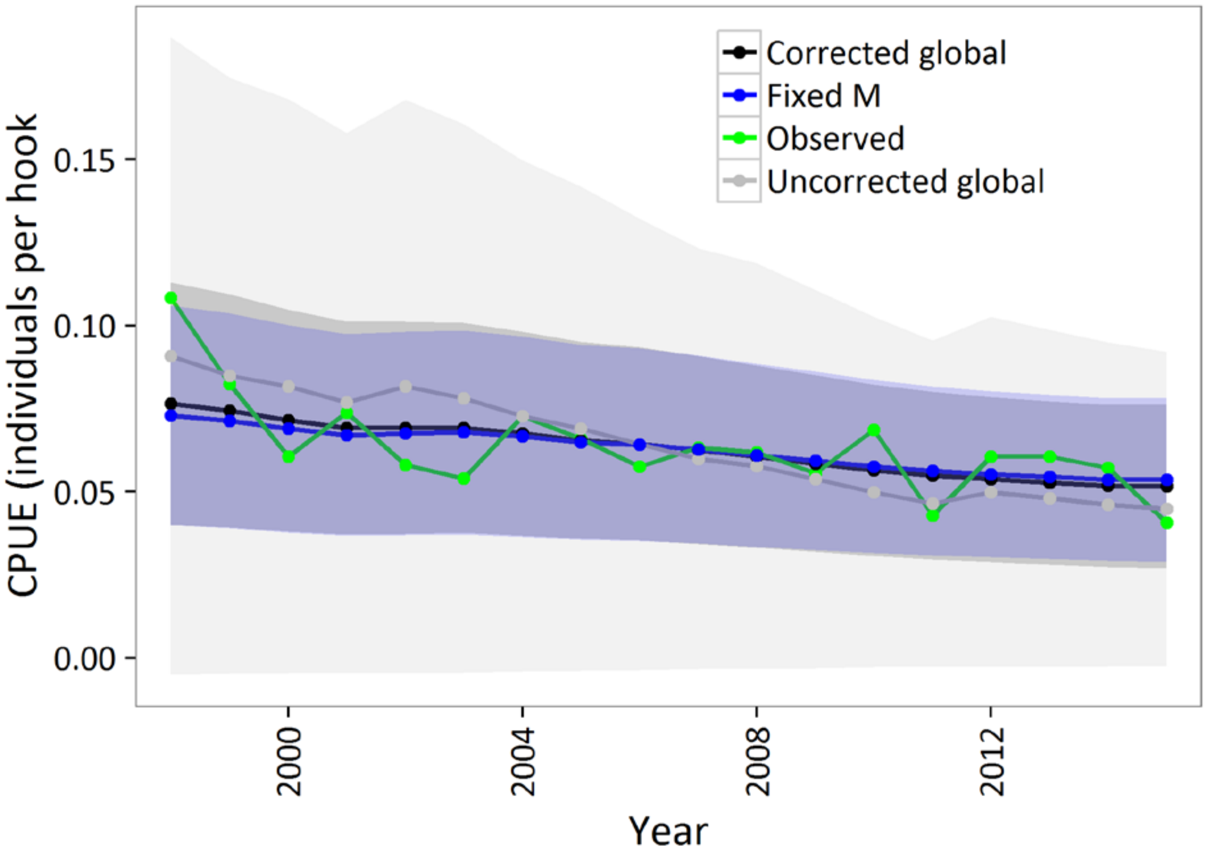


Figure 12. Model fits to International Pacific Halibut Commission longline survey CPUE with 95% confidence intervals.

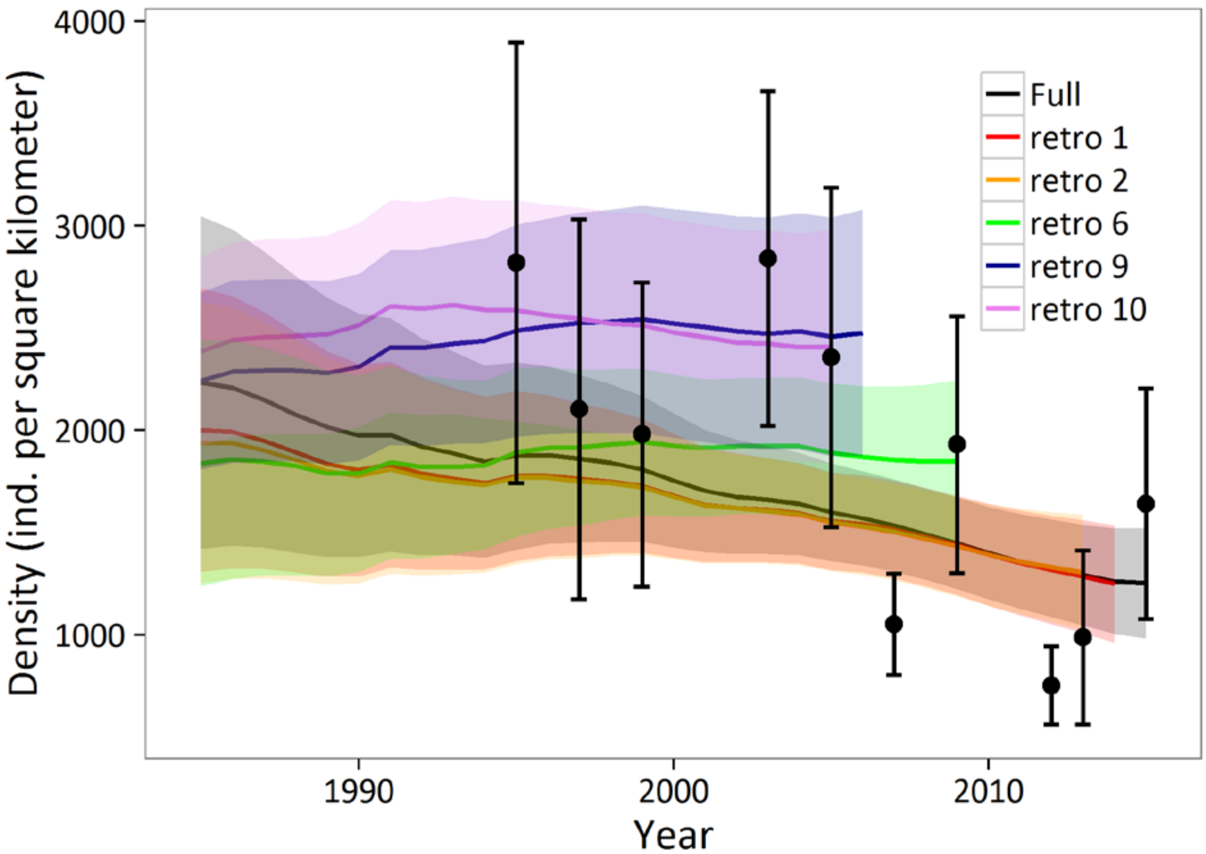


Figure 13. Retrospective estimates of density +/- two standard deviations from the Corrected Global model.

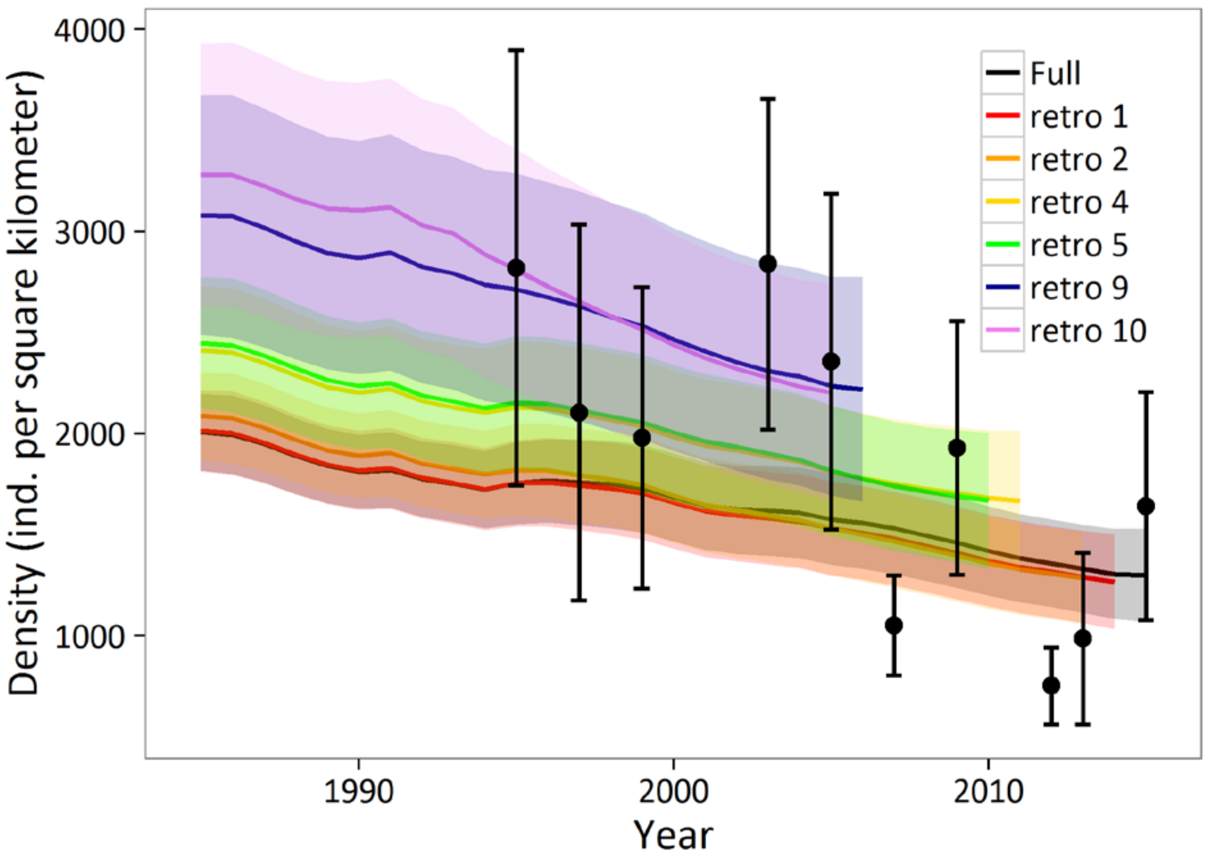


Figure 14. Retrospective estimates of density +/- two standard deviations from the Fixed M model.

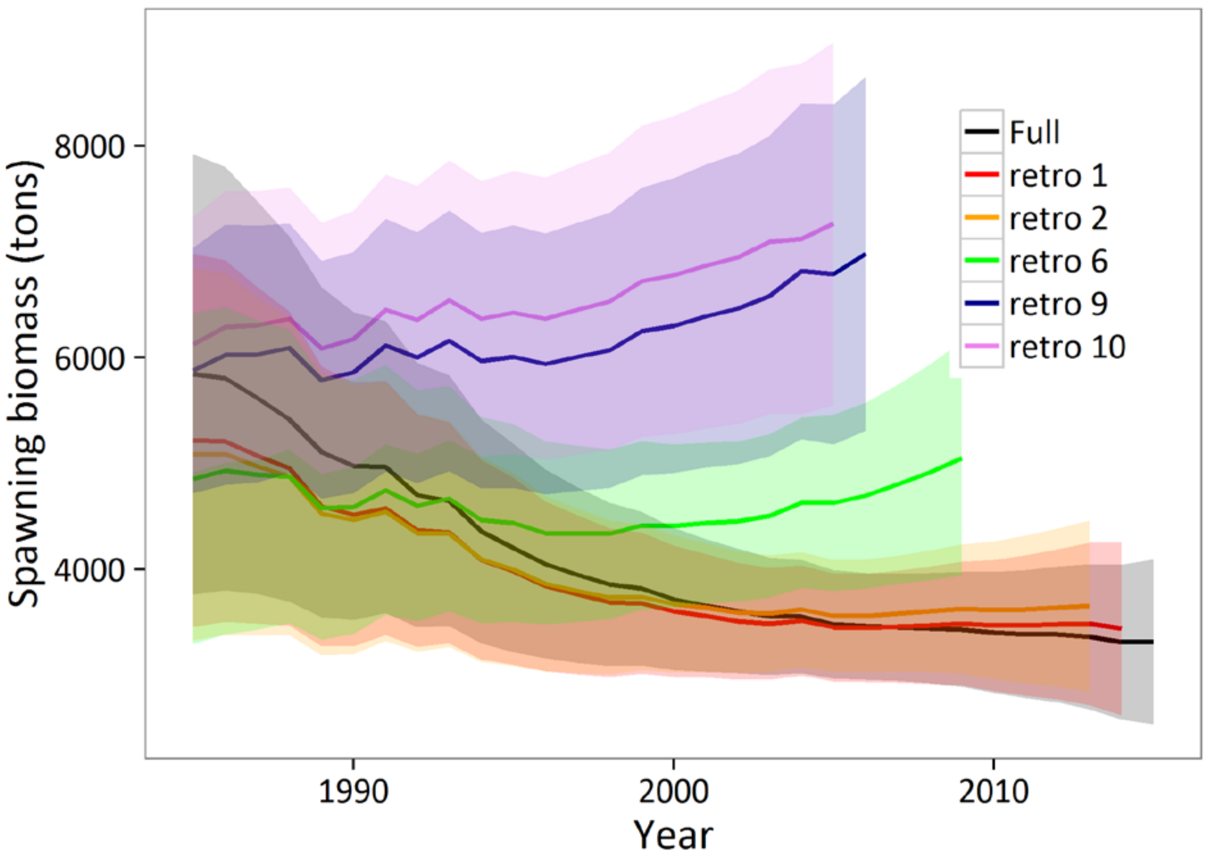


Figure 15. Retrospective estimates of spawning biomass +/- two standard deviations from the Corrected Global model.

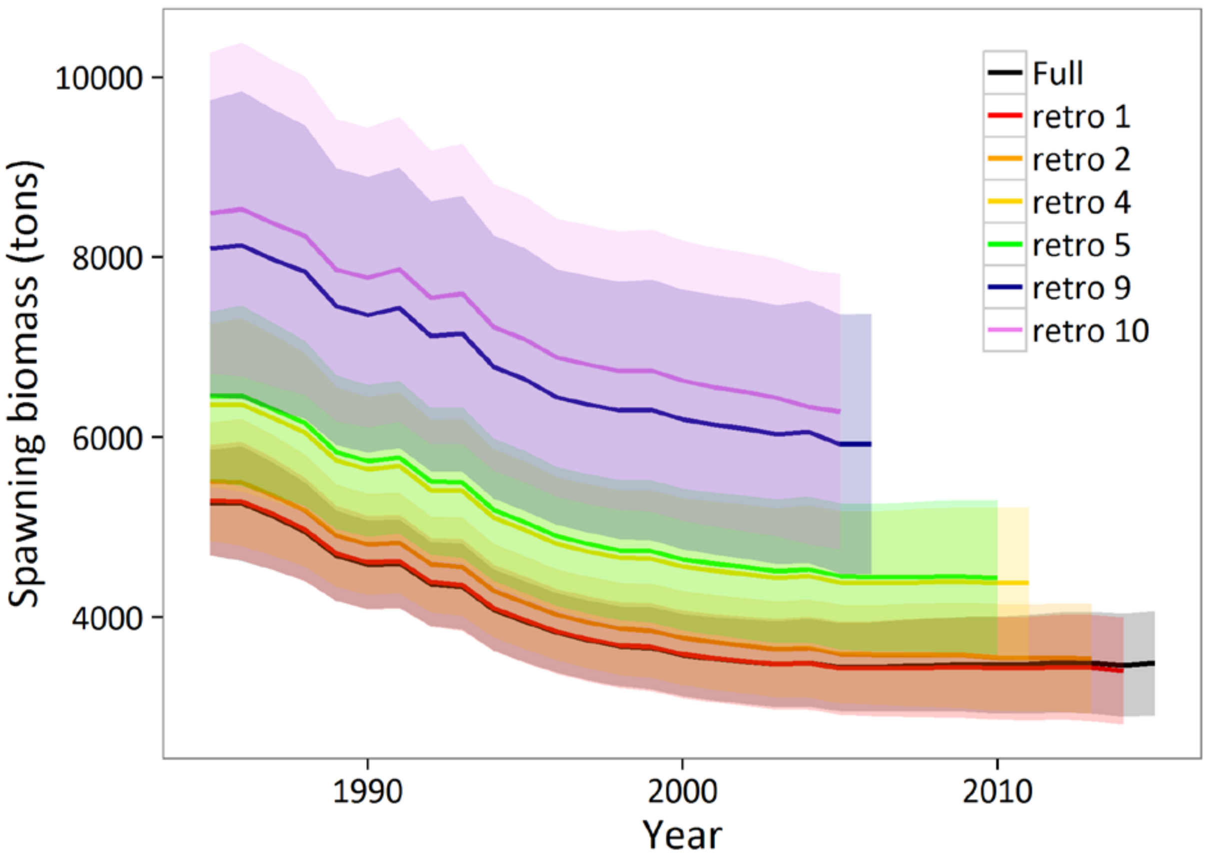


Figure 16. Retrospective estimates of spawning biomass +/- two standard deviations from the Fixed M model.

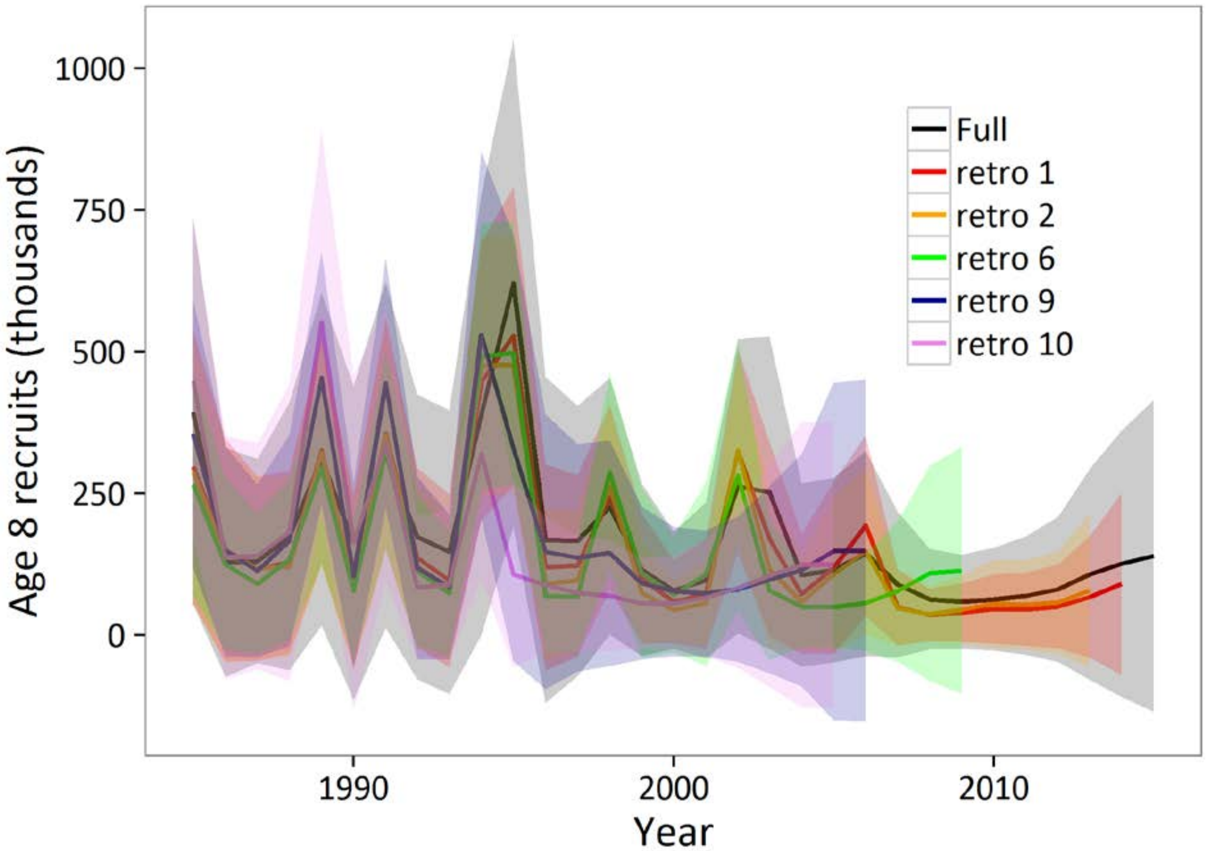


Figure 17. Retrospective estimates of age 8 recruitment +/- two standard deviations from the Corrected Global model.

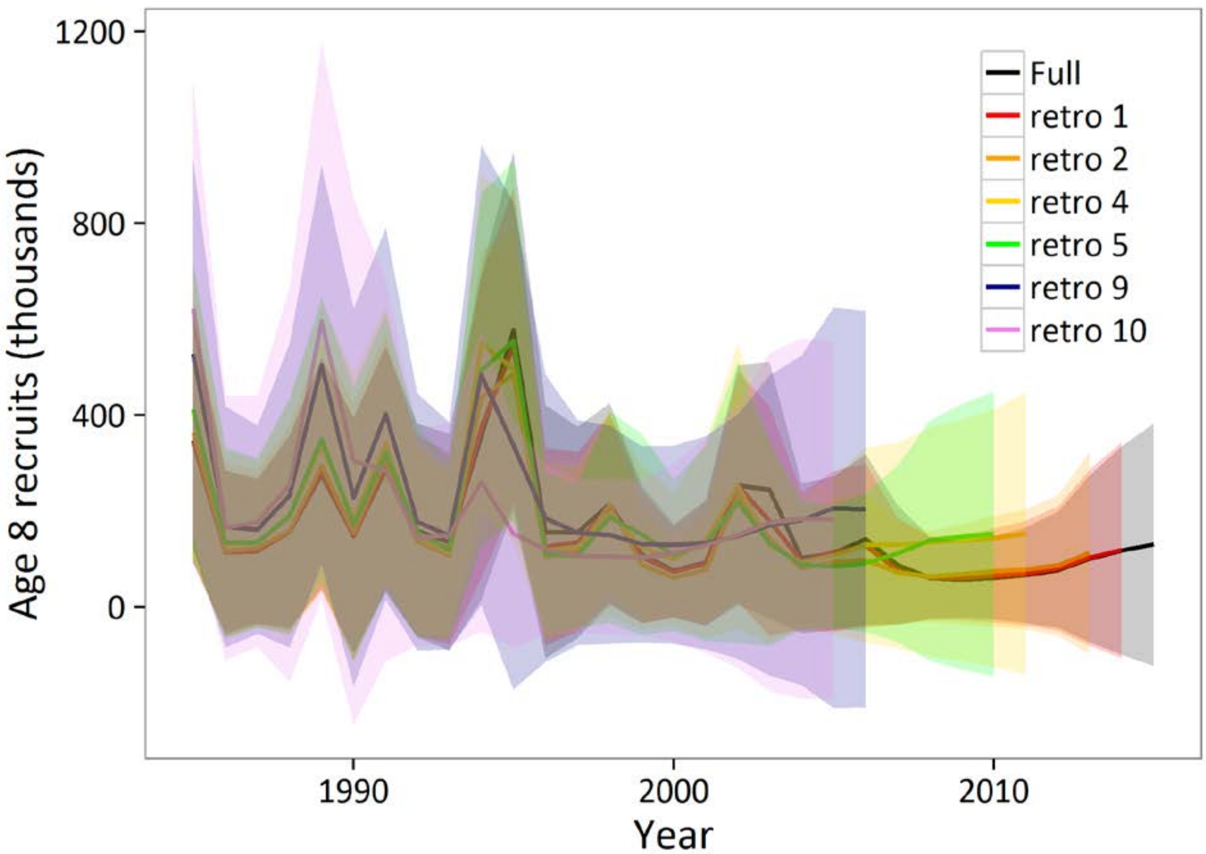


Figure 18. Retrospective estimates of age 8 recruitment +/- two standard deviations from the Fixed M model.

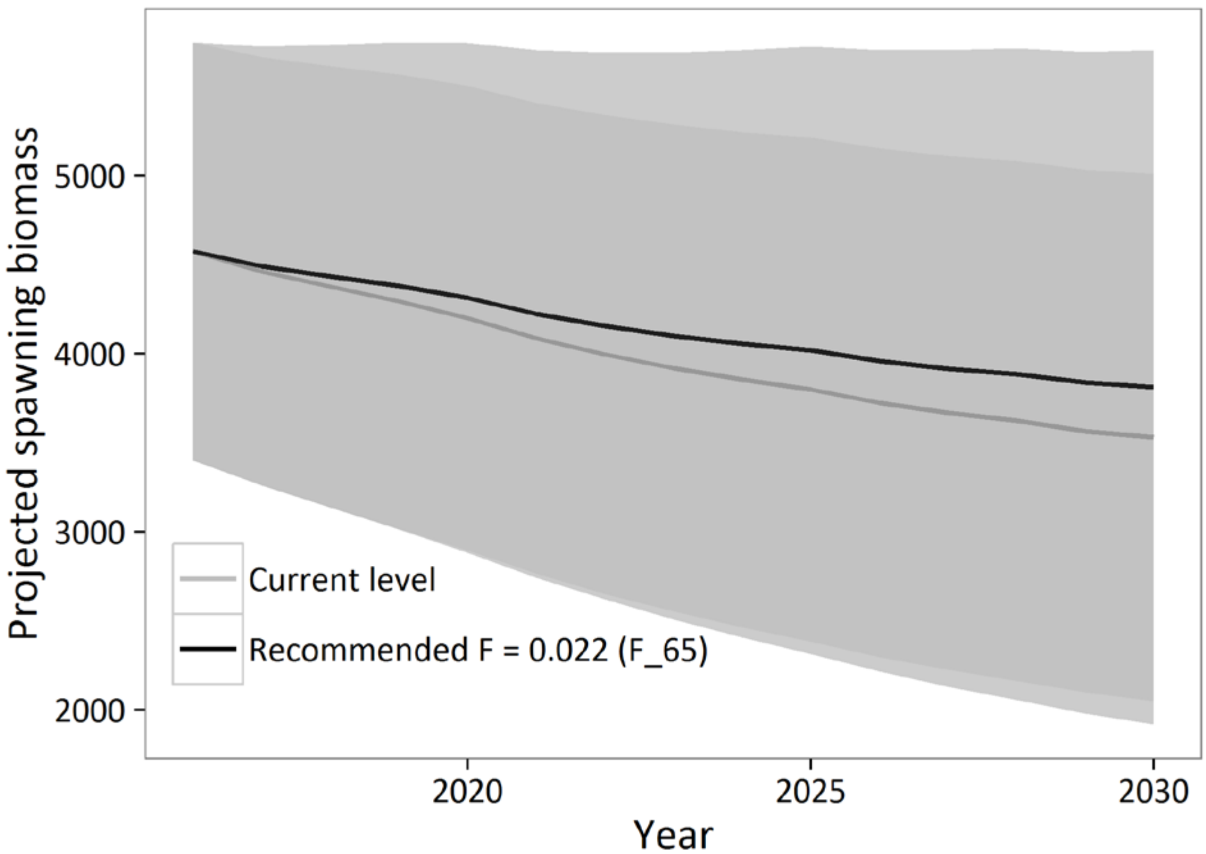


Figure 19. Projections of total biomass, 2016 - 2030, +/- two standard deviations, relative to the current removal level and the recommended harvest level.

BOX 1: Model parameters and quantities for each region

y	Year
a	Age classes
w_a	Vector of estimated weight-at-age, $a_0 \to a_+$; model input
mat_a	Vector of estimated maturity-at-age, $a_0 \to a_+$; model input
a_0	Age at model recruitment (8)
a_+	Plus class (ages 68+)
μ_r	Mean annual recruitment
μ_f	Mean annual full-recruitment fishing mortality (log)
ϕf_y	Annual fishing mortality deviation for fishery and bycatch removals
ϕs_y	Annual fishing mortality deviation for recreational removals
τ_y	Annual recruitment deviation ~ (0, σ_r)
σ_r	Recruitment standard deviation
fs_a	Vector of selectivities-at-age for all fishery removals, $a_0 \to a_+$;
M	Natural mortality
$F_{y,a}$	Fishing mortality by year y and age a $F_{y,a} = fs_a e^{(\mu_f + \phi f_y + \phi s_y)}$
$Z_{y,a}$	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 submersible /ROV survey
$s_{y,a}^{m\_sp}$	Survival by year and age at the spawning month m_sp
$T_{a,a'}$	Aging-error matrix

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 yelloweye fishery and commercial longline Pacific halibut incidental catch (combined), and recreational removals)

$$\hat{D}_y = \sum_a \frac{N_{y,a} * s_{t,a}^{m\_s} * morph_a}{km^2}$$

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

$$\mathrm{CPUE}_y = qB_y$$

CPUE for the directed fishery

$$\mathrm{CPUE}_{ipch\_y} = q_{iphc} N_y$$

CPUE for the IPHC longline survey

Start year

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

Number at age of recruitment (8)
Number at ages between recruitment and plus class
Number in plus class (75+)

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 (75+)

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

Annual female spawning biomass

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

Selectivity (asymptotic)

$$f_a = \frac{1}{1 + e^{\alpha*(age-\beta)}} * 1 - \frac{1}{1 + e^{\delta*(age-\gamma)}}$$

Selectivity (dome-shaped)

BOX 3: Likelihood components

Combined commercial catch and halibut longline fishery incidental catch; recreational catch

$$L = 0.5\ln(2\pi) + \ln(\sigma_{\text{catch}}) + 0.5\frac{(\ln(obs\_catch) - \ln(pred\_catch))^2}{2\sigma_{catch}^2}$$

Density

$$L = 0.5\ln(2\pi) + \ln(\sigma_{\ln(density)}) + 0.5\frac{(\ln(obs\_density) - \ln(pred\_density))^2}{2(\sigma_{\ln(density)}^2)}$$

Commercial CPUE

$$L = 0.5\ln(2\pi) + \ln(\sigma_{CPUE}) + 0.5\frac{((obs\_CPUE) - (pred\_CPUE))^2}{2(\sigma_{\text{CPUE}}^2)}$$

IPHC survey CPUE

$$L = 0.5\ln(2\pi) + \ln(\sigma_{CPUE}) + 0.5\frac{(\ln(obs\_CPUE) - \ln(pred\_CPUE))^2}{2(\sigma_{\text{CPUE}}^2)}$$

Fishery age composition (*n* = sample size)

$$L = \text{n} * \sum_{\text{a,t}} p_{a,t}\ln(\hat{p}_{a,t})$$

BOX 4 Penalties

Penalty for year 1 abundance deviations

$$P_1 = 0.5\frac{(y1_{devs} + \sigma_{y1}^2)^2}{2\sigma_{y1}^2} + number\_of\_ages * \ln(\sigma_{y1})$$

Penalty on recruitment deviations

$$P_2 = 0.5\frac{(rec_{devs} + \sigma_r^2)^2}{2\sigma_r^2} + number\_of\_years * \ln(\sigma_r)$$

Penalty on full-recruitment fishing mortality *F* deviations

$$P_3 = 0.5\ln(2\pi) + \ln(\sigma_F) + 0.5\frac{(F_{devs})^2}{2\sigma_F^2}$$

Penalty on natural mortality parameter (not present in Fixed M model)

$$P_4 = 0.5\ln(2\pi) + \ln(\sigma_M) + 0.5\frac{(M - (\log(0.026))^2}{2\sigma_M^2}$$

Penalty on average *F* parameter

$$P_5 = 0.5\ln(2\pi) + \ln(\sigma_F) + 0.5\frac{(F - (\log(0.02))^2}{2\sigma_F^2}$$

Penalty on average recruitment parameter

$$P_6 = 0.5\ln(2\pi) + \ln(\sigma_R) + 0.5\frac{(Rec - (\log(4))^2}{2\sigma_R^2}$$

Penalty on average year 1 abundance parameter

$$P_7 = 0.5\ln(2\pi) + \ln(\sigma_N) + 0.5\frac{(N - (\log(4))^2}{2\sigma_N^2}$$