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Arrowtooth Flounder (*Atheresthes stomias*) Stock Assessment for the West Coast of British Columbia

Chris J. Grandin and Robyn E. Forrest

Pacific Biological Station
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Arrowtooth Flounder (*Atheresthes stomias*, Turbot) are an important component of the bottom trawl fishery in British Columbia. They are managed as a coastwide stock, with a TAC of 15,000 t and catch of 10,679 t in 2014. Prior to the introduction of freezer trawlers in the mid-2000s, most of the historical catch of Arrowtooth Flounder is understood to have been discarded at sea. This was largely due to proteolysis, which occurs in the muscle tissue of this species a short time after it is caught, making the flesh unpalatable. In the past five years, markets have been established for fillets that have been frozen at sea, and the freezer trawl fleet has taken an increasing proportion of the coastwide catch.

This assessment fits a female only Bayesian age-structured model to catch, survey and age-composition data from the years 1996-2014, for management areas 3CD (West Coast Vancouver Island), 5AB (Queen Charlotte Sound), 5CD (Hecate Strait), and 5E (West Coast Haida Gwaii). Catch data prior to the introduction of at-sea observers in 1996 were considered too unreliable for inclusion in the assessment due to unknown quantities of discarding at sea.

The Reference Case model presented in this assessment estimates the female spawning biomass to have been on a flat to increasing trajectory since 1996, consistent with the catch and survey data. A set of sensitivity analyses was done to test the effects of fixed parameters and assumed prior probability distributions on model outcomes. In all scenarios, there was strong confounding among parameters representing productivity and scale of the population, indicating that there was limited information in the short time series of available data to resolve the population scale.

Management advice is provided in the form of decision tables which forecast the impacts of a range of 2015 catch levels on Arrowtooth Flounder stock status relative to these reference points. The Reference Case decision table suggests that a 2015 catch equal to any of the catch levels tested, ranging from 0 t to 30,000 t (twice the 2014 TAC), would result in a 2016 biomass above all of the candidate biomass-based reference points tested, and 2015 harvest rate below the estimated U_{MSY}. Large uncertainty in the assessment is, however emphasised. The magnitude of catch and discards prior to 1996 is a major source of uncertainty in this assessment that could provide critical information about the scale and productivity of this stock. Ageing of archived otoliths from the freezer trawl fleet is a high priority recommendation.

Évaluation du stock de plie à grande bouche (*Atheresthes stomias*) de la côte ouest de la Colombie-Britannique

RÉSUMÉ

La plie à grande bouche (*Atheresthes stomias* ou flétan noir) est une importante composante de la pêche au chalut de fond en Colombie-Britannique. Ce stock est géré pour l'ensemble de la côte et s'est vu attribuer un total autorisé des captures (TAC) de 15 000 tonnes en 2014; les prises réelles se sont élevées à 10 679 tonnes. On s'entend pour dire qu'avant l'introduction des chalutiers congélateurs au milieu des années 2000, la plupart des prises de plie à grande bouche étaient rejetées à la mer. On procédait ainsi principalement en raison de la protéolyse qui survient dans les tissus musculaires de cette espèce peu de temps après sa capture, ce qui rend la chair impropre à la consommation. Au cours des cinq dernières années, le marché de filets ayant été congelés en mer s'est développé, et la flotte de chalutiers congélateurs s'approprie maintenant une proportion croissante des prises côtières.

La présente évaluation utilise un modèle de population Bayésien structuré par âge et tenant compte des individus femelles seulement pour capturer, étudier et recueillir des données de composition selon l'âge, entre 1996 et 2014, dans les zones de gestion 3CD (côte ouest de l'île de Vancouver), 5AB (détroit de la Reine-Charlotte), 5CD (détroit d'Hécate) et 5E (côte ouest d'Haida Gwaii). Étant donné que l'on ne connaissait pas les quantités des rejets en mer, on a jugé que les données sur les prises recueillies avant l'introduction d'observateurs en mer en 1996 n'étaient pas assez fiables pour être incluses dans l'évaluation.

Selon le modèle de référence présenté dans le cadre de cette évaluation, la biomasse du stock reproducteur femelle se trouve sur une trajectoire neutre ou à la hausse depuis 1996, ce qui reflète bien les données d'enquête et de prise recueillies. Une série d'analyses de sensibilité a été effectuée pour tester les effets des paramètres fixes et de la distribution de probabilité présumée sur les résultats du modèle. Dans chacun des scénarios, on a relevé d'importants facteurs de confusion parmi les paramètres représentant la productivité et la taille de la population, indiquant que l'information tirée de la courte période de collecte de données n'était pas suffisante pour résoudre la question de la taille de la population.

Des conseils de gestion sont fournis sous forme de tables de décision qui prévoient les effets de différents niveaux de captures (en 2015) sur l'état du stock de plie à grande bouche, en fonction de ces points de référence. La table de décision du cas de référence estime qu'un niveau de captures (en 2015) égal à l'un ou l'autre des niveaux de captures testés, soit entre 0 et 30 000 tonnes (le double du TAC de 2014), engendrait une biomasse (en 2016) supérieure à tous les points de références possibles basés sur la biomasse, ainsi qu'un taux de récolte (en 2015) inférieur au rendement maximal soutenu U_{RMS}. On souligne cependant qu'il existe une grande incertitude à l'égard de l'évaluation. L'ampleur des prises et des rejets avant 1996 est l'une des principales sources d'incertitude dans la présente évaluation; s'ils existaient, ces renseignements sur les prises et les rejets pourraient en dire long sur la taille et la productivité de ce stock. La détermination de l'âge des otolithes archivés de la flotte de chalutiers congélateurs fait partie des recommandations prioritaires.

1. INTRODUCTION

Arrowtooth Flounder (*Atheresthes stomias*, Family Pleuronectidae), also commonly called Turbot, is a species of flatfish that occurs in the offshore waters of British Columbia. Arrowtooth Flounder are primarily taken by the groundfish bottom trawl fishery, although they are also encountered by hook and line fisheries, particularly those targeting Pacific Halibut (*Hippoglossus stenolepis*). Prior to the introduction of freezer trawlers in the British Columbia groundfish fleet in the mid 2000s, most of the historical catch of Arrowtooth Flounder is understood to have been discarded at sea. Proteolysis occurs in the muscle tissue of this species a short time after it is caught, making the flesh mushy and unpalatable. In the past five years, Asian markets have been established for fillets that have been frozen at sea as soon as possible after capture to reduce proteolysis. There is also an Asian market for the frills. The stock was last assessed by Fargo and Starr (2001), who presented empirical summaries of catch, commercial and survey catch-per-unit-effort (CPUE) and biological data. This stock assessment covers the combined Pacific Marine Fisheries Commission (PMFC) major areas 3CD and 5ABCDE off the west coast of British Columbia.

1.1 PURPOSE OF DOCUMENT

Arrowtooth Flounder is managed as a coastwide stock in British Columbia, with the majority of the catch coming from Pacific Marine Fisheries Commission (PMFC) major areas 3CD; West Coast Vancouver Island, 5AB; Queen Charlotte Sound and 5CD; Hecate Strait (Figures 1 and 2, Table 1). The Strait of Georgia (management area 4B) is not included in this stock assessment. The 2014 Total Allowable Catch (TAC) was 15,000 metric tonnes, the second largest groundfish TAC in British Columbia, after Pacific Hake (*Merluccius productus*).

The purpose of this stock assessment is to update management advice for Arrowtooth Flounder stocks in British Columbia, as requested by the Pacific Groundfish Management Unit (GMU). This assessment identifies reference points for Arrowtooth Flounder that are consistent with the DFO Decision-making Framework Incorporating the Precautionary Approach (DFO, 2009) and characterizes stock status relative to these reference points, using a Bayesian, age-structured stock assessment model. Management advice is provided in the form of decision tables which forecast the impacts of a range of harvest levels on Arrowtooth Flounder stock status relative to these reference points.

1.2 BIOLOGICAL BACKGROUND

Arrowtooth Flounder are distinguished by their large mouth and arrow-shaped teeth, for which the species is named (Hart, 1973). Their distribution ranges from Baja California to the eastern Bering Sea (Hart, 1973). In British Columbia, the species inhabits depths from 50–900 m (Fargo and Starr, 2001).

Arrowtooth Flounder exhibit sexual dimorphism. After sexual maturity, females grow faster than males and reach a larger maximum size (Appendix A, Figure A.1). Theoretical maximum length,

L_∞, is estimated to be 60.9 cm for females and 47.8 cm for males in British Columbia, although the maximum sizes which have been observed are 73.7 cm for females and 64.5 cm for males (Figure A.1). Age-at-50%-maturity for females is thought to occur around age 5.6 y for females and 4.4 y for males. The maximum observed age is 25 y for females and 20 y for males There were few observations of fish over 20 y in the dataset, and this assessment assumes a plus group of 20 y (Figure 3).

Arrowtooth Flounder are batch spawners with peak spawning occurring at depths deeper than 350 m in the fall and winter months, although the timing of spawning may vary interannually (Rickey, 1995). The species produces pelagic eggs, followed by a pelagic larval stage that may last several months (Rickey, 1995). Fecundity of this species is poorly understood (Cosimo, 1998). One and two year old fish occupy shallower depths than adults, but by the age of three or four years old, they are generally found in deeper water with adults (Fargo and Starr, 2001). Arrowtooth Flounder appear to occupy separate spawning (winter) and feeding (summer) areas, and undergo seasonal bathymetric movement from shallower to deeper water in the fall and winter (Fargo and Starr, 2001).

Juvenile Arrowtooth Flounder feed primarily on mobile prey such as cumaceans, carideans and amphipods. Adults are piscivorous and cannibalistic, feeding on Pacific Herring (*Clupea pallasii*), juvenile Walleye Pollock (*Theragra chalcogramma*) and Pacific Sandlance (*Ammodytes hexapterus*), among other species (Fargo et al., 1981).

1.3 FISHERY AND MANAGEMENT HISTORY

Arrowtooth Flounder has been managed on a status-quo basis in recent years, with an annual allocation of 15,000 t for the groundfish trawl fleet since 2006. Before that time, there were no limits on catches or discards of Arrowtooth Flounder. The areas of high CPUE in Dixon Entrance seen in Figure 1 are mainly from this test fishery. The increased catch can be seen in Figure 2, especially in the northern areas; 5ABCDE (Panel (c) of Figure 2). Unfortunately, due to rapid proteolysis of the flesh, the fishery was not profitable and a large drop in catch is evident after 2005 (Figure 2) when the test fishery ended abruptly. There has also been a recent increase in catch from 2010–2014, which is due to four freezer trawlers joining the fleet. With their ability to freeze the catch a short time after capture, the freezer trawlers have accessed wider markets than the smaller shoreside boats. The freezer trawlers' priority catch is Pacific Hake (Taylor et al., 2015), but when hake become scarce on the fishing grounds the freezer trawlers have the ability to easily switch gears to bottom trawl to fish for Arrowtooth Flounder. Since their introduction, freezer trawlers have taken an increasing proportion of the total Arrowtooth Flounder catch, increasing from 7.0% in 2005 to 65.8% and 79.8% in 2013 and 2014, respectively.

Prior to the introduction of freezer trawlers, most of the historical catch of Arrowtooth Flounder is understood to have been discarded at sea in large quantities due to proteolysis of the flesh if catches were not landed and frozen quickly after capture. Prior to the introduction of 100% at-sea observer coverage in the British Columbia groundfish fleet in 1996, reporting of Arrowtooth Flounder discards in fishery logbooks was voluntary. Since Arrowtooth Flounder were not managed with quotas before 1996, there was little incentive for skippers to record discards. Therefore the quantity of discards in the pre-1996 period is highly uncertain.

Any foreign or U.S. catches were taken outside Canadian management zones and not used in this assessment.

1.4 ASSESSMENT HISTORY

The coastwide Arrowtooth Flounder stock was last assessed by Fargo and Starr (2001), who presented summaries of catch, commercial and survey catch-pre-unit-of-effort (CPUE) analyses, and biological data. They reported commercial and survey CPUE indices that showed cycles but no trends. They also reported lack of trend in size and age composition data, and no evidence that natural mortality had changed over time. Based on this evidence, Fargo and Starr (2001) concluded that harvest rates of Arrowtooth Flounder off the west coast of Canada were at or below sustainable levels. Prior to 2001, the stock was assessed by Fargo (1999). A formal, statistical catch-at-age model-based assessment has never previously been done in British Columbia for this species.

2. STOCK ASSESSMENT MODELLING

We applied a female-only statistical catch-at-age model in a Bayesian estimation framework to assess the coastwide stock of Arrowtooth Flounder. Analysis of the sex composition of the catch data indicated that commercial catches have been 80-90% female; see Appendix B, Table B.1.

The model was fit to catch data, four indices of abundance with associated coefficients of variation, and to age composition data from the commercial trawl fishery and three of the four research surveys. Biological parameters used in the model, including growth, weight-at-age and maturity schedules, were estimated independently (Appendix A) and input to the assessment model as fixed parameters that were assumed to remain constant over time.

Reference points based on Maximum Sustainable Yield (MSY), including the female spawning biomass (B_{MSY}) and the annual harvest rate producing MSY (U_{MSY}), were estimated, along with reference points based on estimated equilibrium unfished spawning biomass, B_0 (Section 2.2.3). Harvest decision tables (Tables 14 and 15) were created by projecting the assessment model one year into the future under a range of constant catch levels. For each level of catch, decision tables show the probability that projected spawning biomass in 2016 will be less than spawning biomass-based reference points, and the probablity that 2015 harvest rate will be greater than harvest rate-based reference points (Section 3.1).

2.1 DATA INPUTS

2.1.1 Data Sources

Data were extracted from three different databases:

1. GFBio - Biological samples and research cruise database. This data archive includes most of the groundfish specimen data collected since the 1950s. It includes data from a variety of sources (port and at-sea commercial sampling, research survey sampling), collected using a variety of sampling methods.
2. PacHarvTrawl - Canadian trawl landings, 1996 to March 31, 2007. SQL Server database, Groundfish Section, Marine Ecosystems and Aquaculture Division, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station.
3. GFFOS - Canadian trawl landings, April 1, 2007 to 2014. View of the Fisheries and Oceans Canada (DFO) Fishery Operations (FOS) database. Groundfish Section, Marine Ecosystems and Aquaculture Division, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station.

2.1.2 Catch Data

Commercial fishing data are presented in this document for the period January 1, 1996 to December 31, 2014. Landings and discards are shown in Table 1 and by area (3CD/5ABCDE) in Table 2. The current assessment fits a female-only Bayesian age-structured model to catch, survey and age-composition data from the years 1996-2014, for management areas 3CD (West Coast Vancouver Island), 5AB (Queen Charlotte Sound), 5CD (Hecate Strait), and 5E (West Coast Haida Gwaii).

Prior to the introduction of freezer trawlers into the British Columbia groundfish trawl fleet in 2005, most of the historical catch of Arrowtooth Flounder is understood to have been discarded at sea in large quantities due to flesh proteolysis, as discussed above. In many cases entire tows were discarded, precluding the use of ratio estimators or other statistical methods of estimating unobserved discards. All catch data prior to the introduction of 100% at-sea observer coverage in 1996 were therefore omitted from this assessment, on the recommendation of our industry advisors and technical working group. See Section 4. for further discussion and research recommendations.

The 1996-2014 catch time series was multiplied by the proportion female for each year (calculated in Appendix B), to give a female-only catch time series. This catch time series was used in the Reference Case and all sensitivity models presented in this document.

2.1.3 Abundance Indices

Four sets of fishery independent survey indices of abundance were used in this assessment. Each series was multiplied by its respective proportion female (calculated in Appendix B), to give female-only indices of abundance (Table 3). The surveys used in this assessment were:

1. The Hecate Strait Multispecies Assemblage Survey (HSMAS)
2. The Hecate Strait Synoptic Survey (HSSS)
3. The Queen Charlotte Sound Synoptic Survey (QCSSS)
4. The West Coast Vancouver Island Synoptic Survey (WCVISS)

Hecate Strait Multispecies Assemblage Survey

A series of multi-species groundfish bottom trawl surveys were conducted in Hecate Strait in May-June of 1984, 1987, 1989, 1991, 1993, 1995, 1996, 1998, 2000, 2002, and 2003 (Westrheim et al., 1984; Fargo et al., 1984, 1988; Wilson et al., 1991; Hand et al., 1994; Workman et al., 1996, 1997; Choromanski et al., 2002, 2005). The present assessment only utilizes observations from 1996 until the survey ended in 2003.

The original design of this survey assigned fishing locations by 10 fathom depth intervals within a 10 nautical mile grid of Hecate Strait. The survey was post-stratified using 10 fathom depth intervals for the entire survey area, thereby treating each depth interval as a single stratum. The Hecate Strait Assemblage survey was designed as a systematic fixed-station survey. Despite attempts to apply post-sampling stratification, this approach had high survey variance (Sinclair et al., 2007). In 2004 the Hecate Strait Assemblage survey was discontinued in favour of the Hecate Strait Synoptic survey (described below).

Hecate Strait Synoptic Survey

The Hecate Strait synoptic groundfish bottom trawl survey is part of a coordinated set of long-term surveys that together cover the continental shelf and upper slope of most of the British Columbia coast. The Queen Charlotte Sound and West Coast Vancouver Island synoptic surveys described below are part of the same set of surveys. All the synoptic surveys follow a random depth stratified design. The relative allocation of blocks amongst depth strata was determined by modelling the expected catches of groundfish and determining the target number of tows per stratum that would provide the most precise catch rate data for as many species as possible.

The Hecate Strait synoptic survey has been conducted during May–June, in odd years starting in 2005. The survey area is divided into 2 km by 2 km blocks and each block is assigned one of four depth strata based on the average bottom depth in the block. The four depth strata for the Hecate Strait survey are 10–70 m, 70–130 m, 130–220 m, and 220–500 m. Each year blocks are randomly selected within each depth strata.

Queen Charlotte Sound Synoptic Survey

The Queen Charlotte Sound survey has been conducted in July–August in 2003, 2004 and in odd years starting in 2005. The survey area is divided into 2 km by 2 km blocks and each block is assigned one of four depth strata based on the average bottom depth in the block. The four depth strata for the QCS survey are 50–125 m, 125–200 m, 200–330 m, and 330–500 m. Each year blocks are randomly selected within each depth strata. In addition, for the purposes of allocating blocks, the QCS survey is divided into northern and southern spatial strata.

West Coast Vancouver Island Synoptic Survey

The West Coast Vancouver Island Synoptic Survey has been conducted in May–June in even years starting in 2004. The survey area is divided into 2 km by 2 km blocks and each block is assigned one of four depth strata based on the average bottom depth in the block. The four depth strata for the WCVI survey are 50–125 m, 125–200 m, 200–330 m, and 330–500 m. Each year blocks are randomly selected within each depth strata. In addition, for the purposes of allocating blocks, the WCVI survey is divided into northern and southern spatial strata.

Swept area analysis for Indices of abundance
For all surveys, the swept area estimate of biomass in year y was obtained by summing the product of the CPUE and the area surveyed across the surveyed strata i:

$$B_y = \sum_{i=1}^{k} C_{y_i} A_i = \sum_{i=1}^{k} B_{y_i} \tag{1}$$

where C_{y_i} is the mean CPUE density (kg/km^2) for species s in stratum i, A_i is the area of stratum i, B_{y_i} is the biomass of Arrowtooth Flounder in stratum i for year y, and k is the number of strata.

CPUE (C_{y_i}) for Arrowtooth Flounder in stratum i for year y was calculated as a density in kg/km^2 by:

$$C_{y_i} = \frac{1}{n_{y_i}} \sum_{j=1}^{n_{y_i}} \frac{W_{y_i,j}}{D_{y_i,j} w_{y_i,j}} \tag{2}$$

where $W_{y_i,j}$ is the catch weight in kg for Arrowtooth Flounder in stratum i, year y, and tow j, $D_{y_i,j}$ is the distance travelled in km for tow j in stratum i and year y, $w_{y_i,j}$ is the net opening in km by tow j, stratum i, and year y, and n_{y_i} is the number of tows in stratum i.

The variance of the survey biomass estimate V_y for Arrowtooth Flounder in year y is calculated in kg^2 as follows:

$$V_y = \sum_{i=1}^{k} \frac{\sigma_{y_i}^2 A_i^2}{n_{y_i}} = \sum_{i=1}^{k} V_{y_i} \tag{3}$$

where $\sigma_{y_i}^2$ is the variance of the CPUE in kg^2/km^4 for year y in stratum i, V_{y_i} is the variance of Arrowtooth Flounder in stratum i for year y, where $\sigma_{y_i}^2$ was obtained from bootstrapped samples (see below).

The CV for Arrowtooth Flounder for each year y was calculated as follows:

$$(CV)_y = \frac{{V_y}^{1/2}}{B_y} \tag{4}$$

where $(CV)_y$ is the CV for year y.

One thousand bootstrap replicates with replacement were constructed from the survey data to estimate bias-corrected 95% confidence regions for each survey year (Efron, 1982). Mean survey biomass estimates obtained from Eq. 1 with CVs (Eq. 4) are presented for the four fishery-independent surveys in Table 3.

Fishery CPUE was not used as an index of abundance due to the behaviour of the fishery. Arrowtooth Flounder are targeted on known grounds, and the location information is shared among fishermen, so there is a bias towards a high CPUE.

2.1.4 Age Data

Extensive ageing was done for this assessment including 4,787 otoliths aged for years spanning 1996–2014, from commercial bottom trawl samples as well as the four research surveys' samples. The samples were aged by the break-and-bake method which involves placing a large number of otoliths in a tray, baking them in a specially-designed oven, then breaking them to perform age reads. During this process, if the person ageing the otoliths finds one which is not baked enough, they will burn the otolith manually to give it the right contrast for age reading. This extra burning step makes this method equivalent to the traditional break-and-burn method in which the age-reader burns each otolith individually (S. Wischniowski, Sclerochronology Laboratory, Pacific Biological Station, Pers. Comm.).

Age composition data represented the whole coast, for the following years:

1. Commercial trawl (Figure 3): 1996–2013, all years (unsorted/discard samples only).
2. QCSSS (Figure 4): 2003, 2005, 2011, 2013.
3. HSSS (Figure 4): 2005, 2007, 2009, 2011, 2013.
4. WCVISS (Figure 4): 2004, 2006, 2008, 2010, 2012, 2014.

Age composition data were input to the assessment models as weighted proportions-at-age. Weighting was based on a stratified weighting scheme that adjusted for unequal sampling effort across spatial or temporal strata. For commercial data, these strata comprised quarterly periods within a year, while, for survey samples, the strata were defined by the survey design. A description of the methods used to calculate weighted age frequencies is given in Appendix C. This is the same method that was used in the 2014 British Columbia Rock Sole (*Lepidopsetta spp.*) assessment (Holt et al., 2014).

Ageing requests included randomly chosen samples from many vessels, including the freezer trawlers. Some of these were not aged, due to time limitations of the sclerochronology laboratory. After ageing was complete it was discovered that the freezer trawlers were under-represented in the age data. Length data for the freezer trawler and shoreside fleets were compared (Section 2.1.5, Figure 5) to check for evidence that the age data was or was not representative of both fleets.

2.1.5 Commercial length data

Length data from the freezer trawler and shoreside fleets are shown in Figure 5. These data are presented to check whether or not there is evidence for differences in the age composition of the catch in the freezer trawl fleet compared to the rest of the fleet. Since 2006, when freezer trawlers began fishing for Arrowtooth Flounder, they have taken an increasingly large proportion of the catch. However, as discussed in the previous section, it was discovered after the commercial otoliths had been processed that age data from this fleet were under-represented in the age composition data.

Females have been sampled more often than males in both fleets. This difference in sampling is due to the proportion of females in the population being higher than males (Appendix B).

Females did not vary in length significantly between the two fleets, with both having a median around 55 cm. Males had a median of around 45 cm for both fleets, except for in 2006–2007, when freezer trawler samples showed slightly larger males. The low sample size (N=97) in 2006 suggests that this may not be representative of the population.

2.2 STATISTICAL CATCH-AT-AGE MODEL

2.2.1 Model Description

A female-only, Bayesian statistical catch-at-age model was applied to assess the coastwide stock status of Arrowtooth Flounder. The model is based on the Integrated Statistical Catch Age Model (iSCAM) framework, Martell et al. (2011). Full model details are provided in Appendix D.

We define a Reference Case with fixed and estimated parameters described in Table 4. A total of 74 model parameters were conditionally estimated by the Reference Case (Table 4). The model estimated time series of log recruitment anomalies and log fishing mortality rates; and time-invariant values of unfished recruitment, steepness of the Beverton-Holt stock-recruit relationship, natural mortality, average recruitment and logistic selectivity parameters for the commercial fishery and the four surveys. Prior probability distributions for the Reference Case are shown in Table 4 and Figure 7 and described in Section 2.2.2. Model sensitivity to fixed parameters and to assumed prior probability distributions are presented in a later section.

In brief, the model was conditioned on observed catch data (1996–2014), which were assumed to be known without error. The model was fit to the four survey indices of abundance described above, and to age composition data from the commercial fishery and three of the fishery-independent surveys (HSSS, QCSSS, WCVISS). Biological parameters determining weight-at-age and maturity-at-age schedules, were estimated independently (Appendix A) and input to the assessment model as fixed parameters that remained constant over time.

Survey biomass indices were treated as relative abundance indices that are directly proportional to the survey vulnerable biomass at the beginning of each year. Observation errors in relative abundance indices were assumed to be log-normally distributed. The survey catchability parameter q_k was estimated for each survey k, with the maximum likelihood estimate of q_k used in the calculation of the objective function (Walters and Ludwig, 1994). Prior probability distributions for $\ln(q_k)$ are described in Section 2.2.2.

Age-composition observations were assumed to come from a multivariate logistic distribution, where predicted proportions-at-age are a function of the predicted population age-structure and the age specific vulnerability to the fishing gear (Richards and Schnute, 1998). The likelihood for the age-composition data was evaluated at the conditional maximum likelihood estimate of the variance (i.e., no subjective weighting scheme was used to scale likelihood for the age-composition information). No age-reading errors were assumed.

Selectivity-at-age for the trawl fishery and four surveys was modelled using a two-parameter logistic function with asymptote at 1. Age-at-50%-vulnerability ($\hat{a}_k$) and the standard deviation of the logistic selectivity curve ($\hat{\gamma}_k$) for each gear k were estimated for the trawl fishery and the three synoptic surveys. No age composition data were available for the HSMAS and selectivity was fixed with $\hat{a}_k$ = 9 and $\hat{\gamma}_k$ = 0.5, similar to estimated values for the other gears. Trial runs indicated that there was little model sensitivity to this assumption.

Variance components of the model were partitioned using an errors in variables approach. The key variance parameter is the inverse of the total variance (i.e., ϑ^2, total precision). The total variance is partitioned into observation and process error components by the model parameter ρ, which represents the proportion of the total variance that is due to observation error (Punt and Butterworth, 1999; Deriso et al., 2007). The total variance is partitioned into observation errors (σ) and process errors (τ) using Eq. D.28. The parameters ϑ^2 and ρ were fixed in the current assessment (Table 4) at values that gave $\sigma = 0.2$ and $\tau = 0.8$. See Section 2.4.1 for sensitivity analyses to this assumption. See Appendix D for further details on the treatment of variance in this assessment.

2.2.2 Prior Probability Distributions

Prior probability distributions for the Reference Case are shown in Figure 7 and Table 4. Model sensitivities to assumed prior distributions are presented in Sections 2.4.2, 2.4.3, and 2.4.4.

Uniform prior probability distributions were assumed for $\ln(R_0)$, $\ln(\overline{R})$, $\ln(\overline{R}_{init})$ and selectivity parameters (Table 4). A Beta distribution was assumed for the steepness (h) of the stock-recruit relationship, with shape parameters that resulted in a distribution with mean = 0.85 and CV = 0.10 (Beta($\alpha = 13.4$, $\beta = 2.4$)). This prior was based on a literature review on steepness parameters for Pacific flatfish species done by Holt et al. (2014). A review of steepness estimates for flatfish species by Maunder (2012) suggested that flatfish steepness using a Beverton-Holt stock-recruit relationship may be around 0.94 (where h approaching 1.0 implies recruitment is independent of spawning biomass).

A normal distribution was assumed for $\ln(M)$ with mean = $\ln(0.2)$ and SD = 0.20 in log space. Holt et al. (2014) reviewed the literature and stock assessments and assumed a prior probability distribution for M with mean = 0.2 in their assessment of British Columbia Rock Sole (*Lepidopsetta spp.*). Spies and Turnock (2013) assumed a value of $M = 0.2$ for females in the assessment of Gulf of Alaska Arrowtooth Flounder, as did Spies et al. (2013) for the Bering Sea Aleutian Islands stock.

Normal prior probability distributions were assumed for the survey catchability parameters q_k for each survey k, where $2 <= k <= 5$. Normal distributions with mean = $\ln(0.5)$ and SD = 1.0 in log space were selected because the survey estimates of biomass were derived from swept area analysis (Eqs. 1, 2, and 3) and could therefore reasonably be expected to be within 1–2 orders of magnitude of unity. A large standard deviation was used to reflect ignorance of the scale of the swept area analysis compared with the true biomass.

2.2.3 Fishery reference points

The DFO Fishery Decision-making Framework Incorporating the Precautionary Approach (PA) policy (DFO, 2009) requires stock status to be characterized using three reference points:

1. a Reference Removal Rate
2. an Upper Stock Reference point (USR)
3. a Limit Reference Point (LRP)

Provisional values of USR = $0.8B_{\text{MSY}}$ and LRP = $0.4B_{\text{MSY}}$ are suggested in the absence of stock-specific reference points. The framework suggests a limit reference removal rate of F_{MSY}. Therefore, we refer to the reference removal rate as the limit removal rate (LRR) throughout this document.

A harvest control rule based on these reference points that is coincident with the choice of LRP, USR, and LRR would apply a linear reduction in fishing mortality as the stock falls below the USR, and would cease fishing when the stock reaches the LRP, but see Cox et al. (2013). This is illustrated for a hypothetical stock in Figure 6, where the USR and LRP are shown as vertical lines and the removal rate is shown as a blue line. We make the observation that the rate at which the fishing mortality should be reduced is unspecified in the PA policy, but is usually depicted as a linear ramp between the USR and LRP (Figure 6).

There is some uncertainty in F_{MSY} (and annual harvest rate U_{MSY}), driven by uncertainty in the trawl fishery selectivity resulting from possible under-representation of freezer trawl ages discussed above (but see Section 2.1.5). We therefore also present alternative candidate reference points for Arrowtooth Flounder that are less reliant on estimated selectivity. We suggest an USR = $0.4B_0$ and a LRP = $0.2B_0$. These thresholds are consistent with biomass targets and limits in place in other jusrisdictions including Australia (Smith et al., 2007) and the U.S.A. (Restrepo et al., 1998). Given the large uncertainty in estimated B_0 in this assessment (see Results, section 2.3), we also suggest B_{1996}, the estimated spawning biomass at the beginning of the time series, as a candidate benchmark to measure relative fishing impacts for this stock. See Appendix D for description of reference points calculations.

2.3 RESULTS

2.3.1 Model diagnostics

The joint posterior distribution was numerically approximated using the Markov Chain Monte Carlo (MCMC) routines built into AD Model Builder (Fournier et al., 2012). For the Reference Case and all sensitivity cases, posterior samples were drawn systematically every 7,500 iterations from a chain of length 15 million, resulting in 2,000 posterior samples (the first 1,000 samples were dropped to allow for sufficient burn-in). Convergence was diagnosed using visual inspection of the trace plots (Figure 9) and visual examination of autocorrelation in posterior chains (Figure 10). Autocorrelation was minor for all parameters and there was no strong evidence for lack of convergence.

2.3.2 Fits to data

Maximum posterior density (MPD) model fits to the four indices of abundance are shown in Figure 12. Fits to the indices of abundance appeared reasonable. The model followed the increasing trend for all three synoptic surveys, although it underestimated or overestimated some observations. The closest fit was obtained for the Hecate Strait Synoptic Survey, although the smallest observation in 2007 was not fit. The West Coast Vancouver Island Synoptic Survey observed its highest mean biomasses in 2010 and 2014, and its lowest in 2012 (Figure 12). The model could not reproduce these large shifts in abundance and estimated biomass to be approximately the average of the 2010–2014 survey observations for this period. The other two surveys covering this period (HSSS and QCSSS) were done in odd-numbered years so there was no 2012 observation. However, neither survey observed a drop in biomass during this period, suggesting that the low observation in the WCVISS may have been a sampling artifact, or due to some other anomaly. For the Hecate Strait Multispecies Assemblage Survey, the model overestimated the three observations in the earliest part of the time series. The median posterior estimate of catchability for this survey (0.13) was close to the median estimates of catchability for the three synoptic surveys (0.14, 0.11, 0.10 for the QCSSS, HSSS, and WCVISS respectively) (Table 5), indicating that the model estimated all four surveys to be similarly scaled to the population biomass. The model therefore treated the HSMAS and the synoptic surveys to essentially be continuous time series. This is not surprising given the absence of age composition data from the HSMAS to inform the respective scales of the surveys. However, we acknowledge that catchability in the HSMAS may have been different from the other surveys due to differences in survey design, and that the fit obtained for the HSMAS is partly a function of fits to the other surveys and to the assumed fixed selectivity for the HSMAS.

MPD fits to the fishery age composition data are shown in Figure 13. Fits were reasonable and there were no strong patterns in the residuals. Fits to the age composition data from the QCSSS were generally poor (Figure 14). Age composition data from this survey were variable, likely reflecting the small sample sizes indicated in Figure 14. Fits to age composition data for the HSSS and WCVISS were reasonable, with no strong patterns in the residuals (Figures 15 and 16). There were no reliable age composition data available for the HSMAS.

2.3.3 Parameter estimates

Prior and posterior probability distributions of estimated parameters are shown in Figure 8. The median, 2.5th percentile and 97.5th percentile posterior parameter estimates, and maximum posterior density (MPD) estimates, are given in Table 5. With the exception of steepness, the posterior estimates did not appear to be strongly influenced by the prior probability distributions. The posterior probability distribution for steepness, h, was very similar to the prior distribution, suggesting that there was little information about this parameter in the available data. Sensitivity to the assumed prior for steepness is tested in section 2.4.2.

Posterior probability estimates of $\ln(M)$ tended to be higher than the prior values, with all of the posterior density located in the right-hand tail of the prior distribution (Figure 8). Normal prior probability distributions were used for the log catchability parameters $\ln(q_k)$ for the Hecate Strait Assemblage Survey and the three Synoptic Surveys (Figure 7). Posterior estimates tended to overlap with the left-hand tail of the prior distributions for each survey (Figures 7 and 8). Sensitivity analyses (discussed in Section 2.4.4) indicated that posterior estimates of catchability were sensitive to the mean and standard deviation of the prior distribution.

Pairs plots of posterior samples (Figure 11) indicated that posterior estimates of R_0, $\overline{R}$, and M

were strongly negatively correlated with survey catchability parameters q_2 – q_5 . This and the influence of the prior distributions on posterior estimates of catchability indicated that there was limited information in the available data to estimate these important scaling parameters. Posterior estimates of R_0 and $\overline{R}$ were also positively correlated with $\ln(M)$ (Figure 11), again indicating that there was insufficient information in the data to unconfound the productivity and scale of the population.

2.3.4 Selectivity

Gear selectivity-at-age was estimated for the trawl fishery and the three synoptic surveys (Figure 17). Posterior estimates of age-at-50%-harvest ($\hat{a}_1$) and the standard deviation in the logistic selectivity ogive ($\hat{\gamma}_1$) are provided in Table 5. The median posterior estimate of age-at-50%-harvest in the trawl fishery was 9.40 y. This estimate was further to the right than expected, but was consistent with the available age composition data (Figure 3), which indicate very few observations of younger fish, especially in the latter part of the time series. Numerous tests of alternative model configurations did not result in a lower estimate of age-at-50%-harvest in the trawl fishery. Female Arrowtooth Flounder are thought to mature at around 5.6 years of age (Figure A.3). Therefore, it appears that individuals have several opportunities to spawn before they become vulnerable to the fishery. This in turn resulted in estimates of maximum sustainable harvest rate U_{MSY} approaching 1 (discussed in section 2.3.5), implying that under theoretical equilibrium conditions, all of the vulnerable (i.e., fully-selected) biomass could be harvested because the population could be sustained by younger spawners that are invulnerable to the fishery. We emphasise that this is a theoretical condition subject to the assumptions in the stock assessment model and the data limitations therein. We strongly advise against this as a harvest strategy and suggest that the age-at-50%-harvest in the trawl fishery is a primary axis of uncertainty in this stock assessment. As discussed above, catches since 2008 have increasingly been represented by the freezer trawler fleet and age composition data from this fleet were under-represented. Model sensitivity to selectivity in the trawl fishery, in terms of spawning biomass and stock status, is presented in a later section. We recommend as a high priority that future aging requests should include a representative proportion of ages from the freezer trawl fleet for all years since 2005.

Selectivities in the three synoptic surveys were also estimated to be quite far to the right (Figure 17) with median posterior estimates of age-at-50%-harvest ($\hat{a}_k$) of 11.43 y, 8.94 y and 9.20 y for the QCSSS, HSSS and WCVIS surveys respectively (Table 5). Standard deviations ($\hat{\gamma}_k$) in the selectivity curves were quite large (Table 5), indicating that selectivity in the surveys was far from knife-edged (Figure 17). This was especially true for the QCSSS, where ages showed a less clearly defined pattern than for the other gears, with larger proportions of younger fish (Figure 4). This was likely due to the relatively small sample sizes for this dataset (Figure 4). We recommend that future ageing requests should include ageing of archival otoliths from the QCSSS in order to increase the number of samples and quality of information from this survey.

2.3.5 Fishery reference points

Posterior estimates of fishery reference points from the Reference Case are provided in Table 6 and Figure 18. The posterior unfished female spawning biomass (B_0) was highly uncertain, with median $492,062$ t and credibility interval ranging from $249,722$ t to $1,245,031$ t (Table 6). Posterior credibility intervals for the candidate LRP 0.2B_0 and USR 0.4B_0 are also provided in Table 6.

Reference points based on maximum sustainable yield (MSY) were strongly impacted by estimates of selectivity in the trawl fishery described in the previous section. Because the selectivity ogive (Figure 17) was estimated to be far to the right of the maturity ogive (Figure A.3), the median estimate of F_{MSY} was 18.43 (Table 6). This instantaneous fishing mortality converts to an annual harvest rate approaching 1, through the equation $U_{\mathrm{MSY}} = 1 - e^{-F_{MSY}}$, implying that all of the vulnerable biomass (i.e., the biomass that is selected by the fishing gear) could be harvested because the population can be sustained by the spawning biomass that is invulnerable to the fishery (i.e., fish that are between 5 and 9 years old). The relationship between age at maturity and age at first harvest and its effect on fishery reference points was discussed by Myers and Mertz (1998), who described a fishing strategy where overfishing could be avoided by allowing all fish to spawn before they were available to be caught. Froese (2004) also discusses reduction in risks of overfishing by allowing fish to spawn before they are caught.

It is important to understand the distinction between vulnerable biomass and spawning biomass. The fishery reference points F_{MSY} and U_{MSY} refer to catch of the vulnerable biomass VB_t, which is determined by the selectivity function:

$$VB_t = \sum_a N_{a,t} w_{a,t} v_{a,t} \tag{5}$$

where a is age, t is year, N is the population number, w is the average weight-at-age, and v is the vulnerability-at-age in the trawl fishery (i.e. selectivity) (Figure 17).

When the selectivity ogive is located to the right of the maturity ogive, this means that a larger proportion of the total population is mature than vulnerable to the fishery. A comparison between vulnerable biomass and spawning biomass is provided in Section 2.3.6.

The median posterior estimate of B_{MSY} (and 95% credibility interval), conditional on estimated trawl selectivity and resulting F_{MSY}, was $119,120$ t ($58,952$–$312,328$ t) (Table 6). Posterior credibility intervals for the default LRP $0.4B_{\mathrm{MSY}}$ and USR $0.8B_{\mathrm{MSY}}$ are also provided in Table 6. The candidate B_0-based LRP and USR were approximately twice as large as the candidate B_{MSY}-based reference points, i.e., B_0-based reference points were more precautionary than the B_{MSY}-based reference points (Table 6).

Median posterior estimates (and 95% credibility interval) of other potential benchmarks of interest to managers (B_{1996}, B_{2015} and F_{2014}) are also provided in Table 6.

2.3.6 Biomass

The Reference Case estimates the female spawning biomass to have been on a flat to increasing trajectory since 1996 (Figure 19; Table 7). The posterior median (and 95% credibility interval) female spawning biomass in 2015 is projected to be $294,436$ t $(156,209–713,340$ t) (Table 6). The median projected beginning-of-year 2015 spawning biomass, which incorporates fishing mortality arising from the observed 2014 catch, is considerably higher than median estimates of both the default USR of $0.8B_{\mathrm{MSY}}$ and the default LRP of $0.4B_{\mathrm{MSY}}$ (Figure 19, Table 6). The 2015 spawning biomass was also projected to be above the candidate USR $0.4B_0$ and LRP $0.2B_0$ (Figure 19, Table 6).

For comparison, posterior estimates of vulnerable biomass and spawning biomass are shown together in Figure 20. The estimated vulnerable biomass is considerably smaller than the spawning biomass, due to the relatively early age at maturity compared to the estimated age-at-50% -harvest, discussed in Section 2.3.5.

2.3.7 Recruitment

Median posterior estimates (and 95% credibility interval) of age-1 recruits are shown in Figure 21 and Table 8. The 95% posterior credibility intervals since 2011 are reasonably broad, with extremely large uncertainty around the estimate of 2014 recruitment. This is expected since there is no information in the data about the strength of this year class. While the 2014 recruitment estimates are shown here, they played no role in projections or the decision tables. Projected recruitment anomalies for 2014 and 2015 were drawn randomly from a normal distribution, $\sim N(0,\tau)$. For most of the time series, recruitment was estimated to fluctuate around the long-term average, with relatively little variation. This is also evident in the posterior estimated recruitment anomalies (Figure 21). Lack of variation in recruitment is consistent with the data sources. The age composition data (Figures 3 and 4) did not show any clear recruitment patterns. Until 2005, fishery catches also remained relatively constant (Figure 2) and there were no strong trends in the survey data (Figure 12).

2.3.8 Fishing mortality

Median posterior estimates of fishing mortality (and 95% credibility interval) are shown in Figure 22 and Table 9. The median posterior estimate of fishing mortality is estimated to have peaked in 2005 at 0.310 $(0.162–0.494)$ as a result of a test fishery described in Section 1.3. Fishing mortality in 2014 was estimated to be 0.136 $(0.069–0.248)$. Fishing mortality rates converted to annual harvest rates can be found in Table 10.

2.3.9 Relative spawning biomass

Median posterior estimates (and 95% credibility interval) of relative female spawning biomass B_t/B_0 are shown in Figure 23. The credibility interval is broad, reflecting the uncertainty in posterior estimates of B_0 (Figure 23, Table 6). The median posterior projected estimate of 2015 relative biomass is 0.596 (0.367–0.936) (Figure 23, Table 11).

2.4 SENSITIVITY ANALYSES

We tested sensitivity of the model outputs to the following assumptions:

1. The assumed fixed value of variance parameters ϑ^2 and ρ
2. The prior probability distribution for steepness (h)
3. The prior probability distribution for $\ln(M)$
4. The prior probability distribution for survey catchability (q_k, $2 <= k <= 5$)
5. The estimated fishery selectivity parameters

Results are presented below. The full list of sensitivity scenarios is provided in Table 12. Reference Case parameter settings are provided in Table 4. In all sensitivity runs, posterior samples were drawn systematically every 7,500 iterations from a chain of length 15 million, resulting in 2,000 posterior samples. The first 1,000 samples were dropped to allow for sufficient burn-in.

2.4.1 Alternative values of variance parameters ϑ^2 and ρ

The Reference Case used fixed values for variance parameters ϑ^2 and ρ (Table 4), which resulted in an observation error term ($\sigma = 0.2$) and a process error term ($\tau = 0.8$) (Appendix D, Eq. D.28). We tested model sensitivity to these fixed parameters by varying ϑ^2 and ρ to give:

1. $\sigma = 0.1$ and $\tau = 0.8$ (Scenario 2)
2. Estimate total variance (Scenario 3)
3. $\sigma = 0.2$ and $\tau = 1$ (Scenario 4)
4. $\sigma = 0.2$ and $\tau = 0.6$ (Scenario 5)

These scenarios were designed to test model sensitivity to:

1. assumed lower observation error in the surveys
2. the effect of freely-estimating total variance
3. assumed higher recruitment variability
4. assumed lower recruitment variability

The effect of reducing observation error in Scenario 2 was to slightly improve the fits to the survey indices (Figure 24), most notably the Hecate Strait Multispecies Assemblage Survey. The predicted final-year index points were estimated to be slightly higher in this scenario (Figure 24), resulting in slightly larger median posterior estimates of spawning biomass (Figure 25). Estimating total variance in Scenario 3 gave MPD estimates of $\sigma = 0.27$ and $\tau = 1.10$, both larger than the assumed fixed values in the Reference Case. Fits to the indices of abundance were, however, almost the same as for the Reference Case (Figure 24). Posterior estimates of recruitment and log recruitment deviations were only marginally different from the Reference

Case (Figure 26).

Increasing the process error variance in Scenario 4 mainly affected the 2014 estimates of recruitment and log recruitment deviations (Figure 27). The estimated final year biomass also increased slightly (Figure 28). As expected, reducing the process error variance in Scenario 5 had the opposite effect, with slightly decreased estimates of final year recruitment, log recruitment deviations and spawning biomass (Figure 27). Estimates of B_0 were sensitive to the assumed fixed values of τ (Figure 28). The resulting impacts on relative spawning biomass are shown in Figure 29. The rescaling of B_0 in Scenario 4 (Figure 28) resulted in a considerable portion of the posterior credibility interval of relative biomass to be below the candidate USR of $0.4B_0$.

2.4.2 Prior probablility distribution for steepness (h)

Sensitivity to the assumed prior probability distribution for steepness was tested in Scenario 6 by decreasing the mean of the prior distribution and increasing the CV. This was achieved by changing the parameters of the Beta prior to give mean = 0.72 and CV = 0.15 (Table 12). This was a similar sensitivity test to that done by Holt et al. (2014) for British Columbia Rock Sole. This sensitivity test resulted in lower posterior estimates of steepness, with median = 0.757 (0.542–0.911), compared to the Reference Case median posterior = 0.874 (0.688–0.975).

Spawning biomass and recruitment estimates are shown in Figures 30 and 31, where it can be seen that there was relatively little effect of the prior distribution on posterior estimates of biomass and recruitment. The median posterior estimate of B_0 was, however, much more uncertain than for the Reference Case, with the credibility interval ranging from $251,970$–$1,821,581$ t, compared to the Reference Case posterior credibility interval of $249,722$–$1,245,031$ t (Table 6). This was due in large part to the increased CV in the prior distribution for steepness. Median posterior estimates of other parameters were very similar to the Reference Case.

2.4.3 Prior probability distribution for $\ln(M)$

The Reference Case assumed a normal prior probability distribution for $\ln(M)$, with mean = $\ln(0.2)$ and standard deviation = 0.20 in log space. Three scenarios were run to test sensitivity of model outcomes to the mean and standard deviation assumed for this prior distribution:

1. mean = $\ln(0.2)$, standard deviation = 0.05 (Scenario 7)
2. mean = $\ln(0.2)$, standard deviation = 0.25 (Scenario 8)
3. mean = $\ln(0.3)$, standard deviation = 0.20 (Scenario 9)

Biomass and recruitment estimates for Scenarios 7 and 8 are shown in Figures 32 and 33. Decreasing the standard deviation in Scenario 7 resulted in a lower median posterior estimates of $M = 0.225$ (0.209–0.244) compared to the Reference Case median posterior estimate of $M = 0.314$ (0.255–0.380). Female spawning biomass was estimated to be on a slightly more increasing trajectory compared with the reference case model, with much less uncertainty in the first years of the time series (Figure 32). The median posterior estimates of recent biomass were less than in the reference case model, and the credibility interval was narrower. Posterior estimates of B_0 were much less uncertain than for the Reference Case, with the credibility interval ranging from $280,948–901,758$ t, compared to the Reference Case posterior credibility interval of $249,722–1,245,031$ t (Table 6). Convergence diagnostics for Scenario 7 were poorer than for the Reference Case, with stronger autocorrelation in the MCMC chains, notably for estimates of $\overline{R}_{init}$.

Increasing the standard deviation in Scenario 8 resulted in very similar estimates of M, spawning biomass and recruitment as the Reference Case (Figures 32 and 33). The median posterior estimate was $M = 0.328$ (0.266–0.388). This can be compared to estimates from the Reference Case (see above and Table 5). Increasing the mean in Scenario 9 resulted in a re-scaling of the estimated population size, with slightly larger estimates of biomass and recruitment (Figures 34 and 35). The median posterior estimate was $M = 0.343$ (0.280–0.402).

Model outcomes were therefore influenced by the assumed prior probability distribution for $\ln(M)$. Alternative assumptions for the mean and standard deviation of the prior tended to increase the median and credibility interval of posterior estimates of B_0 and recent spawning biomass.

2.4.4 Prior probablity distribution for survey catchability (q_k)

The Reference Case assumed a normal prior probability distribution for $\ln(q_k)$, with mean = $\ln(0.5)$ and standard deviation = 1.0 in log space, for all surveys k, $2 <= k <= 5$. Two scenarios were run to test sensitivity of model outcomes to the mean and standard deviation assumed for this prior distribution:

1. mean = $\ln(1.0)$, standard deviation = 1.0 (Scenario 10)
2. mean = $\ln(0.5)$, standard deviation = 1.5 (Scenario 11)

Increasing the mean of the prior distribution in Scenario 10 resulted in higher posterior estimates of q_k for all surveys compared to the reference case model (Table 13). Correspondingly, posterior estimates of spawning biomass and recruitment were lower than in the Reference Case (Figures 36 and 37). Conversely, increasing the standard deviation of the prior distribution in Scenario 11 resulted in lower posterior estimates of q_k for all surveys. Correspondingly, estimates of spawning biomass and recruitment were higher than in the Reference Case, with a much broader credible interval (Figures 38 and 39).

While Scenario 10 illustrates that the assumed prior probability distribution did affect posterior estimates of q_k for all surveys, we do not consider a prior centred on 1 to be reasonable, given that the swept area methodology described in Eqs. 1–4 did not attempt to inflate estimated biomass for the whole coast. The lower posterior estimates for q_k obtained for all surveys in Scenario 11, may or may not be plausible, given the lack of information in the data for informing population scale in this assessment.

2.4.5 Effect of fixing fishery selectivity parameters

In an earlier section, we noted that the estimated selectivity ogive for the trawl fishery was quite far to the right of the maturity ogive (Figure 17), resulting in estimates of U_{MSY} approaching 1. We concluded that the estimated age-at-50%-harvest in the trawl fishery (median = 9.40 y) was consistent with the fishery age composition data (Figure 3) but that these data may not be representative of ages in the freezer trawl fleet due to lack of age samples from this fleet. While we recommend ageing of archival otoliths from the freezer trawl fleet as a future research priority, we ran two simple scenarios in the current assessment to evaluate the effect of alternative fishery selectivity ogives on model outcomes. Trial runs suggested that fixing age-at-50%-harvest at lower values resulted in poor fits to the age composition data and poor model convergence. Therefore, for the two sensitvity runs presented here, the fishery age composition data were removed from the assessment and two alternative fixed ages-at-50%-harvest were assumed:

1. selectivity ogive = maturity ogive (Scenario 12)
2. age-at-50%-harvest = 6 y (Scenario 13)

Trawl selectivity ogives estimated in the Reference Case (MPD) and fixed in Scenarios 12 and 13 are shown in Figure 40. As expected, the effect of reducing the age-at-50%-harvest in the trawl fishery was a large reduction in estimated female spawning biomass (Figure 41), a reduction in estimated U_{MSY} and a corresponding increase in B_{MSY} (Figure 42). Assuming a lower age-at-50%-harvest in the trawl fishery could therefore result in more precautionary advice due to lower spawning biomass, and because the vulnerable biomass would contain a greater proportion of younger fish.

Scenarios 12 and 13 are speculative as there is currently no evidence to support an assumption of a lower age-at-50%-harvest in the trawl fishery. These two scenarios are presented as “what-if” scenarios to illustrate the potential impacts of over-estimating age-at-50%-harvest in the trawl fishery.

3. RECOMMENDATIONS AND YIELD OPTIONS

3.1 DECISION TABLES

3.1.1 Reference Case

Performance measures were calculated over a sequence of alternative 2015 projected catch levels and are based on one-year projections to 2016. Projected, bias-corrected log recruitment anomalies in 2014 and 2015 were drawn randomly from a normal distribution, $\sim N(0, \tau)$.

Median (and 95% credibility interval) posterior estimates of reference points (MSY and B_0-based reference points) and benchmarks (B_{1996}, B_{2015}, F_{2014}) were provided in Table 6. Decision tables are presented showing predicted probabilities of undesirable states under alternative 2015 projected catch levels. An undesirable biomass-based performance measure is defined to occur when the 2016 projected female spawning biomass is below the candidate reference point or benchmark, i.e., the ratio $B_{2016}/B_{ReferencePoint} < 1$. An undesirable fishing mortality-based performance measure is defined to occur when projected 2015 fishing mortality is above the reference point, i.e., $F_{2015}/F_{ReferencePoint} > 1$.

Probabilities in the decision tables are measured as the proportion of burned-in posterior samples that meet criteria above (i.e., proportion of posterior samples <1 for biomass-based performance measures; and proportion of posterior samples >1 for fishing mortality-based performance measures).

The Reference Case decision table is presented in Table 14. Alternative 2015 female-only catch levels are presented from 0 t to 50,000 t. Catches are shown in 2,000 t increments from zero to 10,000 t; then in 1,000 t increments between 10,000 t and 20,000 t; and then in 2,000 t increments from 22,000 t to 30,000 t. A catch level of 50,000 t is also given as requested by the review committee.

The model-predicted probability of the 2016 female spawning biomass being below the 2015 female spawning biomass ranged from 0% under no 2015 catch to 11.5% under 30,000 t, which is double the current total TAC. At 50,000 t, the probability is 43.0%. The probability of being below the candidate USR of $0.4B_0$ ranged between 1.2% and 7.0% over the range of catch levels considered. The probability of being below the candidate USR of $0.8B_{\text{MSY}}$ was 0% over the range of catch levels considered. The probability of being below the both candidate LRPs of $0.2B_0$ or $0.4B_{\text{MSY}}$ was 0% over the range of catch levels considered. The probability that the 2016 female spawning biomass would be less than the 1996 female spawning biomass ranged from 2.1% to 11.8% over the range of catch levels considered.

The model-predicted probability of the 2015 harvest rate being greater than the 2014 harvest rate was 0% under a 2015 catch between 0 and 8,000 t, building up to a probability of 100% at 13,000 t. However, the probability that the 2015 harvest rate would exceed U_{MSY} was 0% under all catch levels considered (Table 14). As discussed, the reason for posterior U_{MSY} estimates approaching 1 (Figure 18) was due to the location of the estimated trawl selectivity-at-age ogive, far to the right of the maturity-at-age ogive. Sensitivity of catch advice to the estimated trawl selectivity is presented in the next section.

3.1.2 Alternative decision table

For comparison, we also present a decision table using the Scenario 12 model (Table 15), where selectivity-at-age in the trawl fishery was fixed to be the same as maturity-at-age (see Table 12). Scenario 12 had the lowest estimates of biomass of all the sensitivity scenarios and represents a worse-case “what-if” scenario.

The decision table generated using the Scenario 12 model had lower probabilities of the 2016 spawning biomass being below any of the biomass-based reference points and benchmarks presented (Table 15). This was because fixing the trawl selectivity with a younger age-at-50%-harvest had the effect of reducing the scale of the whole model, including estimates of B_0 (Figure 41) and B_{MSY} (Figure 42). Therefore, although projected spawning biomass was smaller than in the Reference Case, the B_0 and B_{MSY}-based reference points were also lower, resulting in similar probabilities as in the Reference Case model.

Similarly, despite posterior U_{MSY} estimates being lower in Scenario 12 (Figure 42), the probabilities of the 2015 harvest rate exceeding the 2014 harvest rate were lower than for the Reference Case model. This is because the posterior estimated vulnerable biomass was actually larger than in the Reference Case model because a much larger proportion of the total biomass was vulnerable to the fishing gear due to the assumed shift in selectivity to include younger fish. As for the Reference Case, the probability that the 2015 harvest rate would exceed U_{MSY} was 0% under all catch levels considered.

As with all fishery stock assessments, the uncertainty presented in this assessment is under-representative of the true uncertainty regarding the status of the Arrowtooth Flounder population. We therefore urge caution with the advice presented in Tables 14 and 15. The magnitude of catch and discards prior to 1996 is a major source of uncertainty in this assessment. The short time series of catch and surveys that were available in this assessment were relatively uninformative about the scale of the population, evidence for which can be seen in the high parameter correlations (Figure 11) and the influence of the prior probability distributions for the survey catchability parameters (Section 2.4.4). If reliable pre-1996 catch data had been available, the stock assessment and harvest advice may have been very different to those presented here.

4. FUTURE RESEARCH AND DATA REQUIREMENTS

As with all fishery stock assessments, there are two major types of uncertainty in the advice presented in this document:

1. Uncertainty in the estimates of model parameters within the assessment
2. Structural uncertainty arising from processes and data that were not included in the assessment

The first type, uncertainty within the assessment, is presented in terms of posterior credibility intervals for parameters and state variables such as biomass, recruitment and fishing mortality. This uncertainty was captured in the decision tables and was further explored using sensitivity analyses.

The second type of uncertainty, structural uncertainty, is not captured in this assessment and is not captured in the decision tables. The magnitude of catch and discards prior to 1996 is a major source of uncertainty in this assessment. As discussed in Section 2.1.2, all catch data prior to 1996 were omitted from this assessment on the recommendation of our industry advisors and technical working group. Arrowtooth Flounder is known to have been discarded at sea in very large quantities due to proteolysis of the flesh if catches were not landed and frozen very quickly after capture. Applications of ratio estimators or generalized linear models to estimate historic discard rates were rejected as analytical tools due to:

1. lack of data with which to calibrate models
2. the fact that often whole tows would have been discarded, making ratio estimators or other predictive factors useless
3. discarding behaviour was not expected to have remained consistent through time, and would have varied according to fine-scale spatial, seasonal and market considerations

While the flat to increasing estimated spawning biomass trajectory in the Reference Case and sensitivity scenarios was consistent with available catch, survey and age composition data, a longer catch time series would have provided more information about the productivity of the population and its scale relative to historic levels. We suggest that it may be possible to work with members of the fishing industry with many years of experience of this fishery to reconstruct an agreed upon historical catch series with appropriate uncertainty. Examples of catch reconstructions for data-limited fisheries can be found in Pitcher et al. (2002) and Ainsworth and Pitcher (2005), although there are likely many other appropriate approaches. Key inputs to this kind of analysis would be detailed spatial and temporal knowledge of the fishery, regulations and markets for several decades.

We strongly recommend increasing the number of age samples from the freezer trawl fleet. Archived otoliths are available that have not yet been aged. With large enough sample sizes, it will be possible to model the freezer trawlers and the shoreside fishery as separate fleets. In its current configuration, the stock assessment model treats both components of the fleet as being part of the same fleet with the same selectivity. In the absence of information to the contrary, the model interpreted the increased catches in the latter part of the time series as evidence of a stable or increasing biomass. While this was supported by similar trajectories in the survey data, treating the fleets separately may allow for a more subtle interpretation of increased catches in recent years, which may also have been driven by changes in markets, technology or, importantly, different selectivity.

Stock structure of Arrowtooth Flounder is poorly understood in British Columbia. A number of approaches are available to improve understanding of stock structure including genetic analysis, analysis of otolith microchemistry and analysis of life history traits such as growth and maturity. Arrowtooth Flounder is managed as a coast-wide stock. If there are distinct stocks within British Columbia waters, there may be risks associated with taking a large proportion of the TAC from one area.

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7. TABLES

Table 1. Recent coastwide commercial fishery catch (t) for Arrowtooth Flounder.

Year	Landings	Discards
1996	4,598.8	3,278.0
1997	2,894.5	2,451.5
1998	3,827.3	3,279.6
1999	3,555.4	3,817.6
2000	4,284.4	3,560.0
2001	8,236.5	2,454.2
2002	5,164.3	2,914.7
2003	4,321.4	3,200.9
2004	5,475.1	3,241.5
2005	16,474.3	2,752.4
2006	5,935.2	1,140.5
2007	4,508.2	1,830.3
2008	3,399.0	1,455.0
2009	1,664.7	2,453.6
2010	494.3	2,667.4
2011	4,949.4	2,575.1
2012	5,131.1	2,338.5
2013	8,259.4	2,449.3
2014	11,990.5	1,580.3

Table 2. Recent commercial fishery catch (t) for Arrowtooth Flounder by area.

Year	Area			
	3CD		5ABCDE	
	Landings	Discards	Landings	Discards
1996	2,993.6	791.3	1,571.7	2,486.6
1997	1,493.3	530.8	1,384.9	1,920.7
1998	2,429.8	655.1	1,382.4	2,623.5
1999	1,385.1	738.9	2,149.6	3,078.8
2000	1,748.0	668.4	2,507.2	2,891.5
2001	5,024.3	650.3	3,191.9	1,802.3
2002	2,260.0	577.6	2,858.0	2,329.8
2003	2,166.2	818.4	2,118.2	2,382.0
2004	2,820.5	710.7	2,633.9	2,529.9
2005	6,682.9	599.9	9,766.5	2,152.1
2006	1,537.3	177.8	4,354.7	962.4
2007	1,905.3	515.1	2,595.2	1,315.0
2008	2,689.1	607.1	709.3	847.7
2009	1,061.7	621.4	602.6	1,830.5
2010	181.6	682.5	312.7	1,983.1
2011	2,548.9	1,075.2	2,400.2	1,499.6
2012	4,342.8	766.6	788.2	1,571.7
2013	6,888.3	1,004.2	1,371.0	1,444.7
2014	8,709.9	613.5	3,280.5	966.6

Table 3. Annual female-only indices of abundance and CVs for the four indices used in this assessment.

Year	QCS Synoptic		HS Multispecies Assemblage		Hecate Strait Synoptic		WCVI Synoptic	
	Index	**CV**	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**
1996			7.076	0.468				
1998			7.734	0.390				
2000			12.584	0.258				
2002			10.379	0.207				
2003	5.905	0.136	11.087	0.270				
2004	12.198	0.221					8.711	0.308
2005	14.022	0.205			15.194	0.309		
2006							8.215	0.206
2007	7.600	0.178			6.774	0.262		
2008							6.729	0.364
2009	9.614	0.158			13.064	0.233		
2010							15.037	0.214
2011	13.703	0.247			15.805	0.170		
2012							5.581	0.184
2013	11.676	0.234			14.593	0.234		
2014							14.124	0.143

Table 4. Estimated and fixed parameters and prior probablilty distributions used in the Reference Case.

Parameter	**Number estimated**	**Bounds [low, high**	**Prior (mean, SD) (single value = fixed)**
Log recruitment ($ln(R_0)$)	1	[-2, 6]	Uniform
Steepness (h)	1	[0.2, 1]	Beta($\alpha = 13.4, \beta = 2.4$)
Log natural mortality ($ln(M)$)	1	[-3, 2]	Normal($ln(0.2), 0.2$)
Log mean recruitment ($\ln(\overline{R})$)	1	[-2, 6]	Uniform
Log initial recruitment ($\ln(\overline{R}_{init})$)	1	[-5, 6]	Uniform
Variance ratio (ρ)	0	Fixed	0.059
Inverse total variance (ϑ^2)	0	Fixed	1.471
Survey age at 50% selectivity ($\hat{a}_k$)	3	[0, 1]	None
Fishery age at 50% selectivity ($\hat{a}_k$)	1	[0, 1]	None
Survey SD of logistic selectivity ($\hat{\gamma}_k$)	3	[0, Inf)	None
Fishery SD of logistic selectivity ($\hat{\gamma}_k$)	1	[0, Inf)	None
Survey catchability (q_k)	4	None	Normal($0.5, 1$)
Log fishing mortality values ($\Gamma_{k,t}$)	19	[-30, 3]	[-30, 3]
Log recruitment deviations (ω_t)	19	None	Normal($0, \tau$)
Initial log recruitment deviations ($\omega_{init,t}$)	19	None	Normal($0, \tau$)

Table 5. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters from the Reference Case. Subscripts on q (catchability), $\hat{a}$ (selectivity age-at-50%), and $\hat{\gamma}$ (selectivity standard deviation-at-50%) parameters indicate: 1 = Trawl fishery, 2 = QCSSS, 3 = HSMAS, 4 = HSSS, 5 = WCVISS.

Parameter	2.5%	50%	97.5%	MPD
R_0	0.220	0.571	2.014	0.694
$Steepness(h)$	0.688	0.874	0.975	0.916
M	0.255	0.314	0.380	0.328
$\overline{R}$	0.155	0.371	1.176	0.474
$\overline{R}_{init}$	0.050	0.145	0.566	0.211
q_2	0.069	0.144	0.444	0.128
q_3	0.069	0.125	0.187	0.116
q_4	0.060	0.115	0.197	0.107
q_5	0.051	0.100	0.169	0.094
$\hat{a}_1$	8.960	9.401	9.892	9.405
$\hat{\gamma}_1$	0.838	0.942	1.057	0.927
$\hat{a}_2$	8.940	11.434	17.080	11.143
$\hat{\gamma}_2$	1.803	2.326	3.337	2.195
$\hat{a}_4$	7.934	8.942	9.947	9.004
$\hat{\gamma}_4$	1.247	1.431	1.678	1.396
$\hat{a}_5$	8.518	9.196	9.999	9.250
$\hat{\gamma}_5$	0.997	1.119	1.270	1.102

Table 6. Posterior (2.5th percentile, Median, and 97.5th percentile) of proposed reference points for the Reference Case. Biomass numbers are in thousands of tonnes.

Reference Point	2.5%	50%	97.5%
B_0	249.722	492.062	1,245.031
B_{MSY}	58.952	119.120	312.328
MSY	30.452	65.346	182.073
F_{MSY}	4.474	18.427	72.162
U_{MSY}	0.989	1.000	1.000
B_{1996}	124.610	208.177	429.181
B_{2015}	156.209	294.436	713.340
B_{2015}/B_{1996}	0.900	1.440	2.243
F_{2014}	0.069	0.136	0.248
$0.2B_0$	49.944	98.413	249.006
$0.4B_0$	99.889	196.825	498.012
$0.4B_{MSY}$	23.581	47.648	124.931
$0.8B_{MSY}$	47.162	95.296	249.863

Table 7. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of female spawning biomass (1000 t) for the Reference Case.

Year	2.5%	50%	97.5%	MPD
1996	124.610	208.177	429.181	233.029
1997	123.194	201.407	409.711	225.235
1998	122.627	195.620	391.603	217.567
1999	120.613	189.204	379.408	209.671
2000	117.588	183.818	375.277	203.314
2001	114.645	182.137	376.497	200.294
2002	111.820	180.294	389.208	199.699
2003	115.478	186.938	406.306	208.756
2004	120.802	199.635	448.568	224.181
2005	127.249	214.821	493.883	241.051
2006	124.900	220.233	514.446	247.818
2007	131.534	233.195	533.599	260.760
2008	135.896	239.940	540.498	266.793
2009	136.628	241.323	534.023	267.665
2010	139.194	240.542	527.936	267.483
2011	141.282	241.725	536.866	269.312
2012	139.950	243.887	547.671	271.398
2013	142.438	249.611	572.428	280.466
2014	144.768	264.077	620.355	299.864
2015	156.209	294.436	713.340	338.410

Table 8. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of recruitment (millions) for the Reference Case.

Year	2.5%	50%	97.5%	MPD
1997	0.101	0.245	0.835	0.308
1998	0.083	0.210	0.718	0.257
1999	0.137	0.342	1.148	0.425
2000	0.150	0.401	1.377	0.500
2001	0.148	0.369	1.245	0.458
2002	0.131	0.339	1.182	0.417
2003	0.132	0.339	1.180	0.418
2004	0.104	0.278	0.924	0.340
2005	0.088	0.226	0.737	0.282
2006	0.118	0.311	1.037	0.392
2007	0.101	0.252	0.866	0.323
2008	0.133	0.354	1.222	0.455
2009	0.116	0.304	1.178	0.399
2010	0.157	0.444	1.673	0.572
2011	0.152	0.454	1.699	0.596
2012	0.396	1.243	4.368	1.621
2013	0.102	0.349	1.345	0.448
2014	0.649	2.629	12.414	3.448

Table 9. Posterior (2.5^{th} percentile, Median, and 97.5^{th} percentile) and MPD estimates of fishing mortality, F, for the Reference Case.

Year	2.5%	50%	97.5%	MPD
1996	0.061	0.110	0.175	0.100
1997	0.040	0.073	0.112	0.066
1998	0.044	0.079	0.122	0.072
1999	0.050	0.088	0.133	0.081
2000	0.054	0.096	0.143	0.090
2001	0.084	0.150	0.223	0.139
2002	0.058	0.104	0.157	0.098
2003	0.058	0.103	0.152	0.096
2004	0.073	0.128	0.193	0.121
2005	0.162	0.310	0.494	0.288
2006	0.051	0.099	0.168	0.092
2007	0.042	0.087	0.146	0.080
2008	0.035	0.066	0.113	0.061
2009	0.020	0.038	0.065	0.036
2010	0.012	0.022	0.037	0.020
2011	0.033	0.064	0.107	0.060
2012	0.037	0.072	0.123	0.068
2013	0.053	0.102	0.179	0.096
2014	0.069	0.136	0.248	0.127

Table 10. Posterior (2.5^{th} percentile, Median, and 97.5^{th} percentile) and MPD estimates of annual harvest rate, U, for the Reference Case.

Year	2.5%	50%	97.5%	MPD
1996	0.059	0.104	0.161	0.095
1997	0.039	0.070	0.106	0.064
1998	0.043	0.076	0.114	0.070
1999	0.049	0.084	0.125	0.078
2000	0.053	0.092	0.133	0.086
2001	0.080	0.140	0.200	0.130
2002	0.057	0.099	0.145	0.093
2003	0.057	0.097	0.141	0.091
2004	0.070	0.121	0.175	0.114
2005	0.150	0.266	0.390	0.250
2006	0.050	0.094	0.154	0.088
2007	0.042	0.083	0.135	0.077
2008	0.034	0.064	0.107	0.060
2009	0.019	0.037	0.063	0.035
2010	0.011	0.021	0.036	0.020
2011	0.032	0.062	0.101	0.058
2012	0.037	0.070	0.116	0.066
2013	0.052	0.097	0.164	0.092
2014	0.066	0.127	0.220	0.119

Table 11. Derived posterior (2.5th percentile, Median, and 97.5th percentile) and MPD values of relative female spawning biomass for the Reference Case.

Year	2.5%	50%	97.5%	MPD
1996	0.216	0.423	0.742	0.685
1997	0.214	0.410	0.712	0.663
1998	0.211	0.397	0.689	0.650
1999	0.205	0.383	0.658	0.644
2000	0.201	0.373	0.628	0.655
2001	0.201	0.368	0.609	0.687
2002	0.204	0.366	0.596	0.726
2003	0.218	0.384	0.610	0.773
2004	0.240	0.412	0.653	0.813
2005	0.261	0.439	0.693	0.833
2006	0.262	0.447	0.716	0.823
2007	0.277	0.474	0.750	0.826
2008	0.289	0.485	0.765	0.826
2009	0.292	0.487	0.768	0.832
2010	0.298	0.486	0.760	0.850
2011	0.309	0.488	0.765	0.887
2012	0.309	0.492	0.758	0.966
2013	0.316	0.508	0.787	1.107
2014	0.331	0.539	0.831	1.335
2015	0.367	0.596	0.936	1.675

Table 12. Sensitivity cases and their parameters.

Scenario	Description	Parameters
2	Decrease σ to 0.1	$\vartheta^2 = 1.538; \rho = 0.015$
3	Estimate Total Variance	ϑ^2 estimated; $\rho = 0.059$
4	Increase τ to 1.0	$\vartheta^2 = 0.962; \rho = 0.038$
5	Decrease τ to 0.6	$\vartheta^2 = 2.500; \rho = 0.100$
6	Decrease mean of h prior to 0.72	h =Beta($\alpha = 12.7, \beta = 5.0$)
7	Decrease SD of ln(M) prior to 0.05	ln(M)=Normal(ln(0.2), 0.05)
8	Increase SD of ln(M) prior to 0.25	ln(M)=Normal(ln(0.2), 0.25)
9	Increase mean of ln(M) prior to ln(1.0)	ln(M)=Normal(ln(0.3), 0.20)
10	Increase mean of ln(q_k) prior to ln(1.0)	ln(q_k)=Normal(ln(1.0), 1.0)
11	Increase SD of ln(q_k) prior to 1.5	ln(q_k)=Normal(ln(0.5), 1.5)
12	Selectivity Ogive = Maturity Ogive	$\hat{a} = 4.99$ yrs; $\hat{\gamma} = 1.27$ yrs
13	Age-at-50%-harvest set to 6 yrs	$\hat{a} = 6$ yrs; $\hat{\gamma} = 1$ yrs

Table 13. Sensitivity cases for q_k; posterior quantiles. For sensitivity case descriptions, see Table 12.

Index	Low steepness		
q_k	2.5%	50%	97.5%
QCS Synoptic	0.064	0.145	0.471
HS Multispecies Assemblage	0.069	0.129	0.194
Hecate Strait Synoptic	0.056	0.113	0.205
WCVI Synoptic	0.049	0.100	0.172

Table 14. Decision Table for the Reference Case showing posterior probabilities that 2016 projected biomass B_t is below a set of candidate reference points and benchmarks (Table 6), and probabilities that the 2015 projected harvest rate U_t is above U_{2014} or U_{MSY} for a given level of female-only catch. Total catch is shown in columns 2 and 3 and is calculated by adding the male proportion based on the average of the last 4 years' proportions (column 2) and the average of the entire time series proportions (column 3). See table B.1 for proportion values.

2015 Female Catch (1000 t)	**2015 Total Catch Last 4 yrs avg (1000 t)**	**2015 Total Catch all yrs avg (1000 t)**	$\mathbf{P(B_{2016} < B_{2015})}$	$\mathbf{P(B_{2016} < 0.4B_0)}$	$\mathbf{P(B_{2016} < 0.2B_0)}$	$\mathbf{P(B_{2016} < B_{1996})}$	$\mathbf{P(B_{2016} < 0.8B_{MSY})}$	$\mathbf{P(B_{2016} < 0.4B_{MSY})}$	$\mathbf{P(U_{2015} > U_{2014})}$	$\mathbf{P(U_{2015} > U_{MSY}}$
0	0.000	0.000	0.000	0.012	0.000	0.021	0.000	0.000	0.000	0.000
2	2.545	2.437	0.000	0.013	0.000	0.024	0.000	0.000	0.000	0.000
4	5.089	4.874	0.000	0.014	0.000	0.028	0.000	0.000	0.000	0.000
6	7.634	7.312	0.000	0.016	0.000	0.031	0.000	0.000	0.000	0.000
8	10.178	9.749	0.000	0.016	0.000	0.035	0.000	0.000	0.000	0.000
10	12.723	12.186	0.000	0.017	0.000	0.037	0.000	0.000	0.273	0.000
11	13.995	13.405	0.000	0.017	0.000	0.040	0.000	0.000	0.855	0.000
12	15.267	14.623	0.001	0.018	0.000	0.041	0.000	0.000	0.995	0.000
13	16.539	15.842	0.003	0.019	0.000	0.042	0.000	0.000	1.000	0.000
14	17.812	17.061	0.006	0.019	0.000	0.043	0.000	0.000	1.000	0.000
15	19.084	18.279	0.012	0.020	0.000	0.043	0.001	0.000	1.000	0.000
16	20.356	19.498	0.014	0.020	0.000	0.044	0.001	0.000	1.000	0.000
17	21.628	20.717	0.016	0.021	0.000	0.046	0.001	0.000	1.000	0.000
18	22.901	21.935	0.021	0.021	0.000	0.048	0.001	0.000	1.000	0.000
19	24.173	23.154	0.023	0.021	0.000	0.052	0.001	0.000	1.000	0.000
20	25.445	24.372	0.028	0.021	0.000	0.052	0.001	0.000	1.000	0.000
22	27.990	26.810	0.035	0.023	0.000	0.056	0.001	0.000	1.000	0.000
24	30.534	29.247	0.050	0.029	0.000	0.061	0.001	0.000	1.000	0.000
26	33.079	31.684	0.072	0.030	0.000	0.063	0.002	0.000	1.000	0.000
28	35.623	34.121	0.093	0.034	0.000	0.066	0.002	0.000	1.000	0.000
30	38.168	36.559	0.115	0.041	0.000	0.075	0.002	0.000	1.000	0.000
50	63.613	60.931	0.430	0.070	0.000	0.118	0.003	0.000	1.000	0.000

Table 15. Decision Table for a sensitivity model (Selectivity = Maturity, Table 12) showing posterior probabilities that 2016 projected biomass B_t is below a set of candidate reference points and benchmarks (Table 6), and probabilities that the 2015 projected harvest rate U_t is above U_{2014} or U_{MSY} for a given level of female-only catch. Total catch is shown in columns 2 and 3 and is calculated by adding the male proportion based on the average of the last 4 years' proportions (column 2) and the average of the entire time series proportions (column 3). See table B.1 for proportion values.

2015 Female Catch (1000 t)	2015 Total Catch Last 4 yrs avg (1000 t)	2015 Total Catch all yrs avg (1000 t)	$P(B_{2016} < B_{2015})$	$P(B_{2016} < 0.4B_0)$	$P(B_{2016} < 0.2B_0)$	$P(B_{2016} < B_{1996})$	$P(B_{2016} < 0.8B_{MSY})$	$P(B_{2016} < 0.4B_{MSY})$	$P(U_{2015} > U_{2014})$	$P(U_{2015} > U_{MSY}$
0	0.000	0.000	0.000	0.114	0.012	0.000	0.020	0.006	0.000	0.000
2	2.545	2.437	0.000	0.117	0.012	0.000	0.021	0.006	0.000	0.000
4	5.089	4.874	0.000	0.122	0.012	0.000	0.022	0.007	0.000	0.000
6	7.634	7.312	0.000	0.125	0.012	0.000	0.022	0.007	0.000	0.000
8	10.178	9.749	0.000	0.131	0.012	0.000	0.022	0.007	0.000	0.000
10	12.723	12.186	0.000	0.135	0.013	0.000	0.022	0.007	0.130	0.000
11	13.995	13.405	0.000	0.138	0.013	0.000	0.022	0.007	0.760	0.000
12	15.267	14.623	0.000	0.139	0.013	0.000	0.022	0.007	0.994	0.000
13	16.539	15.842	0.000	0.140	0.013	0.000	0.022	0.007	1.000	0.000
14	17.812	17.061	0.000	0.142	0.013	0.000	0.022	0.007	1.000	0.000
15	19.084	18.279	0.000	0.145	0.013	0.000	0.022	0.007	1.000	0.000
16	20.356	19.498	0.001	0.148	0.013	0.000	0.022	0.007	1.000	0.000
17	21.628	20.717	0.001	0.151	0.013	0.000	0.022	0.007	1.000	0.000
18	22.901	21.935	0.003	0.151	0.013	0.000	0.022	0.007	1.000	0.000
19	24.173	23.154	0.004	0.152	0.013	0.000	0.023	0.007	1.000	0.000
20	25.445	24.372	0.007	0.157	0.013	0.000	0.024	0.007	1.000	0.000
22	27.990	26.810	0.015	0.164	0.013	0.000	0.024	0.007	1.000	0.000
24	30.534	29.247	0.022	0.170	0.014	0.000	0.024	0.007	1.000	0.000
26	33.079	31.684	0.039	0.174	0.014	0.000	0.024	0.007	1.000	0.000
28	35.623	34.121	0.063	0.188	0.014	0.000	0.024	0.007	1.000	0.000
30	38.168	36.559	0.094	0.195	0.014	0.000	0.024	0.007	1.000	0.000

8. FIGURES

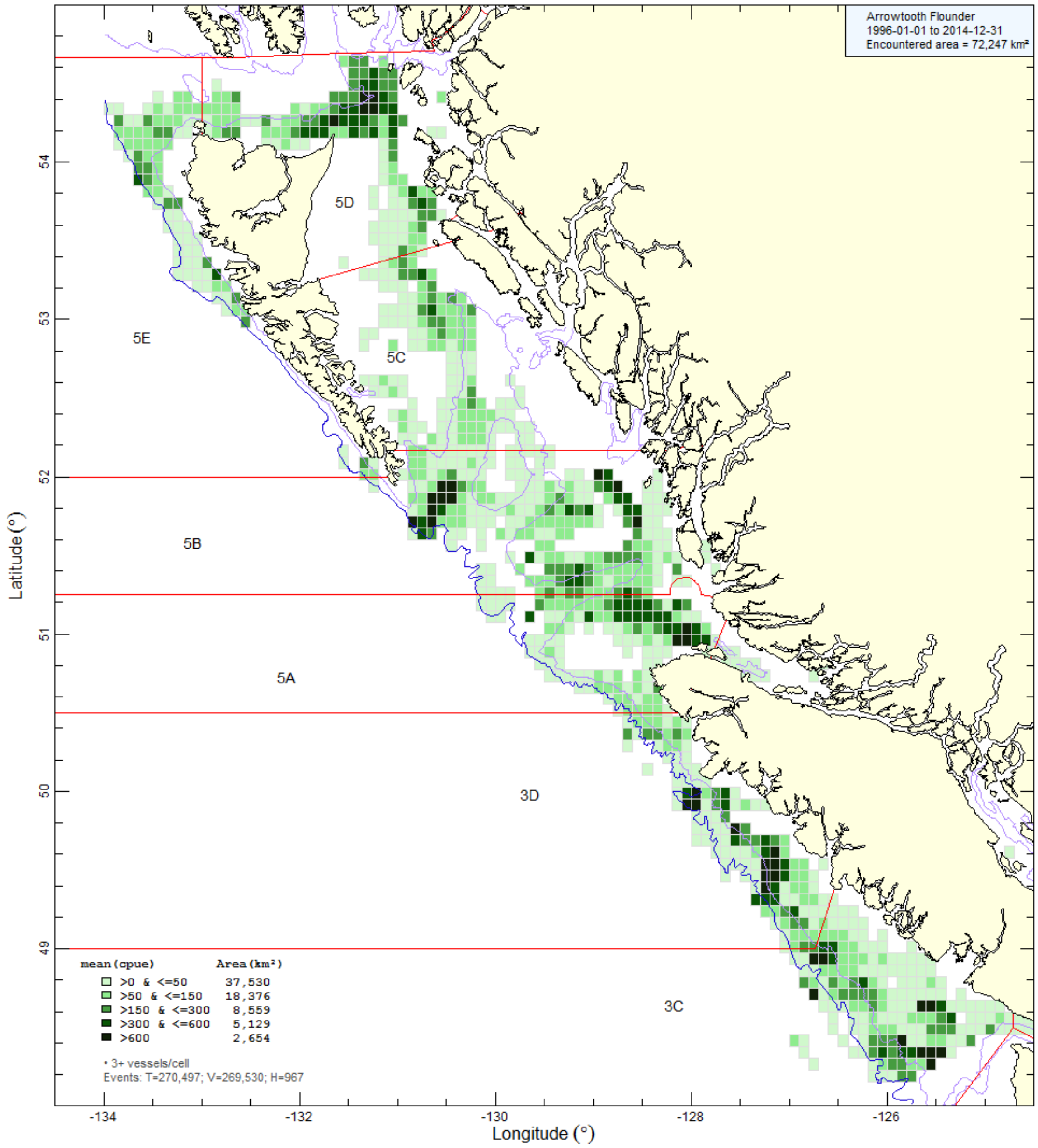


Figure 1. Mean catch-per-unit-effort (CPUE, kg/h) of Arrowtooth Flounder in grid cells 0.1° longitude by 0.075° latitude (roughly 57.8 km^2). The shaded cells give an approximation of the area where Arrowtooth Flounder was encountered by fishing events from the groundfish trawl fishery from January 1, 1996 to December 31, 2014. Contours are 200 m and 1000 m isobaths. Red lines are PFMA area boundaries.

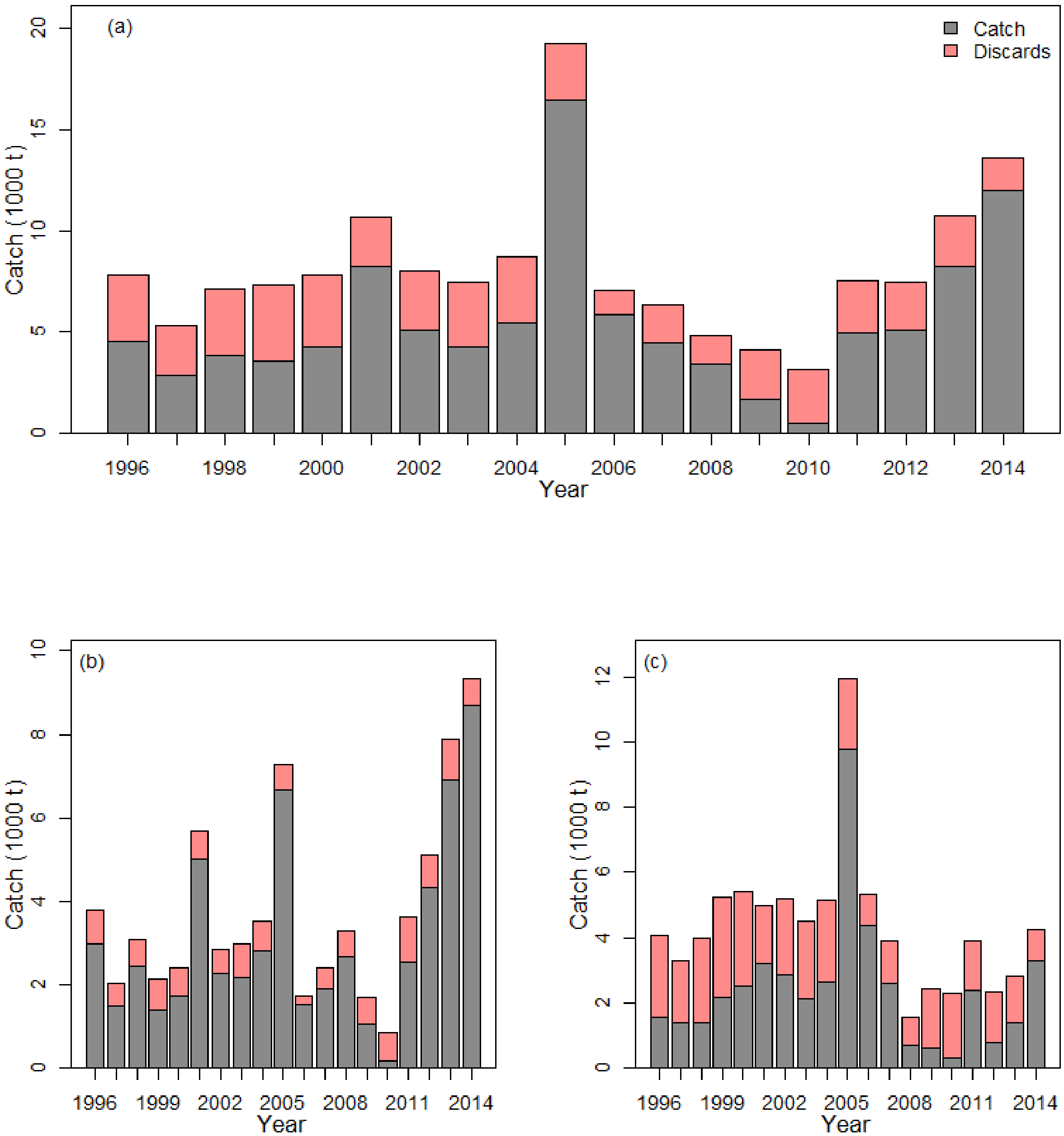


Figure 2. Total coastwide catch of Arrowtooth Flounder, including both landings and discards (a). Panels (b) and (c) represent areas 3CD and 5ABCDE respectively. See Table 1 for values.

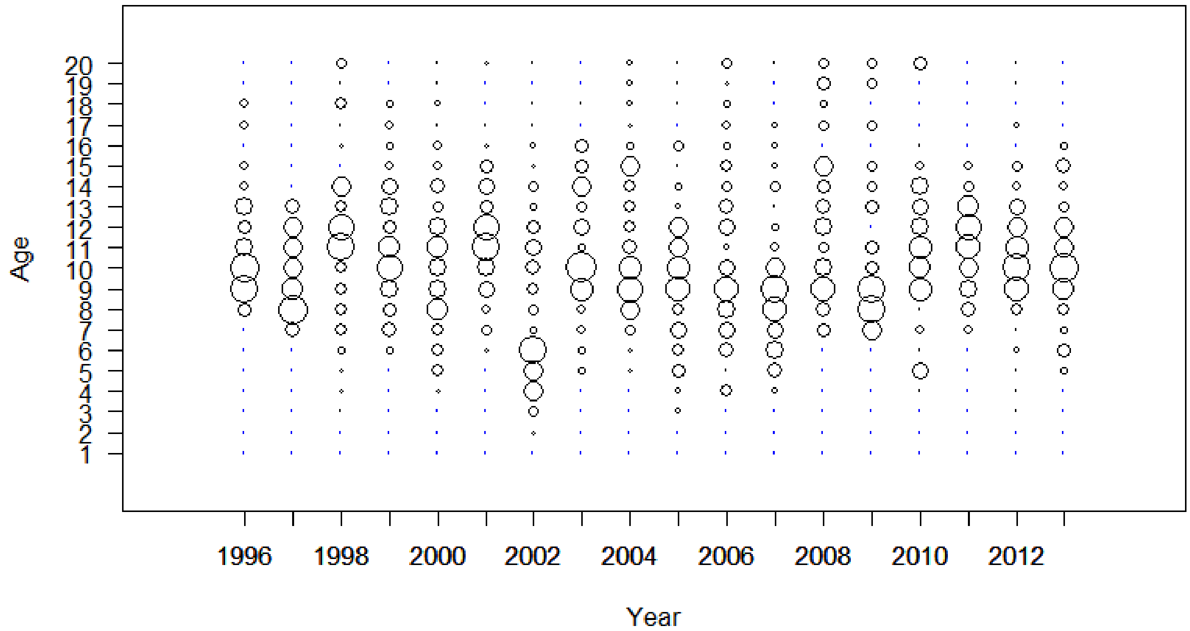


Figure 3. Age composition data for the Reference Case for the commercial trawl fishery. Blue points represent zero samples.

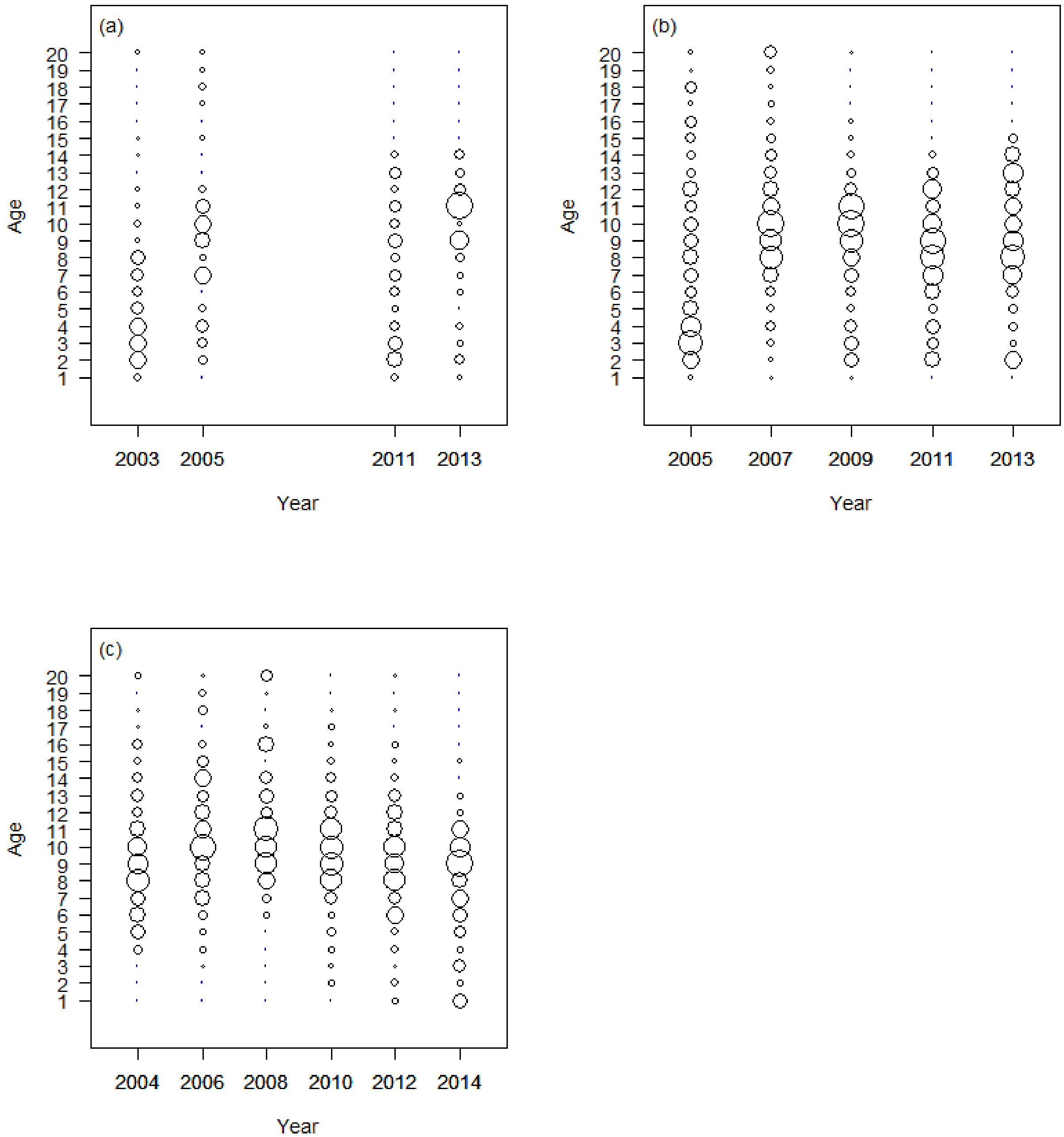


Figure 4. Age composition data for the Reference Case for the surveys (a) QCSSS, (b) HSSS, and (c) WCVISS. Blue points represent zero samples.

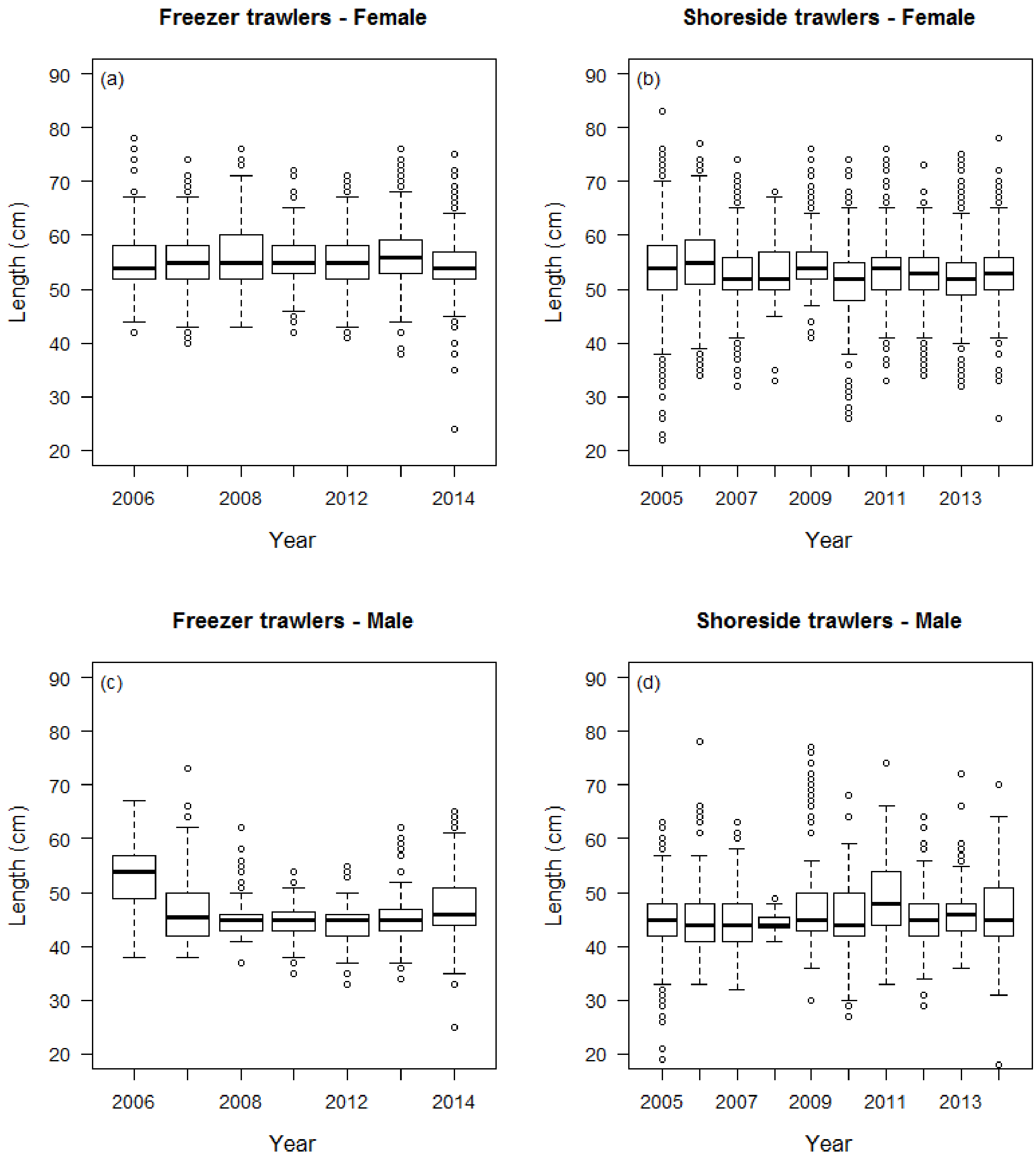


Figure 5. Length quantiles (2.5th, 50th, and 97.5th percentiles) from samples taken on freezer trawler vessels (a and c) and shoreside vessels (b and d) for females (a and b) and males (c and d).

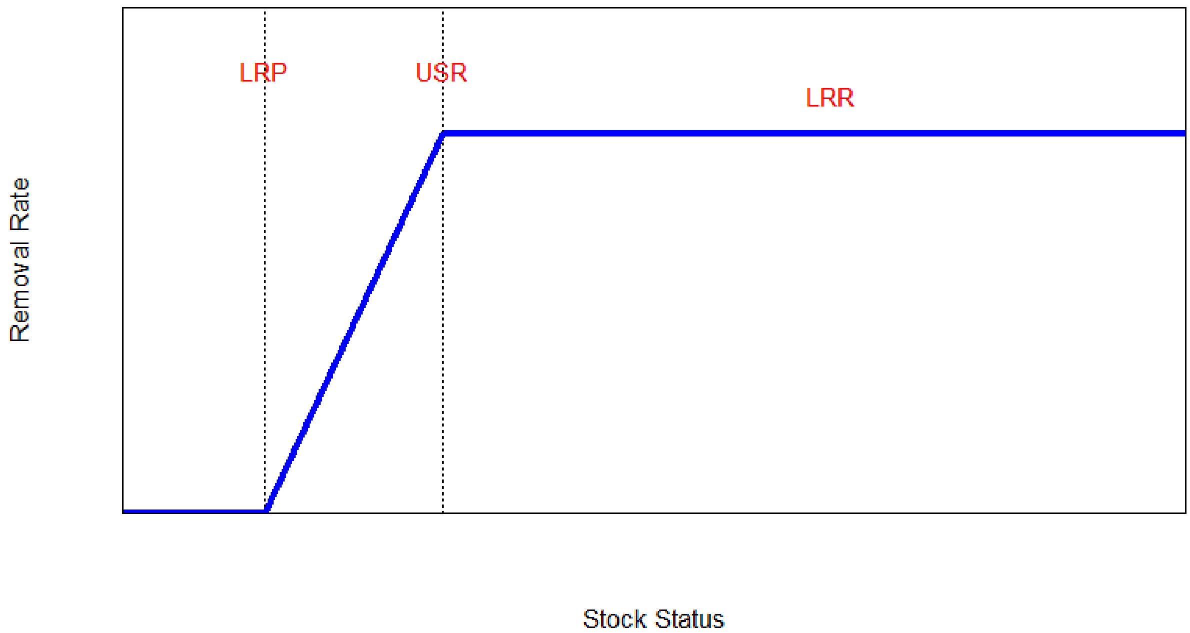


Figure 6. Illustration of a harvest control rule consistent with the Precautionary Approach for a hypothetical stock. The biomass-based reference points are shown as vertical dotted lines. The limit removal rate is shown as a horizontal blue line. In this illustration, biomass (unspecified units) is shown on the bottom axis. LRP = Limit Reference Point; USR = Upper Stock Reference; LRR = Limit Removal Rate. See DFO (2009) for more detail.

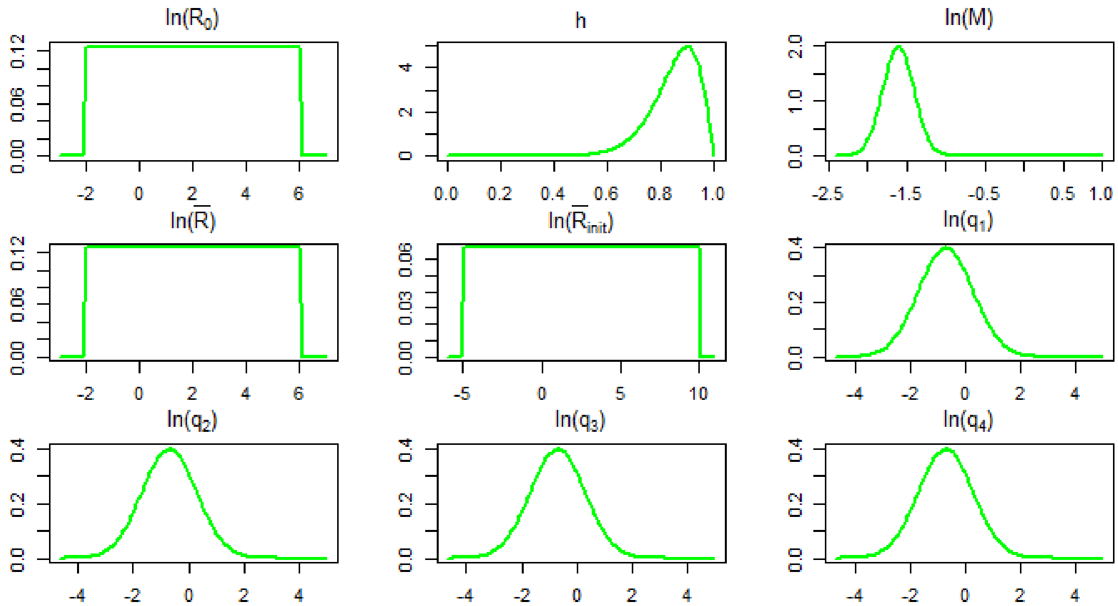


Figure 7. Prior probability distributions used in the Reference Case. Parameters q_k represent gears where: $k = 2$ is the QCSSS, $k = 3$ is the HSMAS, $k = 4$ is the HSSS, and $k = 5$ is the WCVISS.

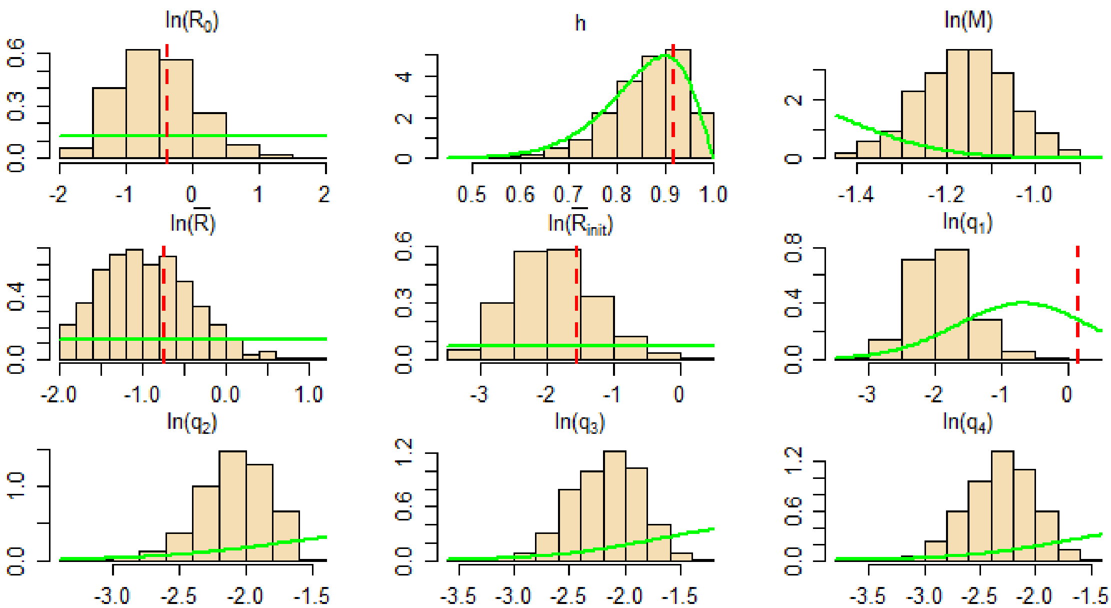


Figure 8. Prior probability distributions used in the Reference case with comparative posterior histograms. Parameters q_k represent gears where: $k = 2$ is the QCSSS, $k = 3$ is the HSMAS, $k = 4$ is the HSSS, and $k = 5$ is the WCVISS. The dotted red lines are the MPD estimates from the Reference Case.

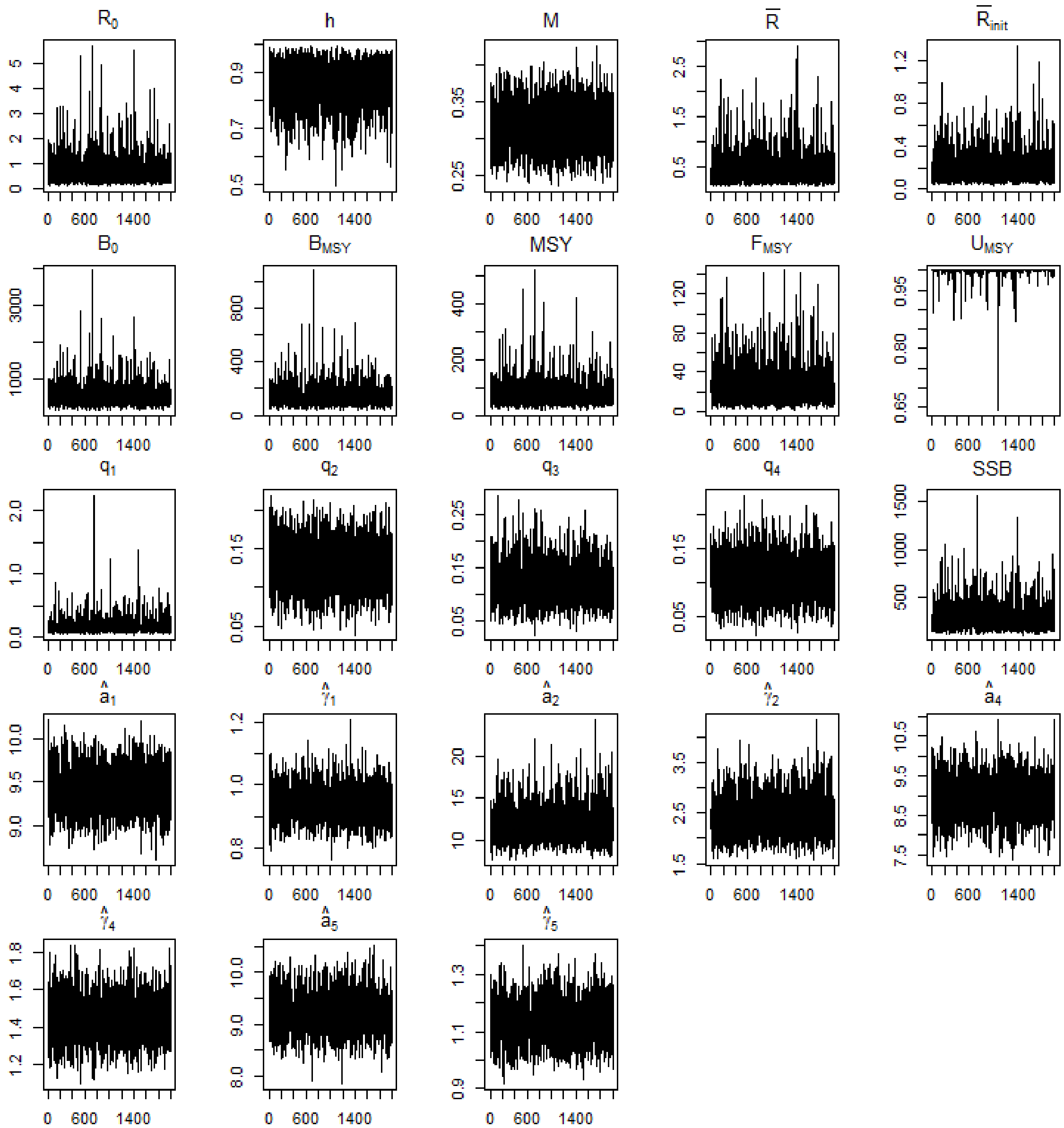


Figure 9. Trace plots for MCMC output of estimated parameters in the Reference Case. The MCMC run had chain length 15 million, with a sample taken at every 7,500th iteration. Of the 2,000 samples saved, the first 1,000 were removed as a burn-in period. Parameters q_k (catchability), $\hat{a}_k$ (selectivity-at-age-50%), and $\hat{\gamma}_k$ (selectivity standard deviation-at-50%) represent gears as follows: $k = 1$: commercial trawl; $k = 2$: QCSSS: $k = 3$; HSMAS: $k = 4$; HSSS, and $k = 5$; WCVISS. The HSMAS did not have estimates selectivity, so there are no $\hat{a}_3$ or $\hat{\gamma}_3$ parameters.

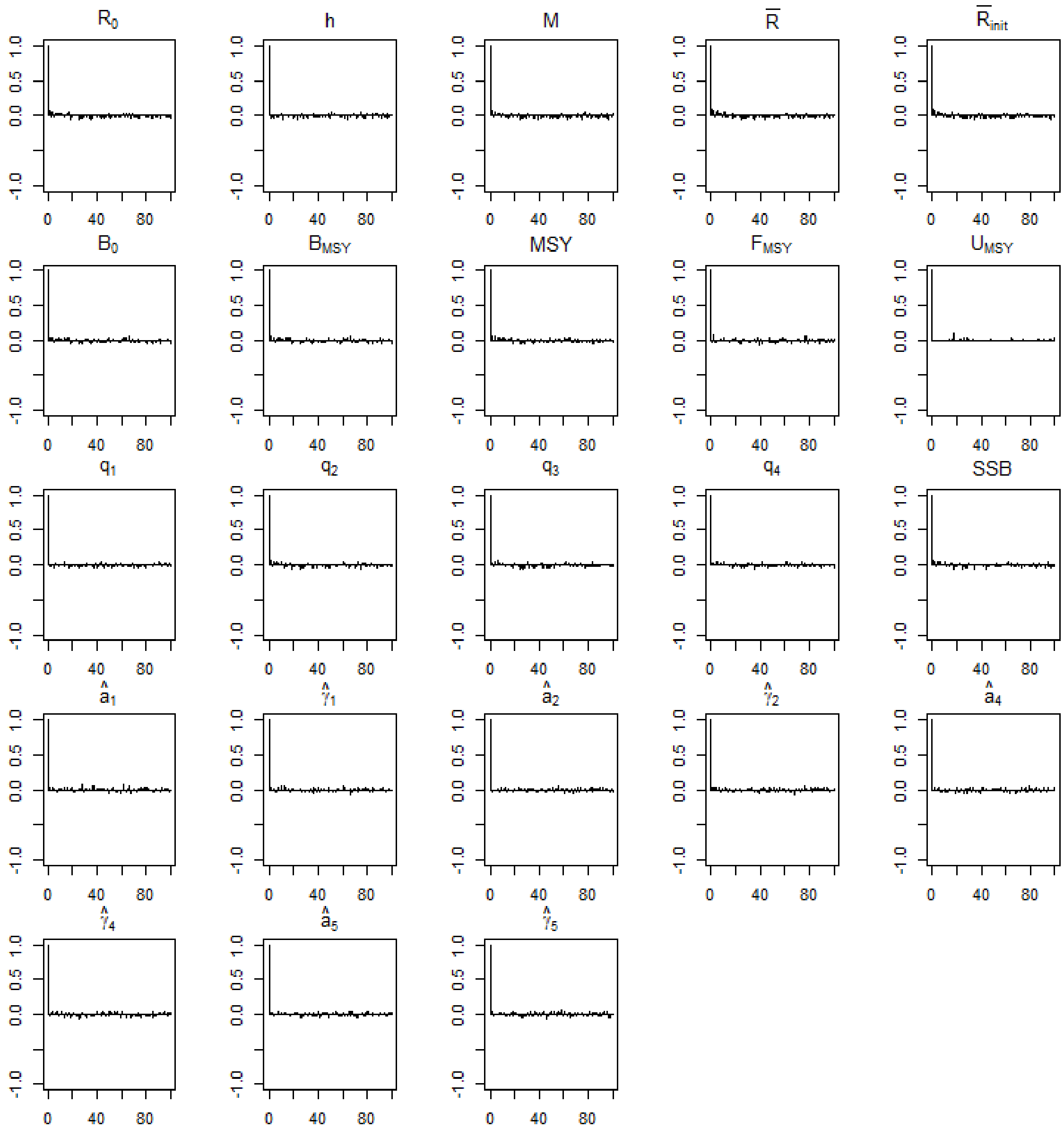


Figure 10. Autocorrelation plots for MCMC output of estimated parameters in the Reference Case. See Figure 9 for parameter descriptions.

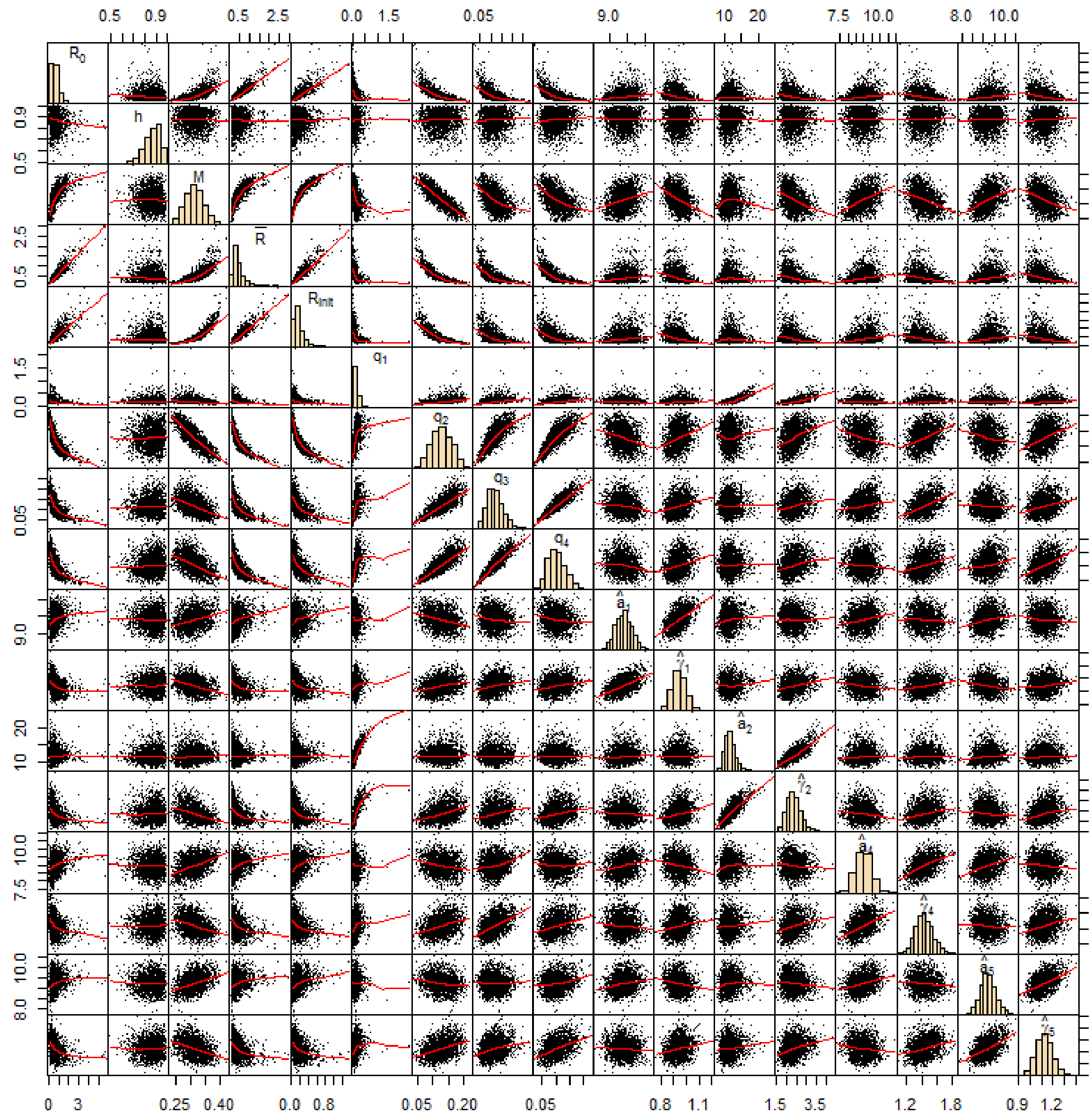


Figure 11. Pairs plots for MCMC output of estimated parameters in the Reference Case. See Figure 9 for parameter descriptions.

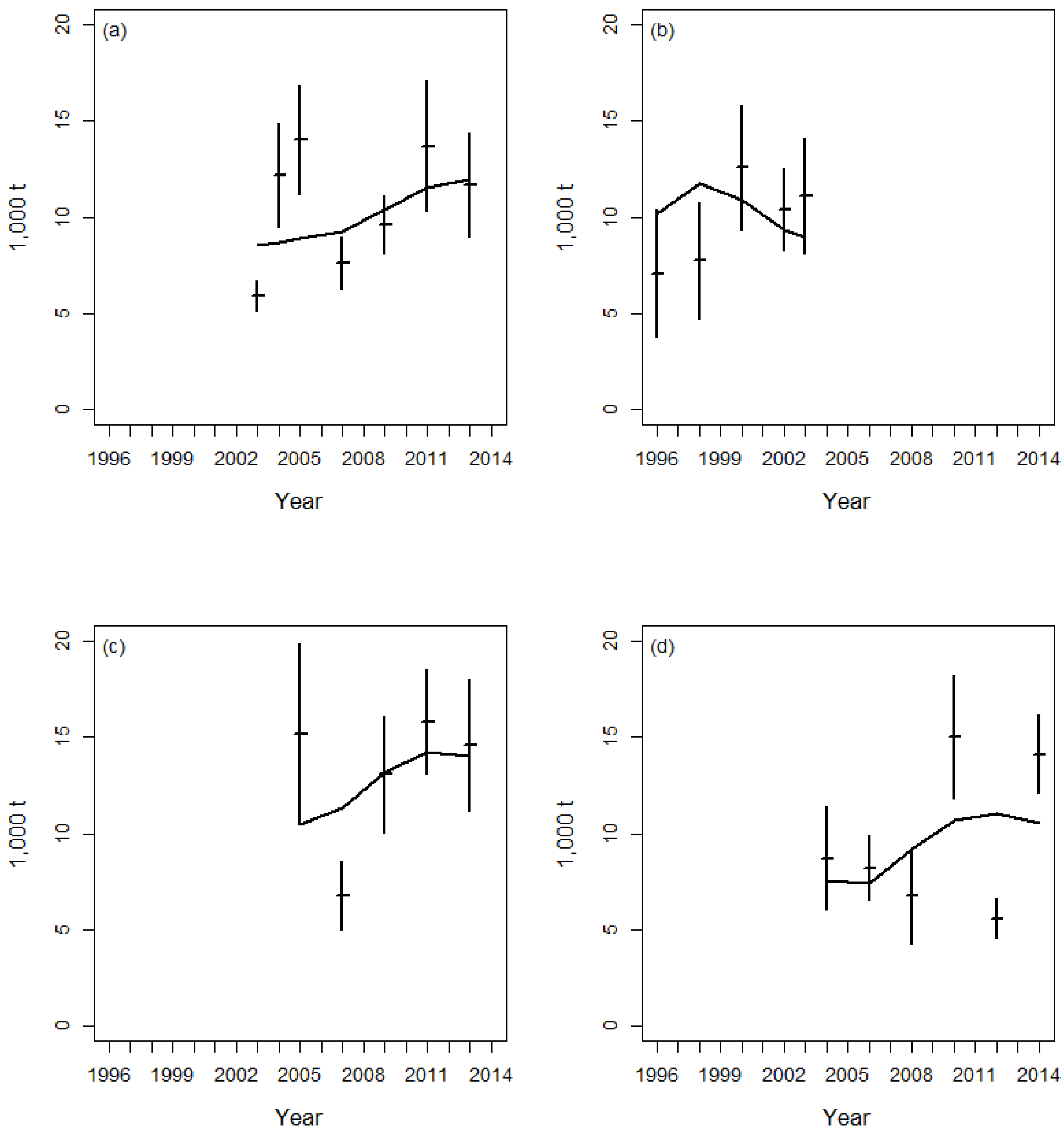


Figure 12. Reference Case MPD Index fits for (a) QSSS, (b) HSMAS, (c) HSSS, (d) WCVISS.

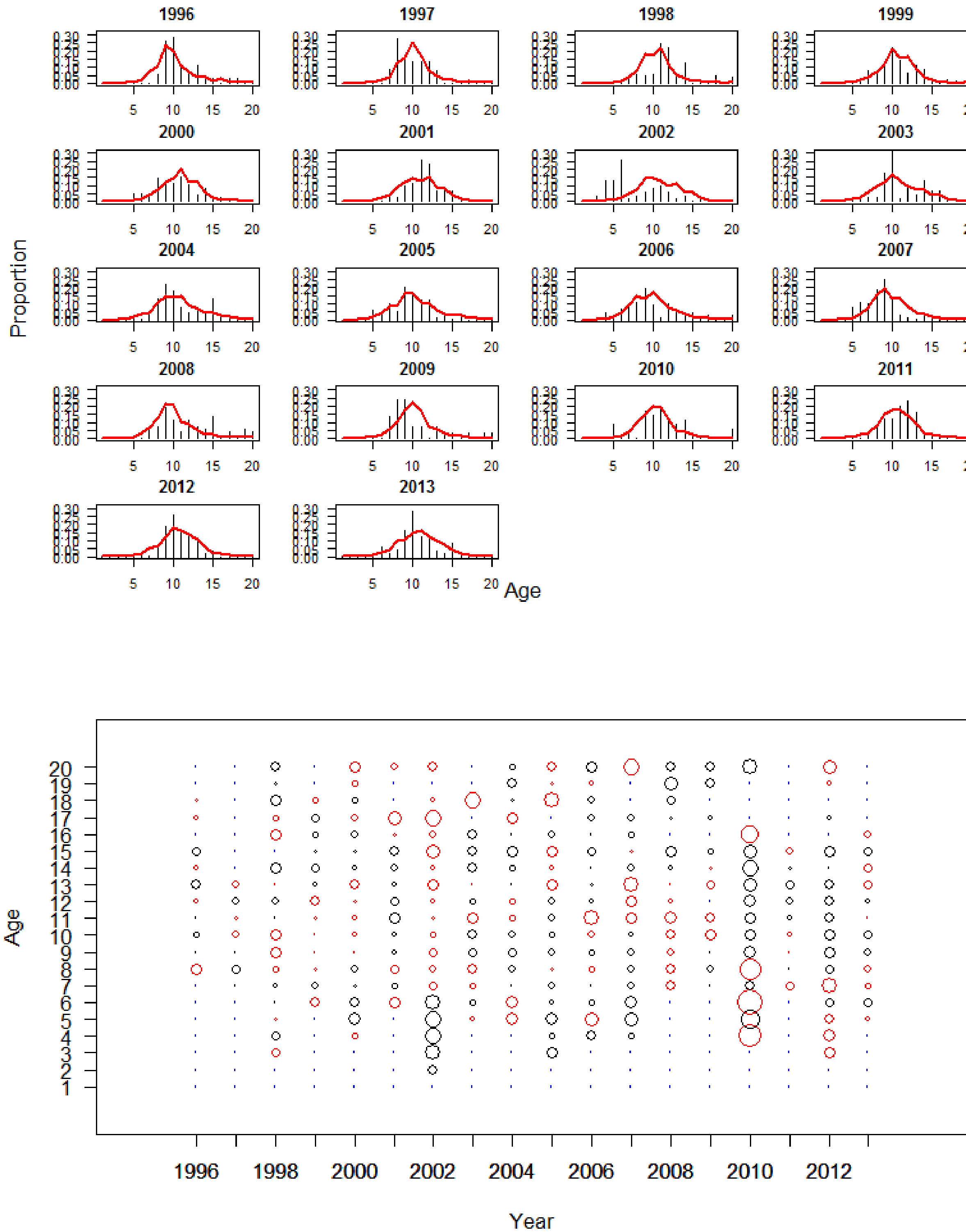


Figure 13. Age composition fits (top) and residuals (bottom) for the Reference Case for the commercial trawl fishery. Blue points represent zero samples, red are positive residuals, and black are negative residuals.

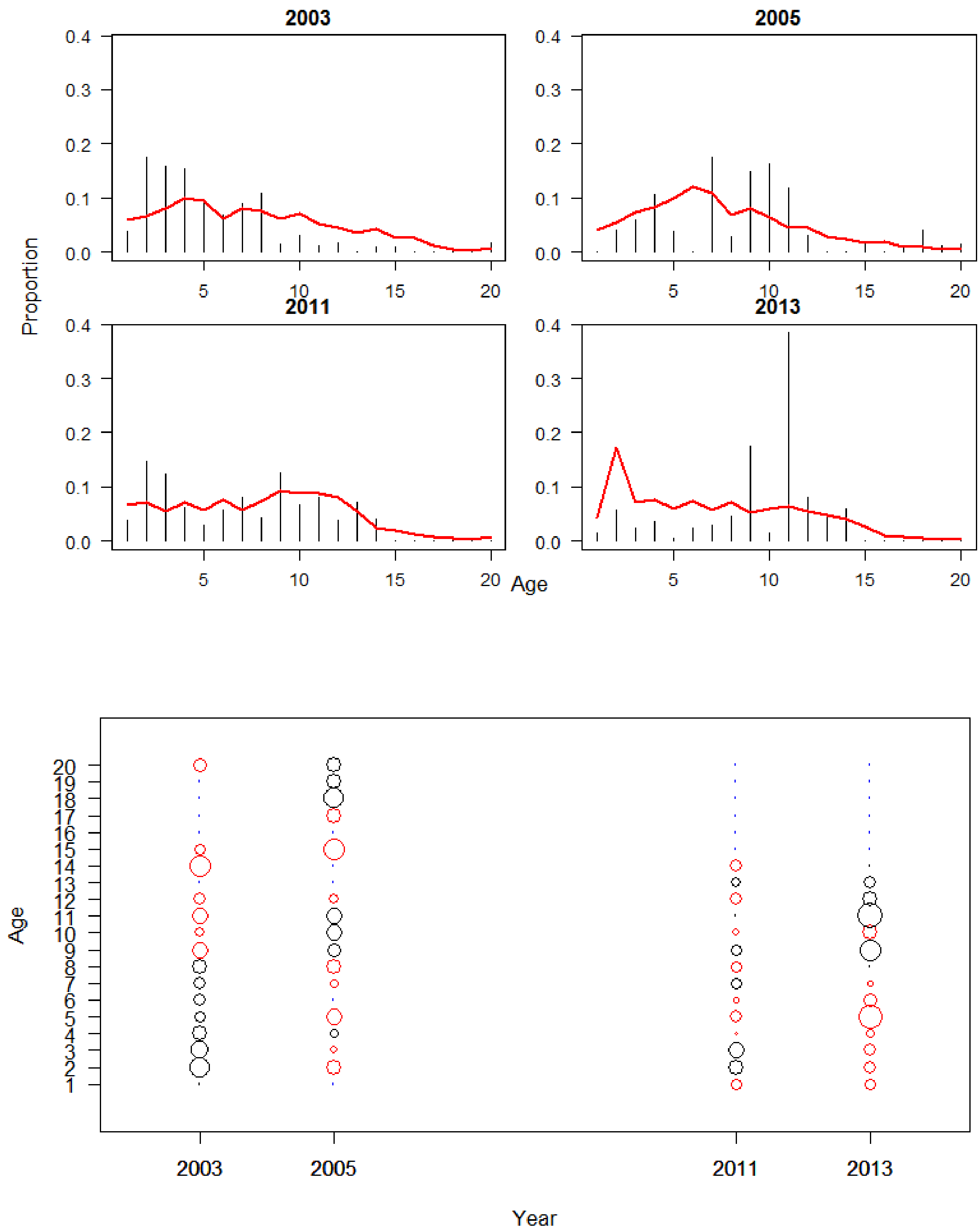


Figure 14. Age composition fits and residuals for the Reference Case for the QCSSS. Blue points represent zero samples, red are positive residuals, and black are negative residuals.

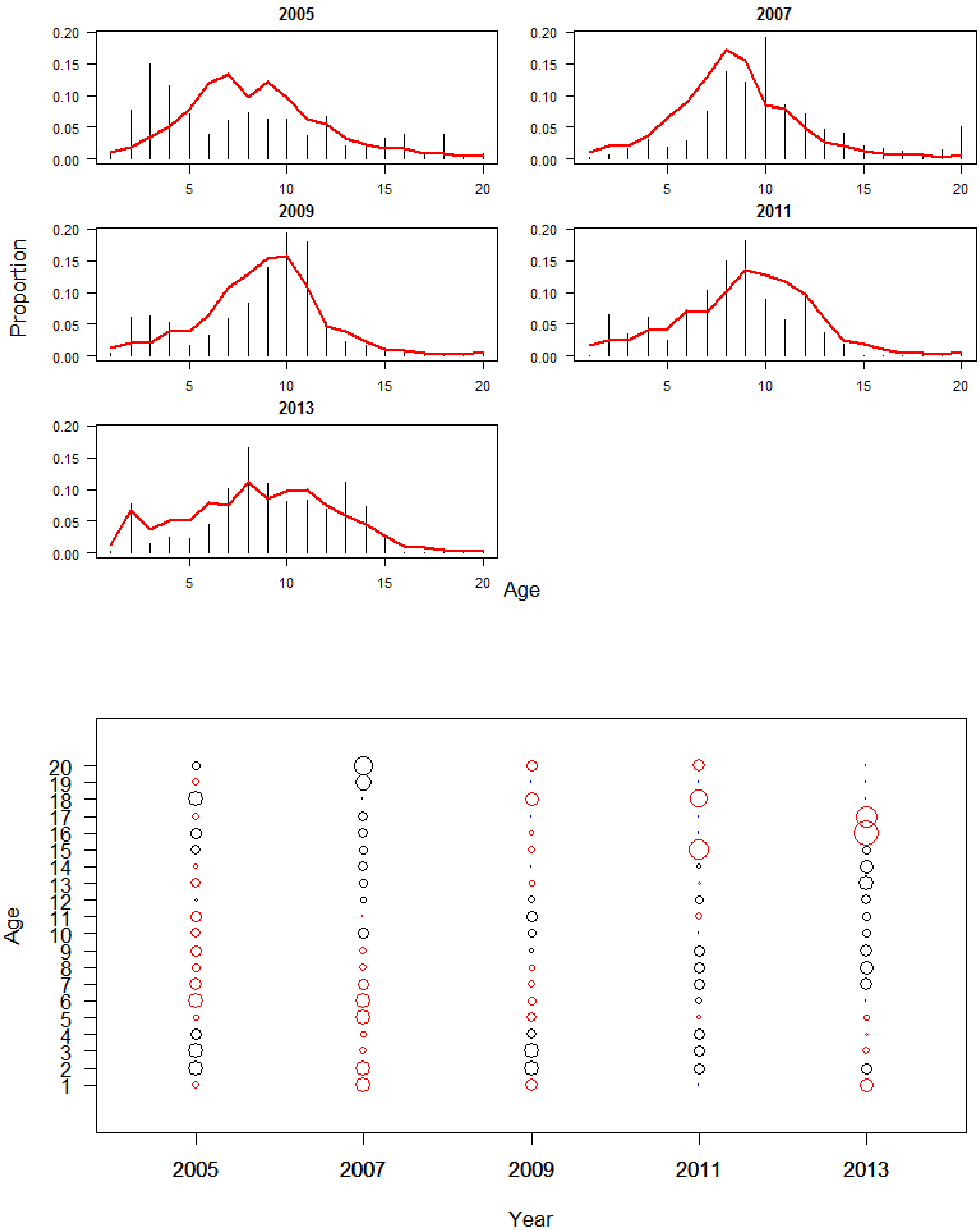
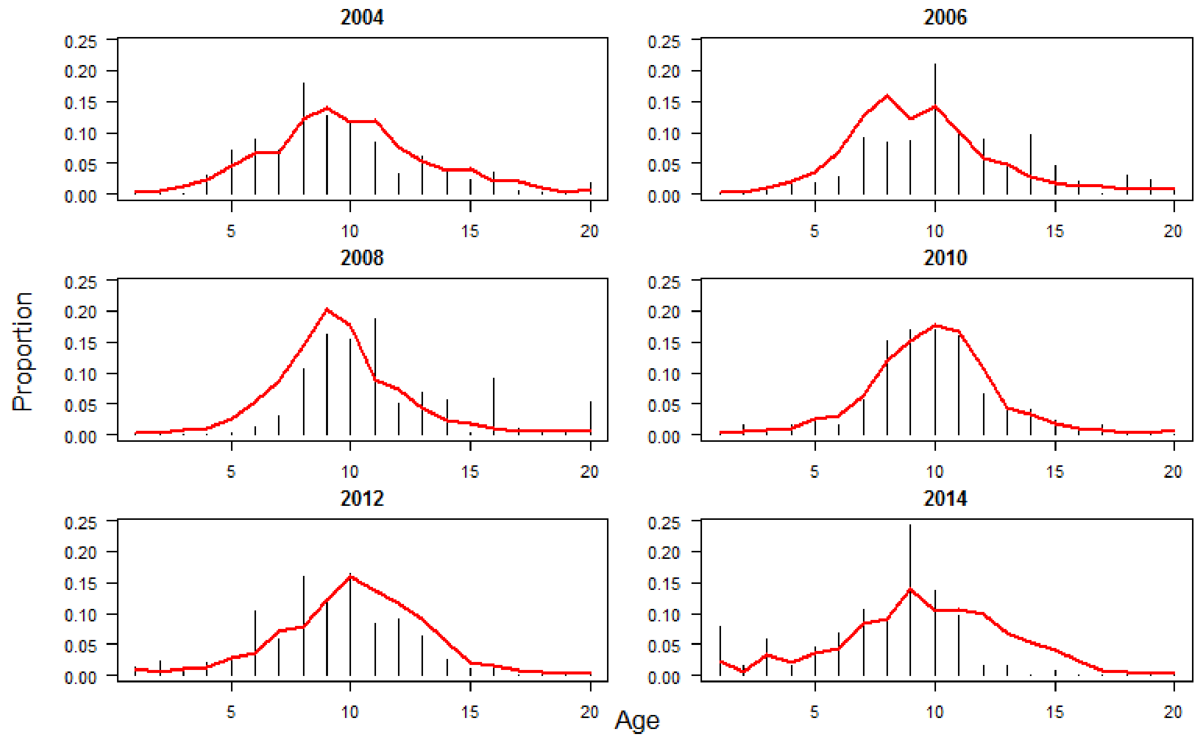


Figure 15. Age composition fits and residuals for the Reference Case for the HSSS. Blue points represent zero samples, red are positive residuals, and black are negative residuals.



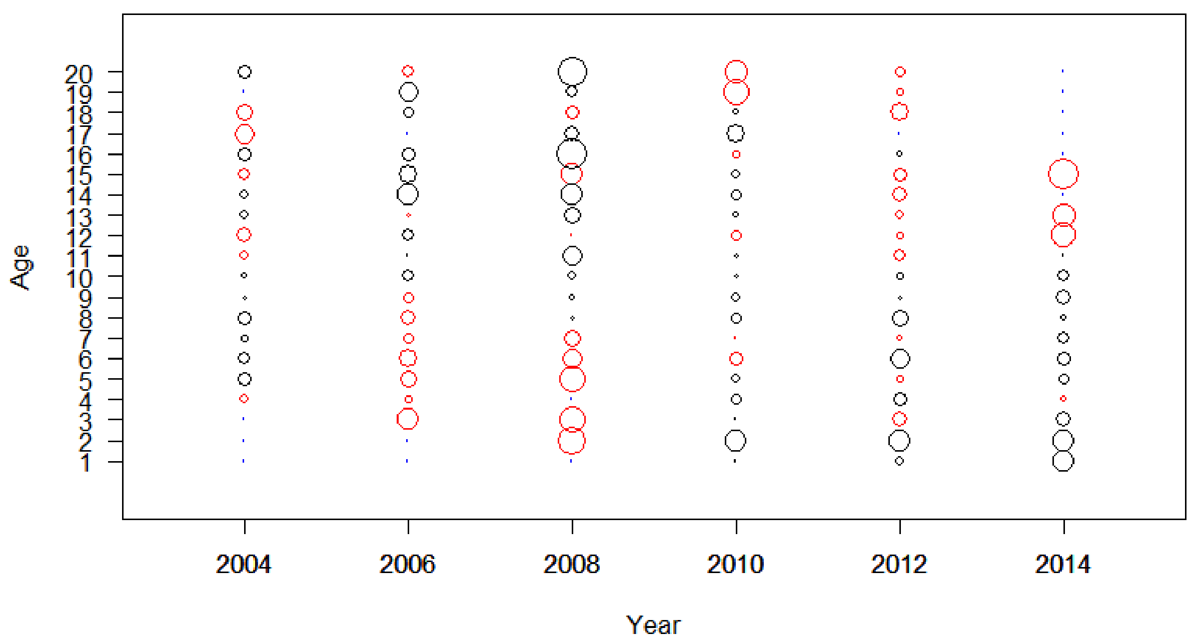


Figure 16. Age composition fits and residuals for the Reference Case for the WCVISS. Blue points represent zero samples, red are positive residuals, and black are negative residuals.

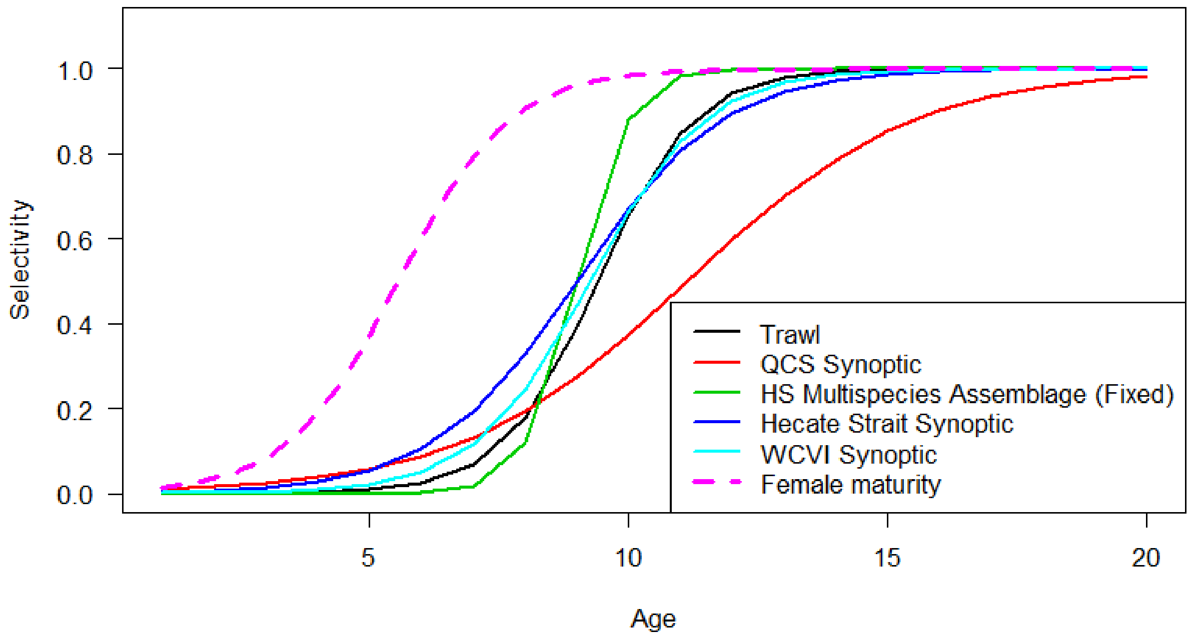


Figure 17. Estimated and Fixed selectivities for the Reference Case, compared with female maturity.

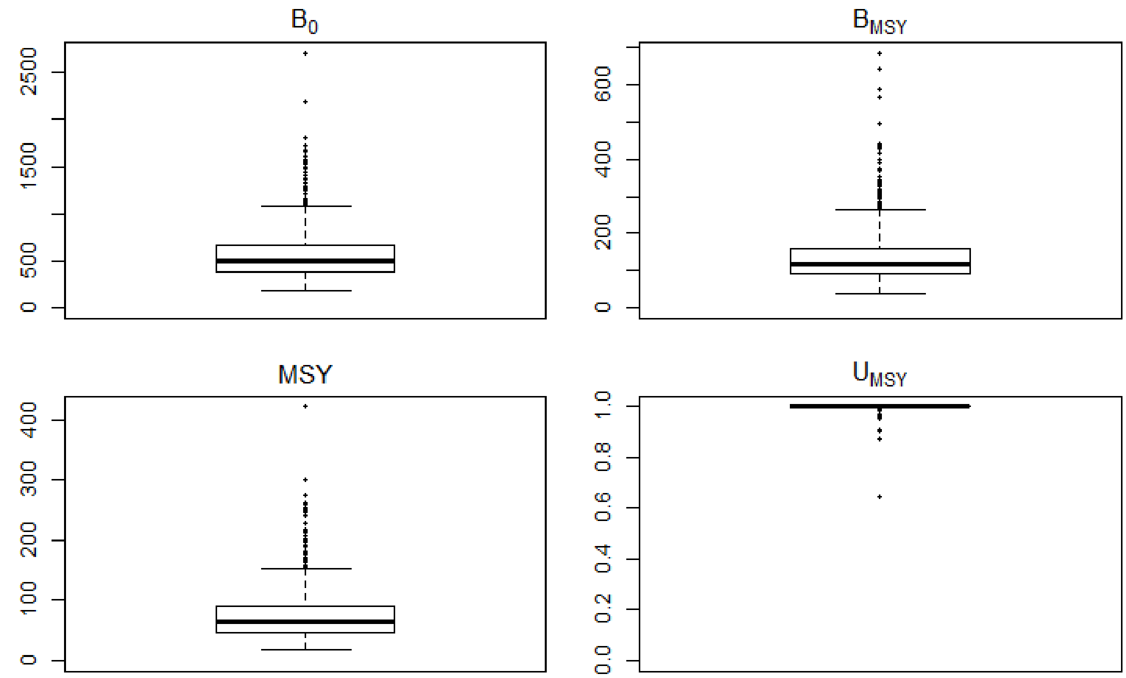


Figure 18. Posterior reference points for the Reference Case. Bars represent 95% credible intervals. MSY, B_0, and B_{MSY} values are in thousands of tonnes.

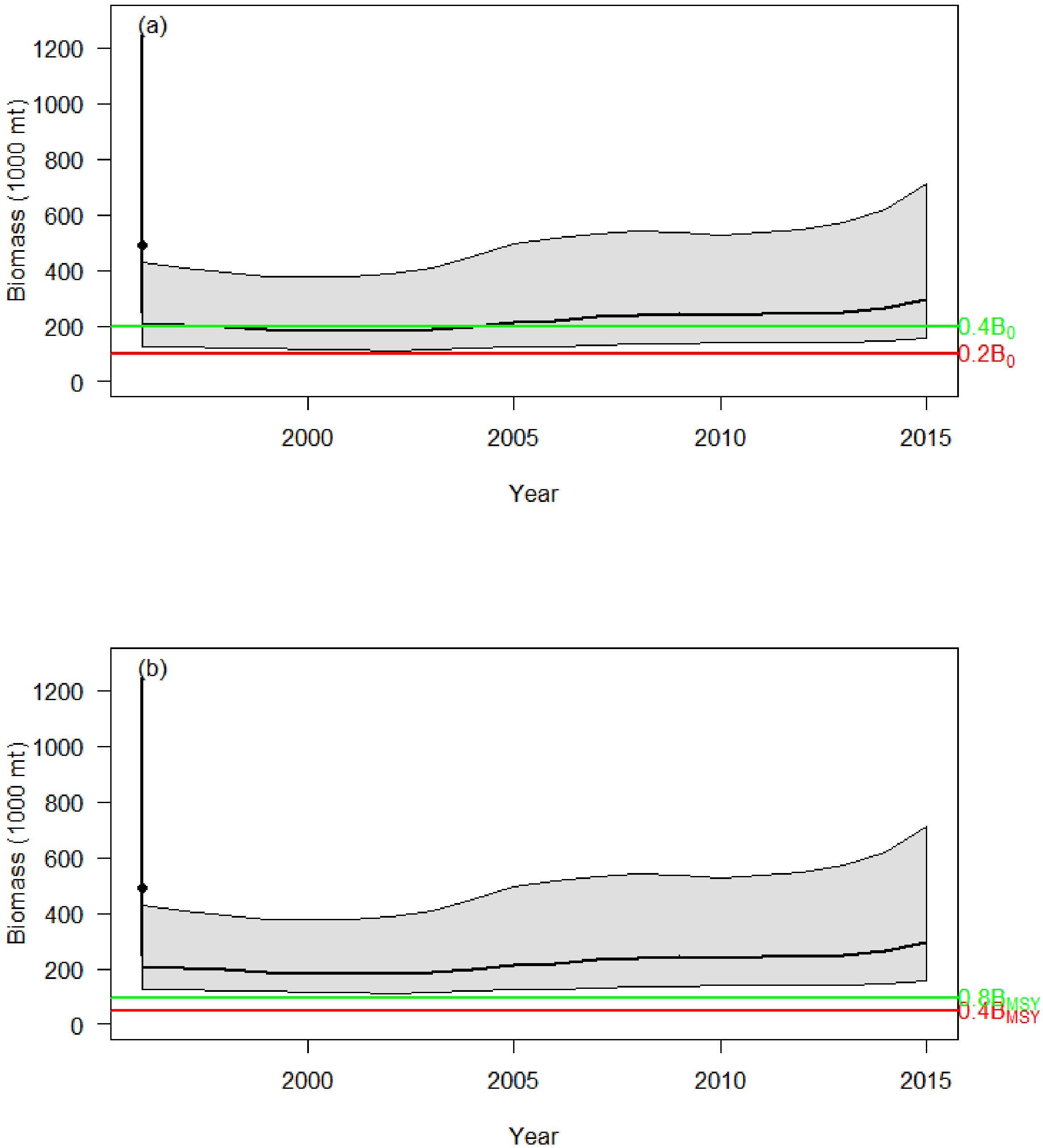


Figure 19. Median posterior spawning biomass for the Reference Case. The shaded area represents the 95% credible interval. The point and bars represent the median estimate of B_0 and with a credible interval of 95%. Panel (a) shows posterior median estimates of reference points 0.2B_0 and 0.4B_0, Panel (b) shows posterior median estimates of reference points 0.4B_{MSY} and 0.8B_{MSY}.

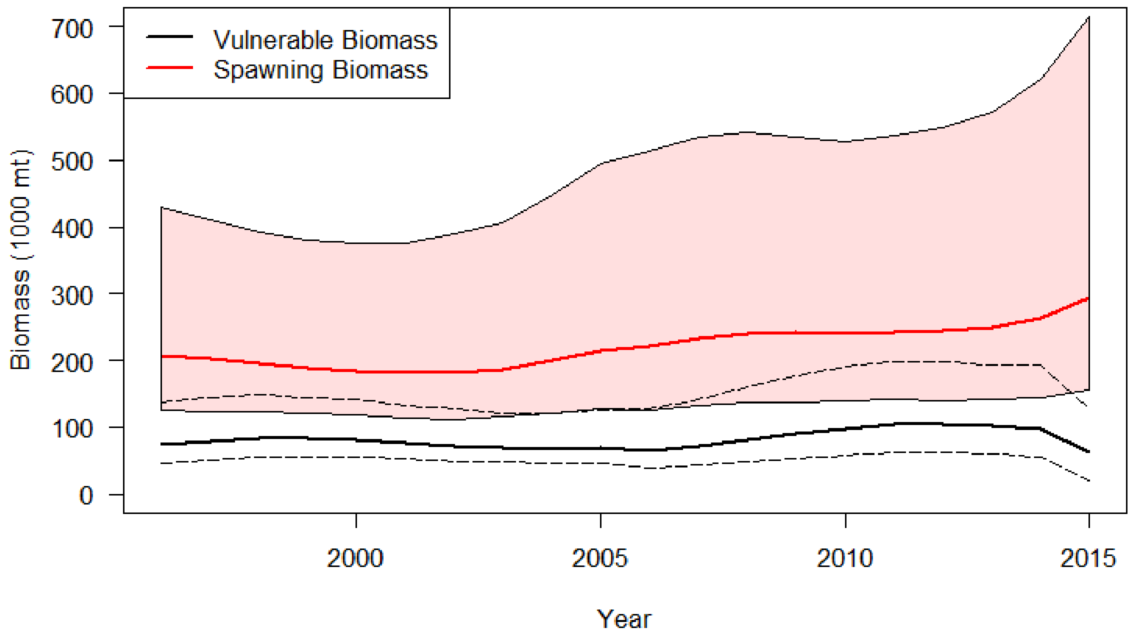


Figure 20. Median posterior vulnerable and spawning biomass for the Reference Case. The shaded area and dotted lines represent the 95% credible interval.

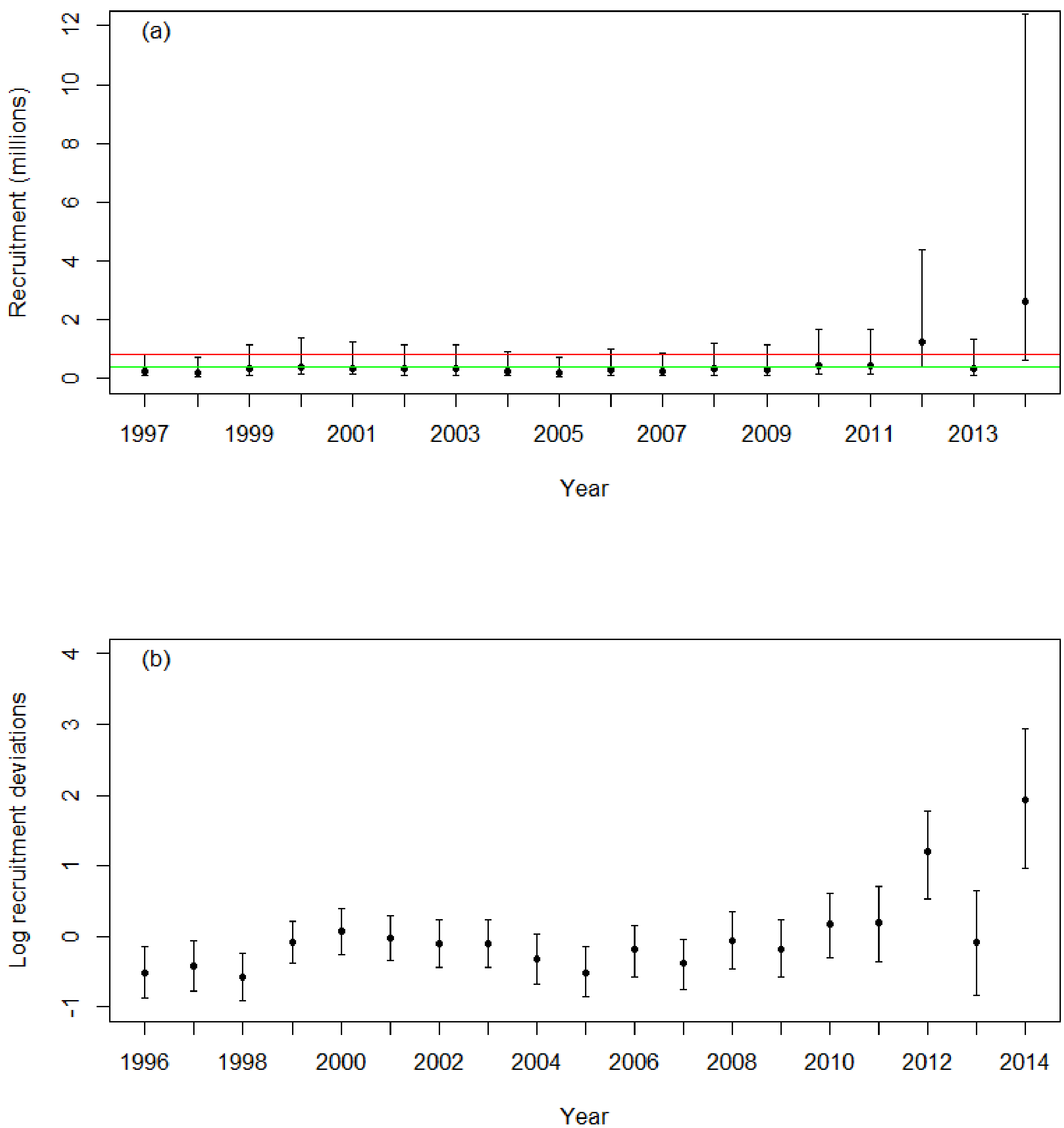


Figure 21. Median posterior recruitment (a) and recruitment deviations (b) for the Reference Case. The bars represent the 95% credible interval. The red line is the long-term mean; the green line is the long-term median.

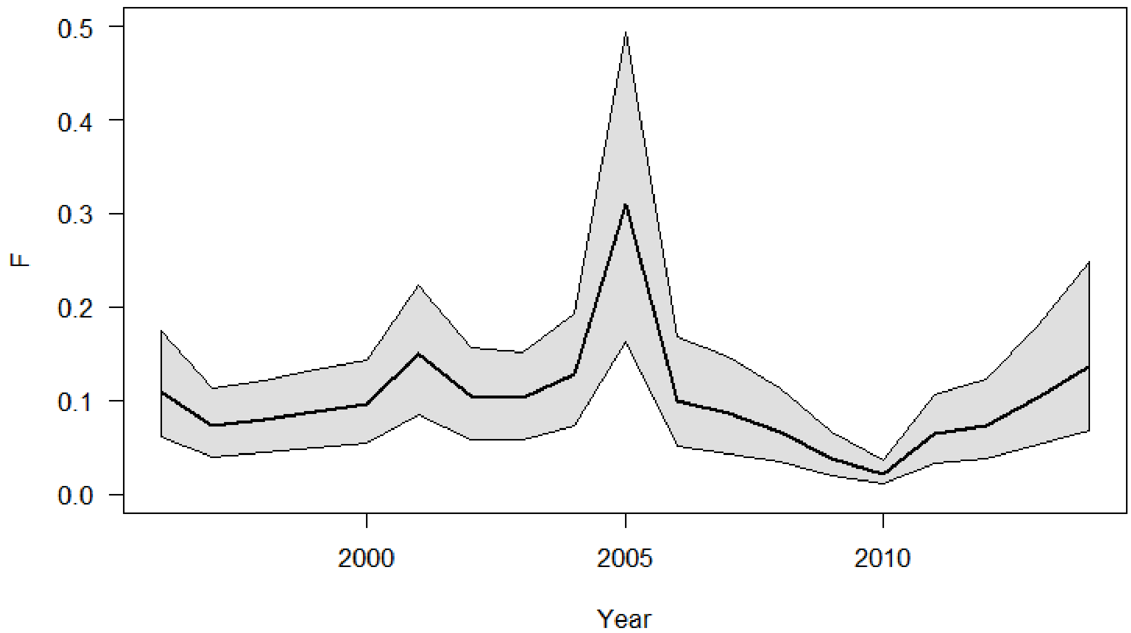


Figure 22. Fishing mortality for the Reference Case. The shaded area represents the 95% credible interval.

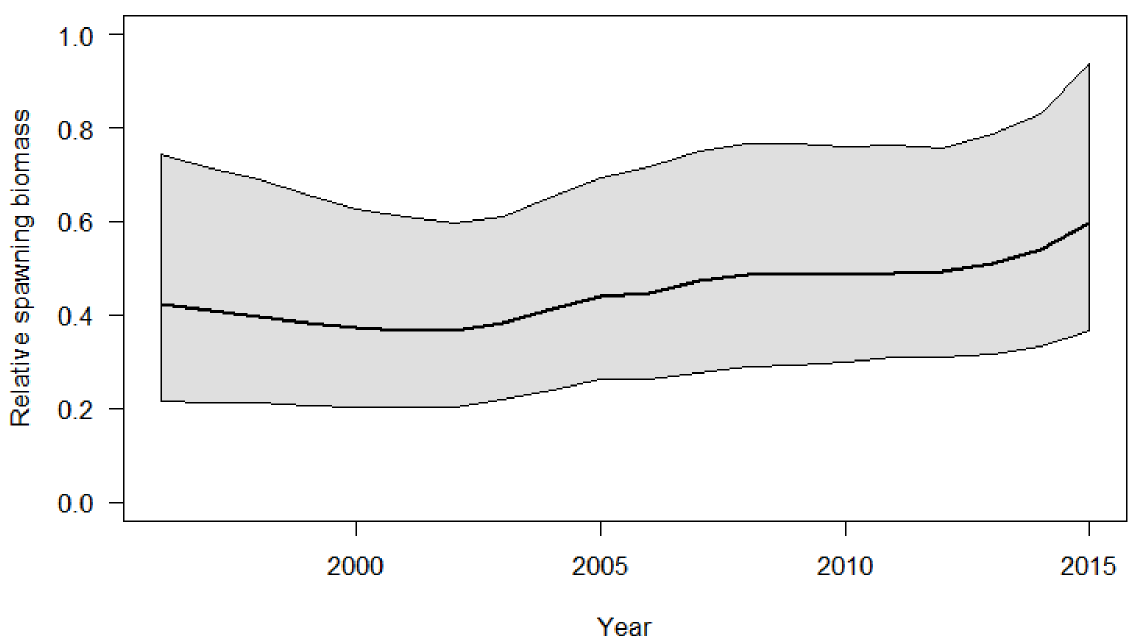


Figure 23. Relative median posterior spawning biomass for the Reference Case. The shaded area represents the 95% credible interval.

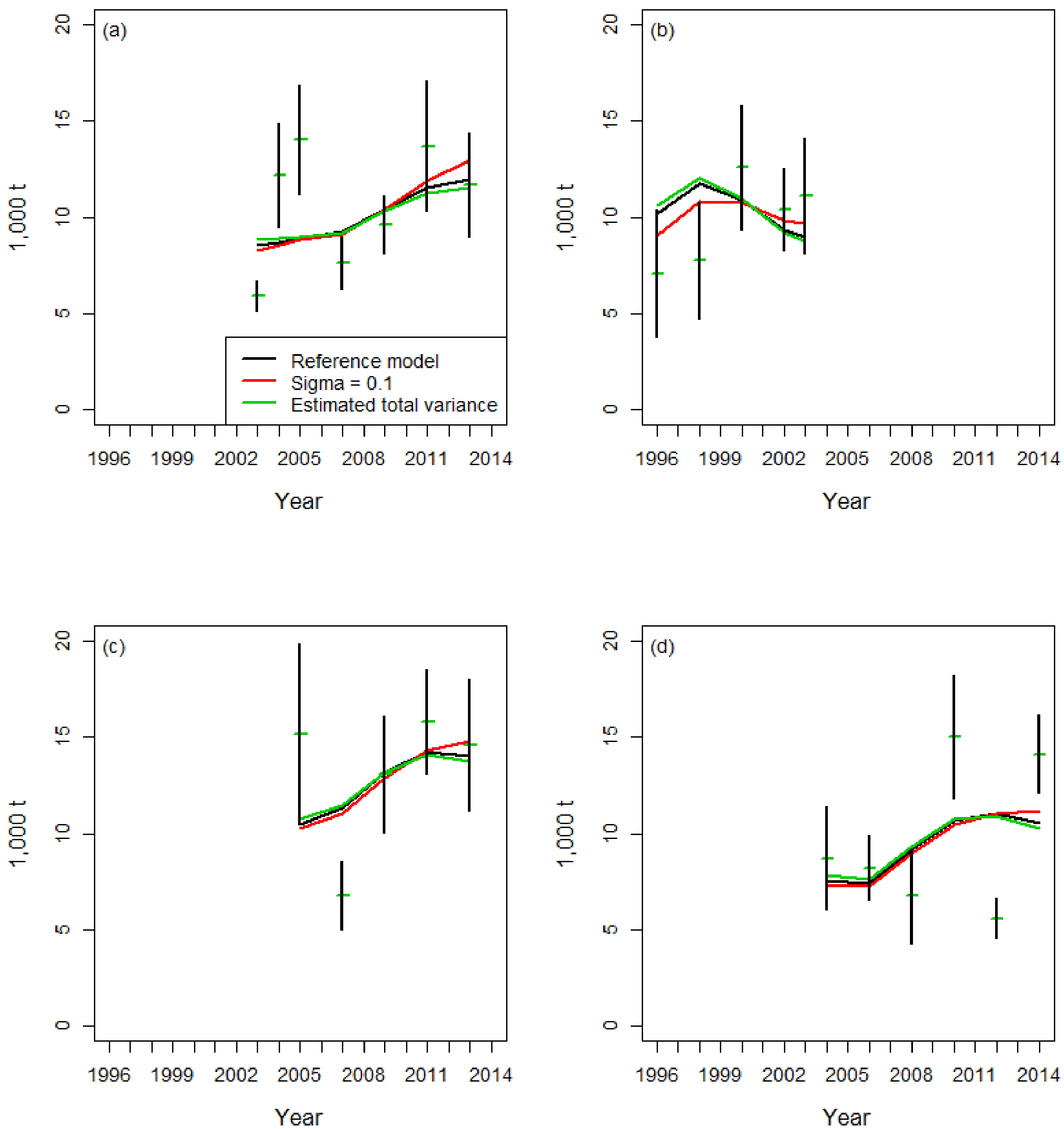


Figure 24. MPD Index fits for (a) QSSS, (b) HSMAS, (c) HSSS, (d) WCVISS for models examining sensitivity to the σ parameter.

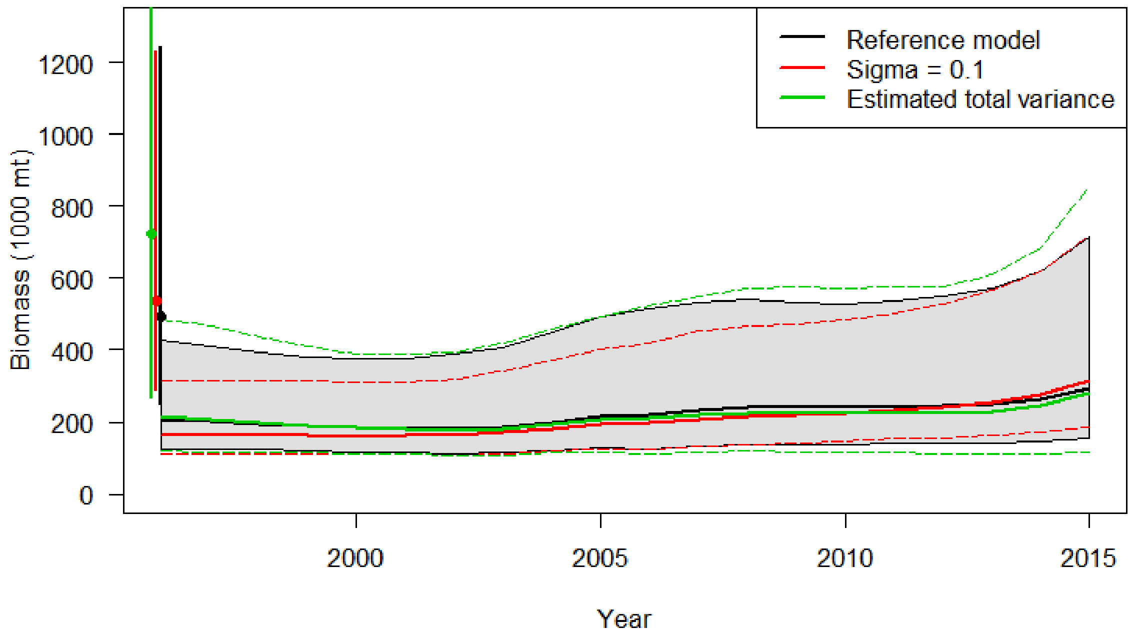
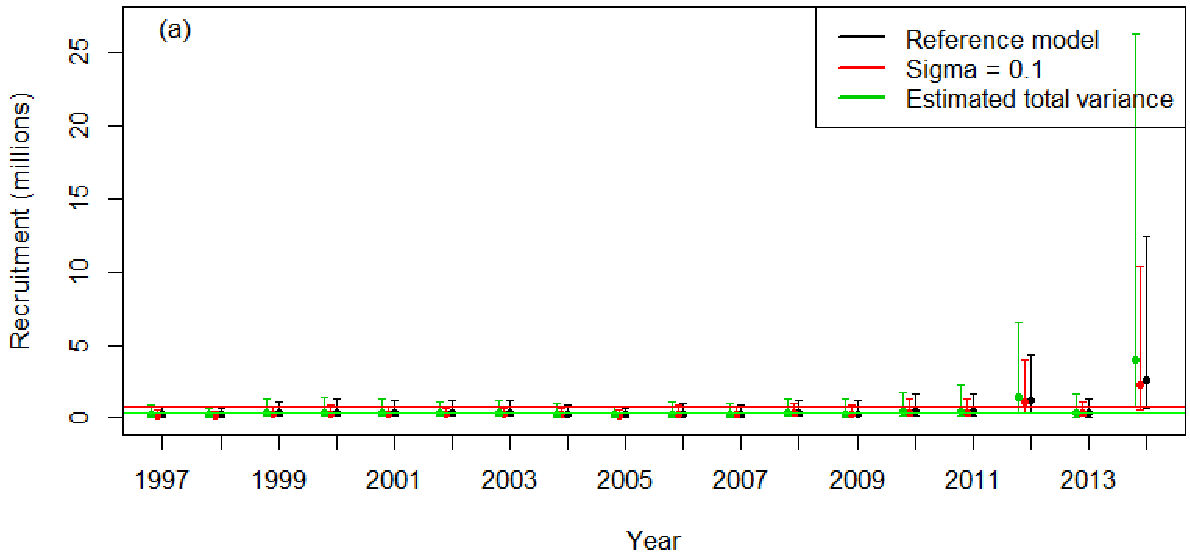


Figure 25. Estimated median spawning biomass with 95% credible intervals, for models examining sensitivity to the σ parameter. Points and bars represent the estimates of B_0 with 95% credible interval.



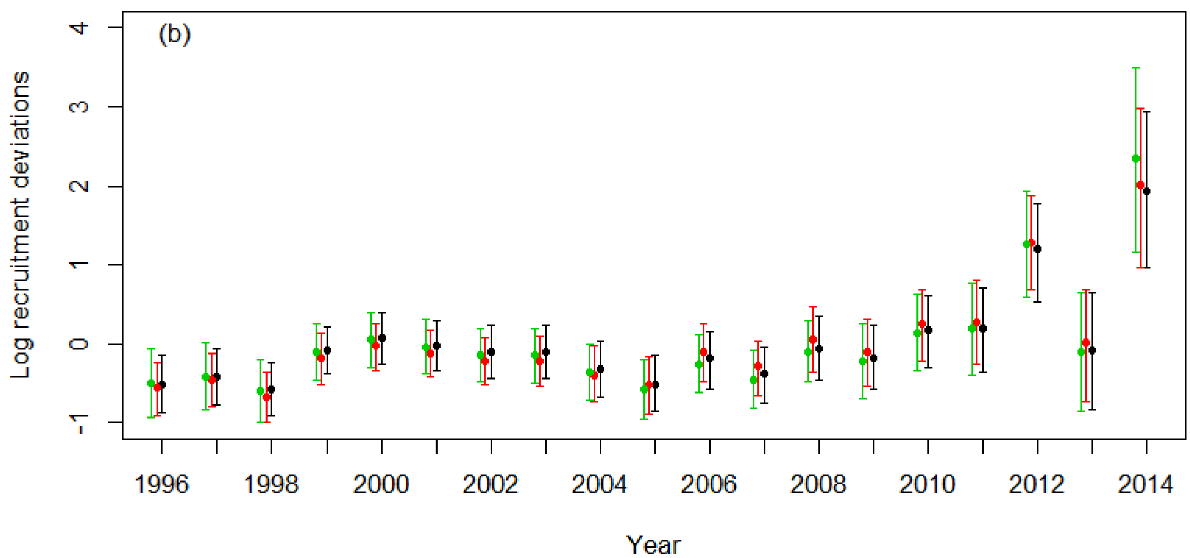


Figure 26. Estimated recruitment (a) and recruitment deviations (b) with 95% credible intervals, for models examining sensitivity to the σ parameter.

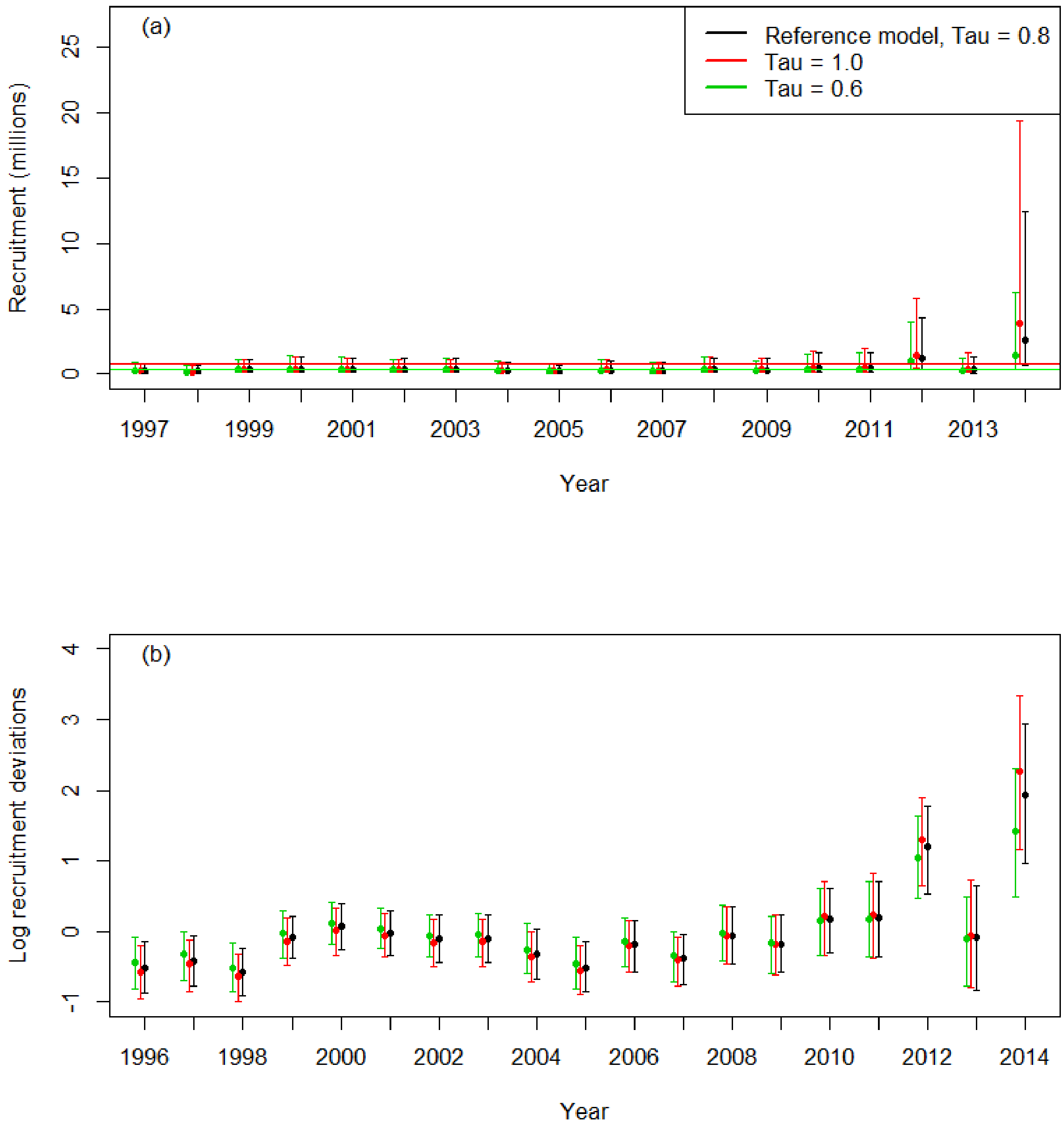


Figure 27. Estimated recruitment (a) and recruitment deviations (b) with 95% credible intervals, for models examining sensitivity to the τ parameter.

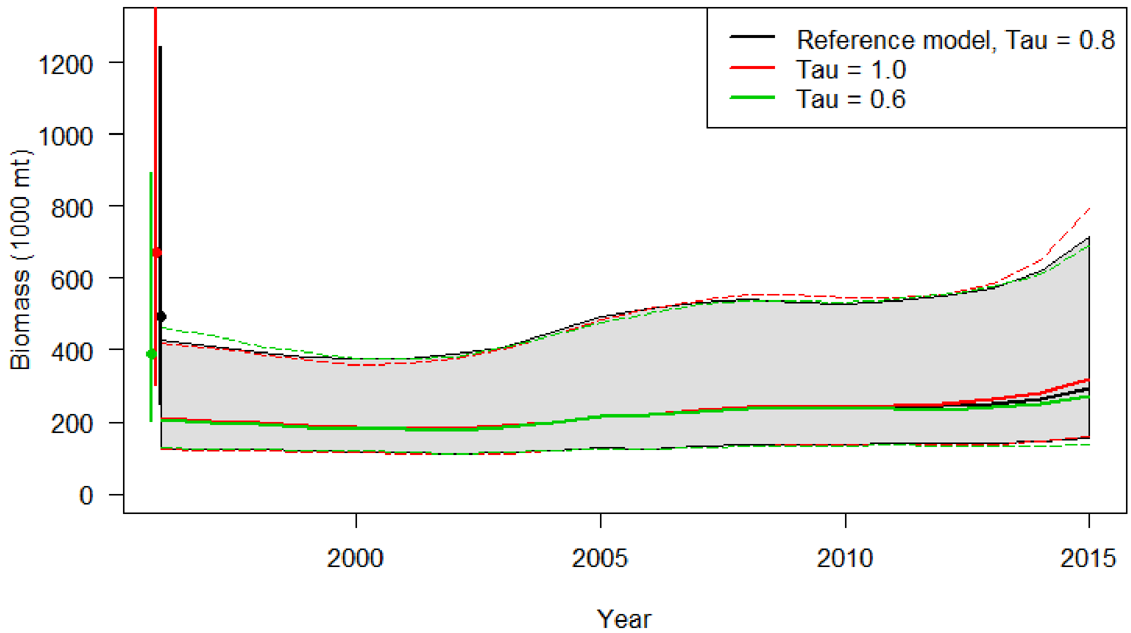


Figure 28. Estimated median spawning biomass with 95% credible intervals, for models examining sensitivity to the τ parameter. Points and bars represent the estimates of B_0 with 95% credible interval.

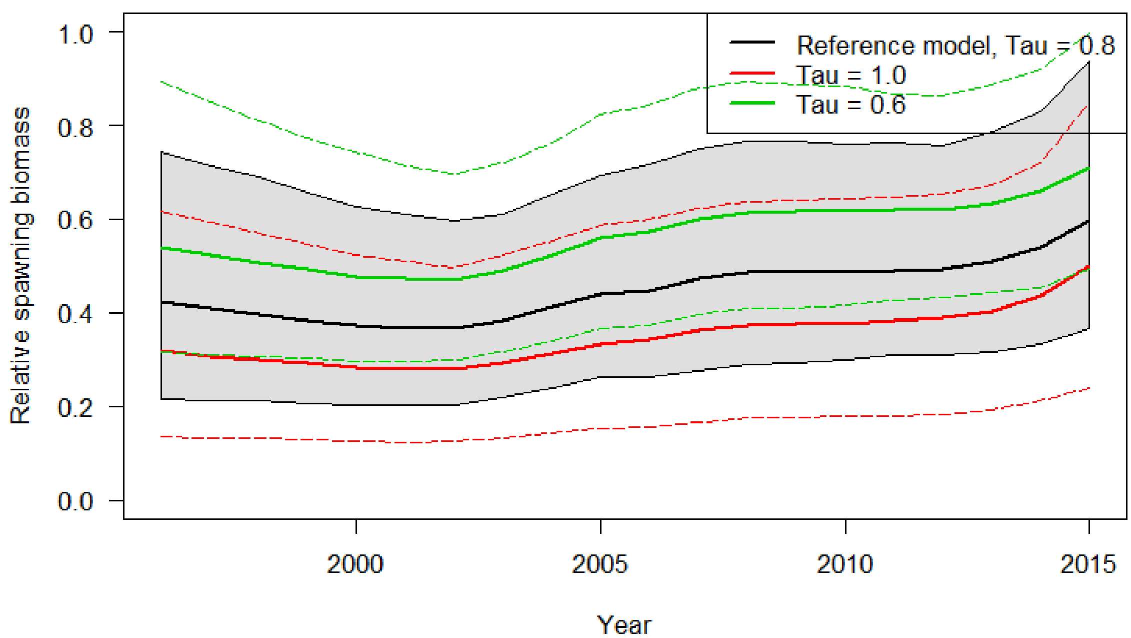


Figure 29. Estimated relative median spawning biomass with 95% credible intervals, for models examining sensitivity to the τ parameter.

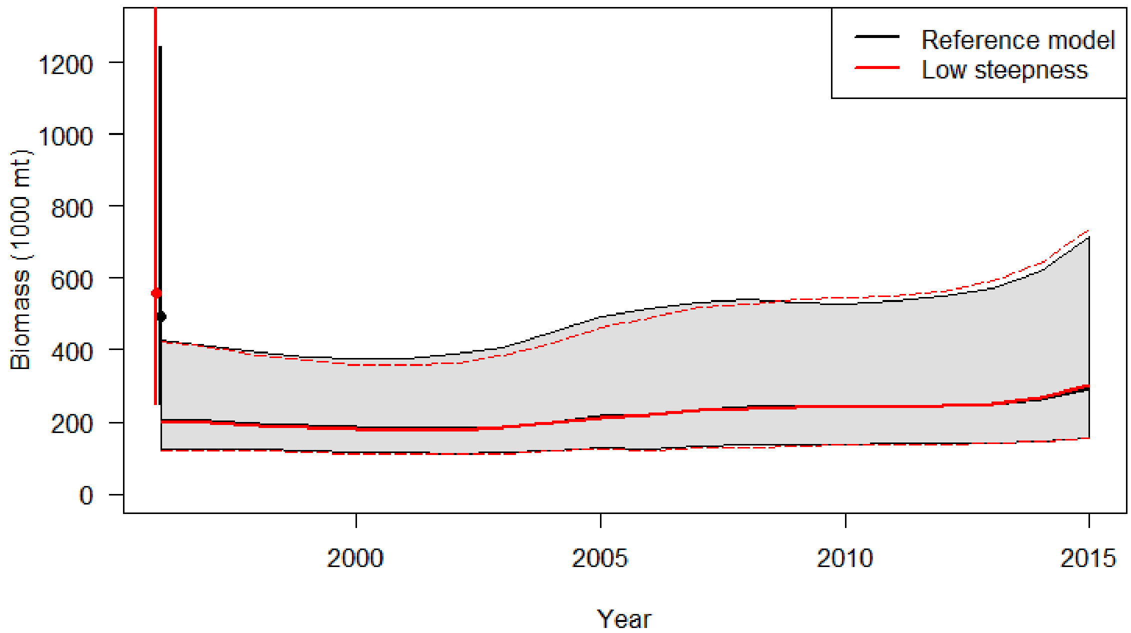


Figure 30. Estimated median spawning biomass with 95% credible intervals, for models examining sensitivity to the steepness parameter. Points and bars represent the estimates of B_0 with 95% credible interval.

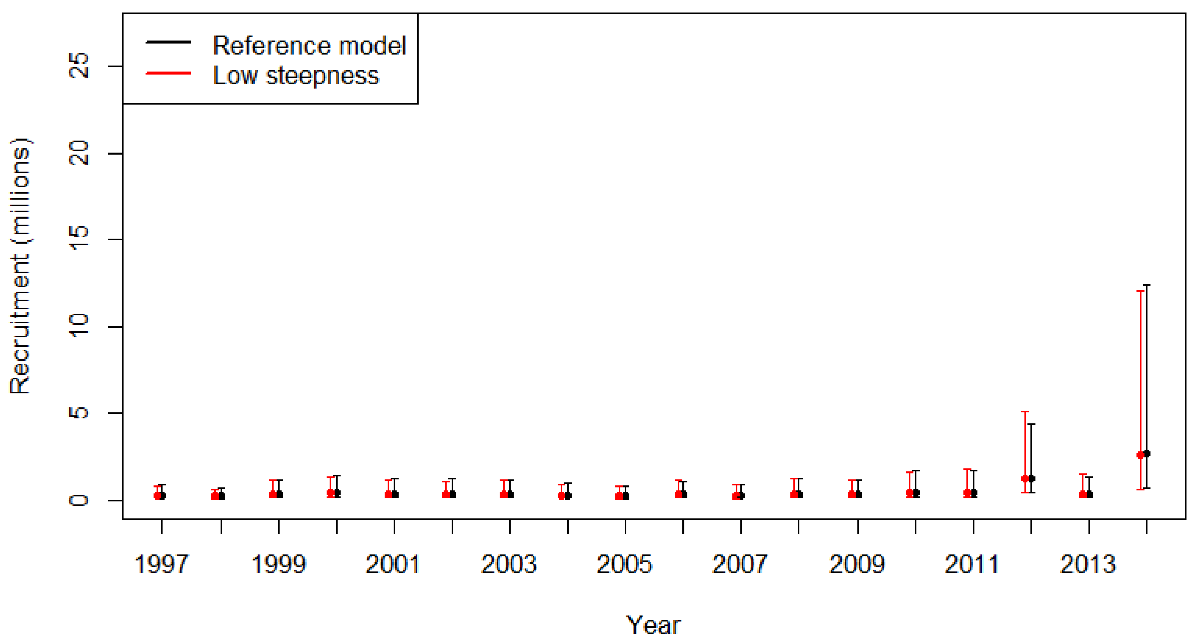


Figure 31. Estimated median recruitment with 95% credible intervals, for models examining sensitivity to the steepness parameter.

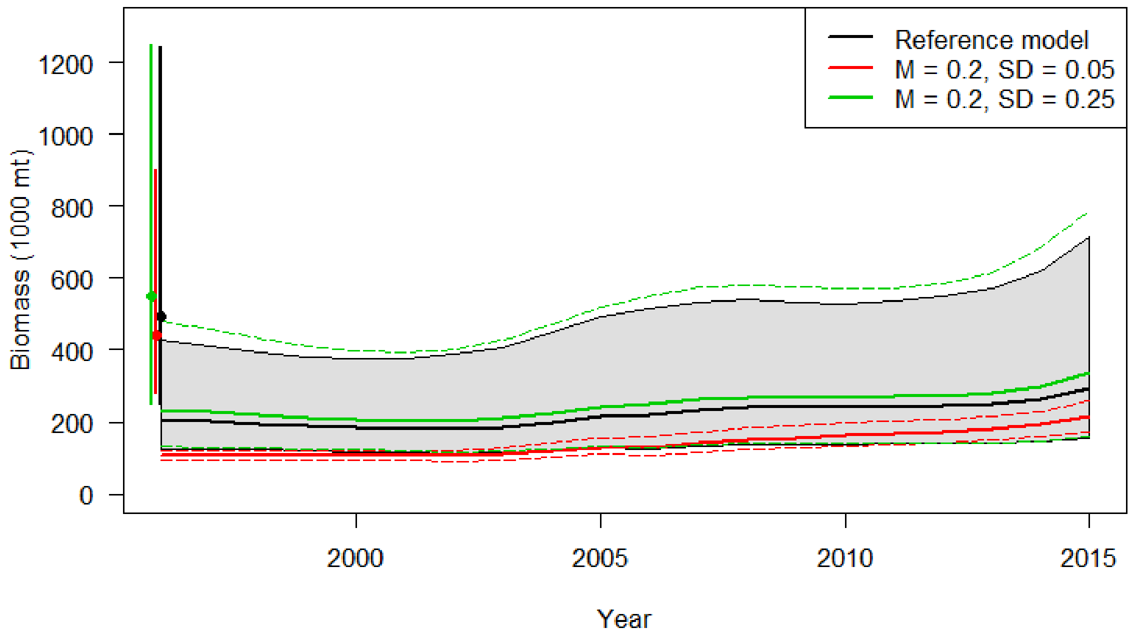


Figure 32. Estimated median spawning biomass with 95% credible intervals, for models examining sensitivity to the standard deviation of the natural mortality parameter. Points and bars represent the estimates of B_0 with 95% credible interval.

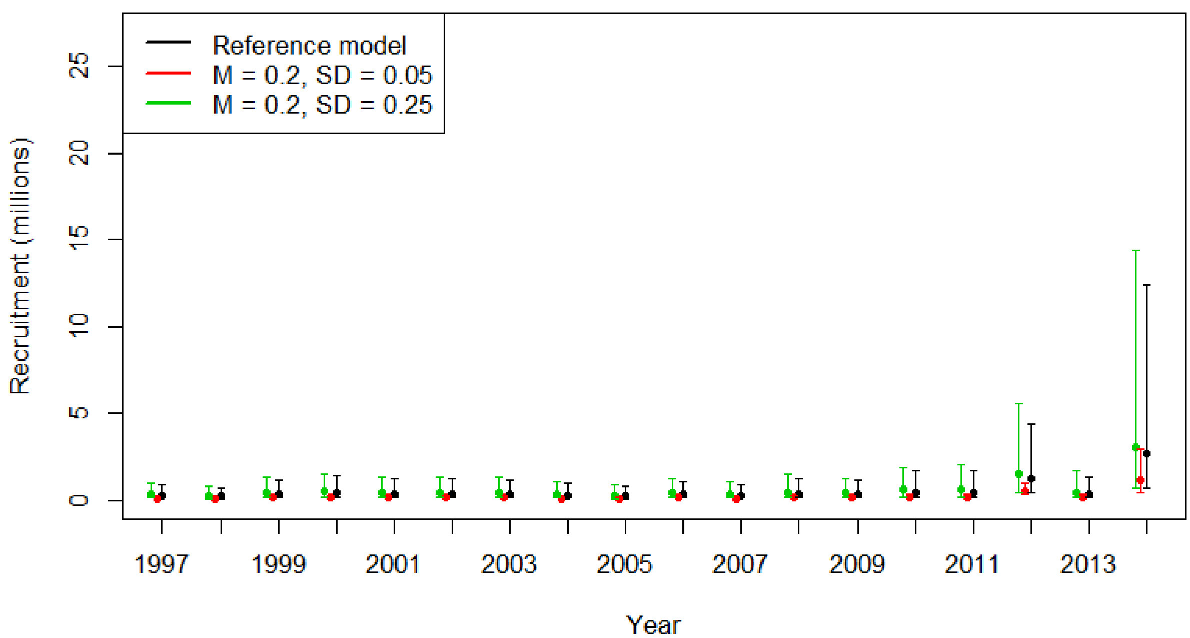


Figure 33. Estimated median recruitment with 95% credible intervals, for models examining sensitivity to the standard deviation of the natural mortality parameter.

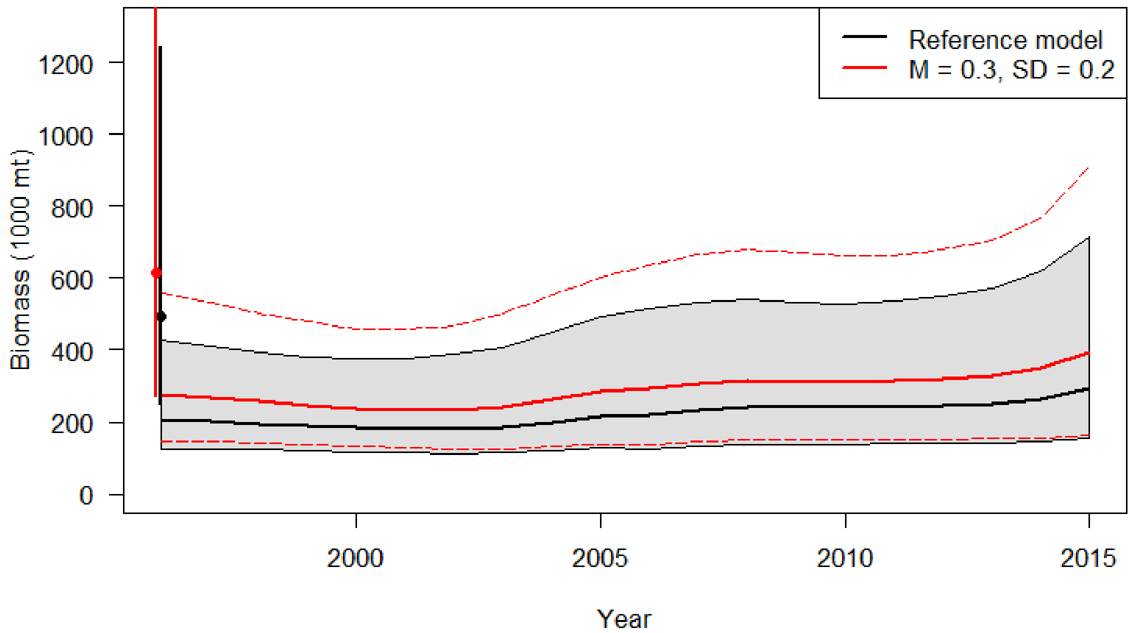


Figure 34. Estimated median spawning biomass with 95% credible intervals, for models examining sensitivity to the natural mortality parameter. Points and bars represent the estimates of B_0 with 95% credible interval.

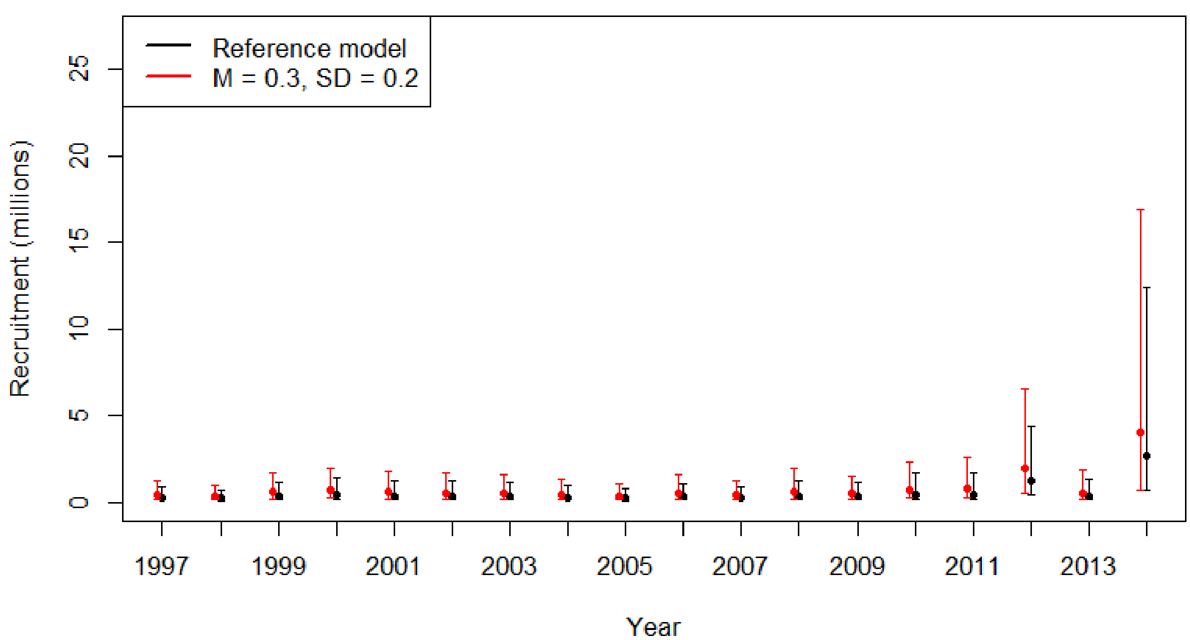


Figure 35. Estimated median recruitment with 95% credible intervals, for models examining sensitivity to the the natural mortality parameter.

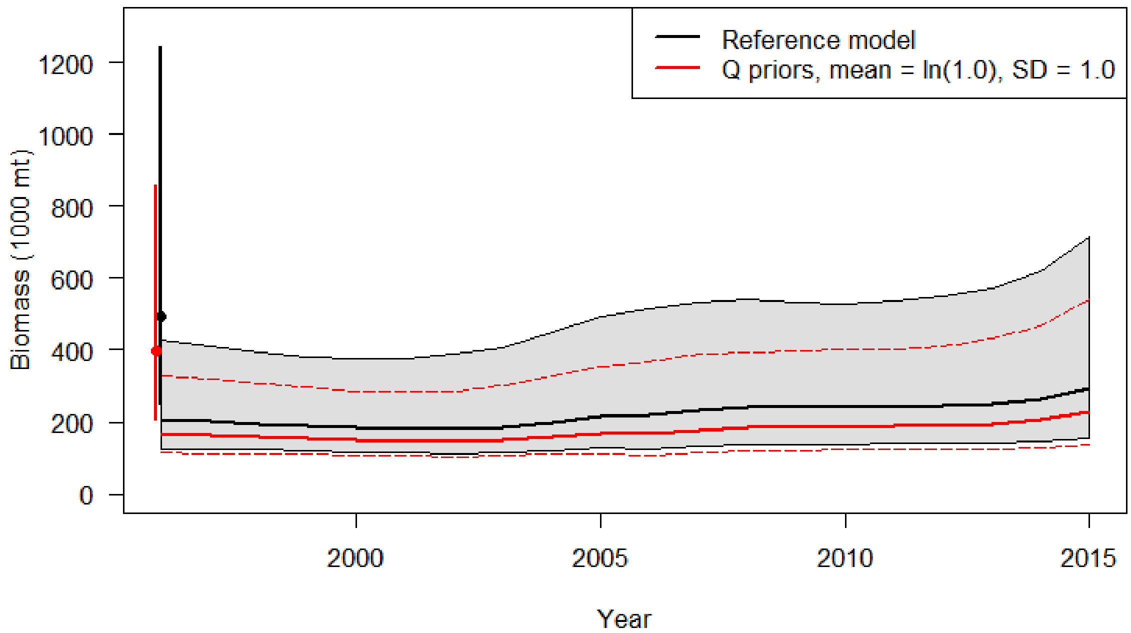


Figure 36. Estimated median spawning biomass with 95% credible intervals, for models examining sensitivity to the catchability parameter. Points and bars represent the estimates of B_0 with 95% credible interval.

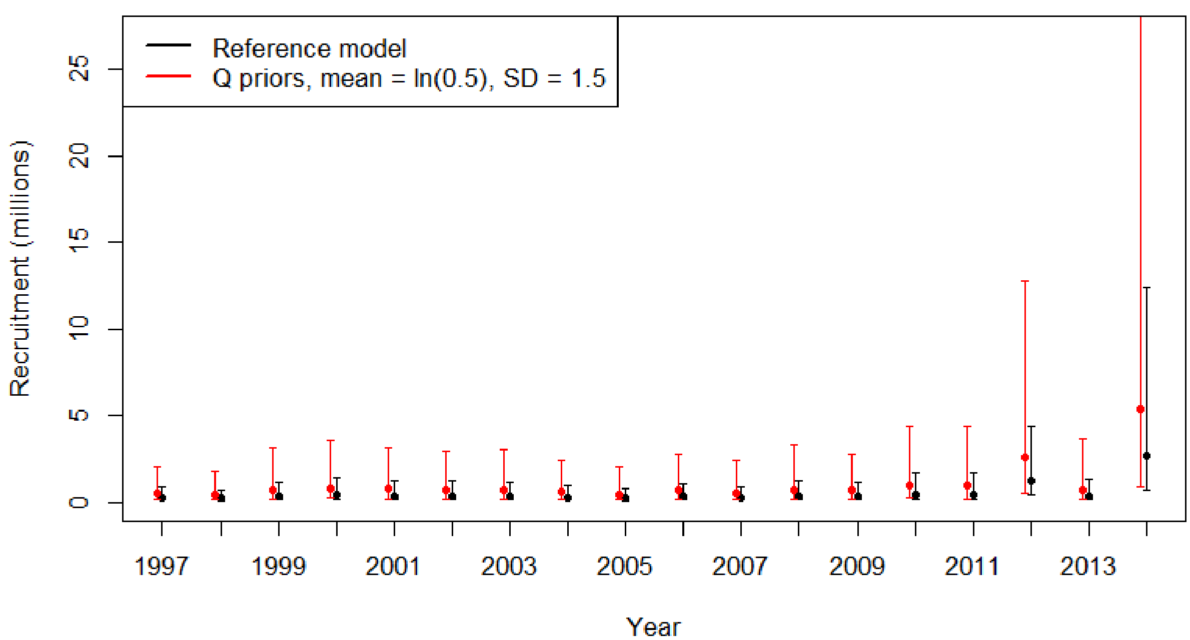


Figure 37. Estimated median recruitment with 95% credible intervals, for models examining sensitivity to the the catchability parameter.

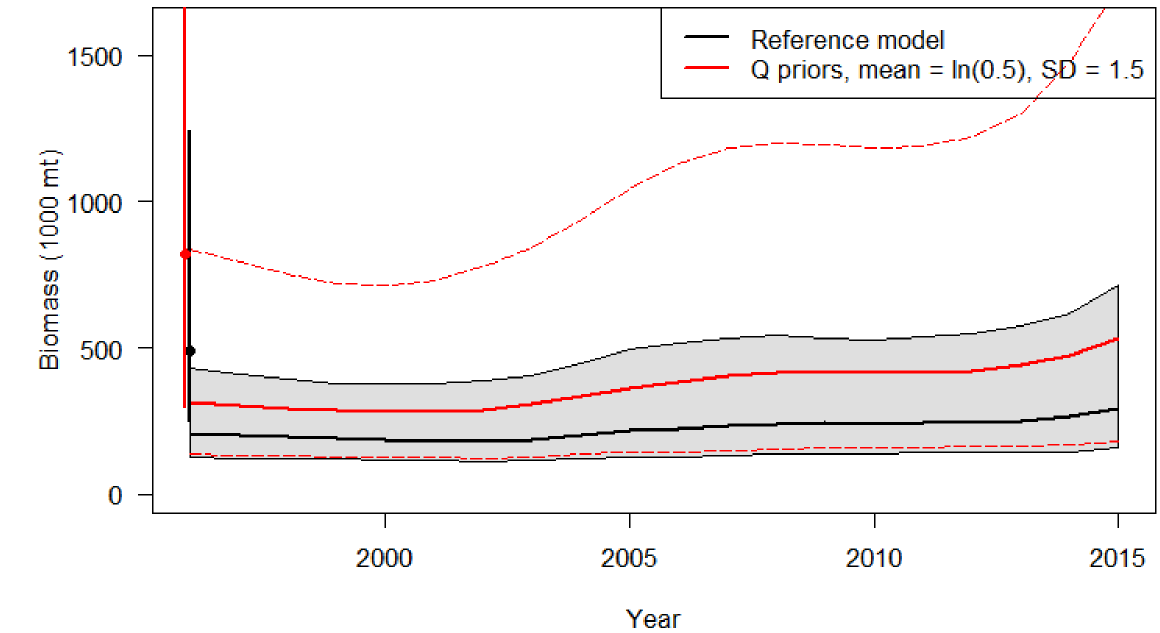


Figure 38. Estimated median spawning biomass with 95% credible intervals, for models examining sensitivity to the catchability standard deviation parameter. Points and bars represent the estimates of B_0 with 95% credible interval.

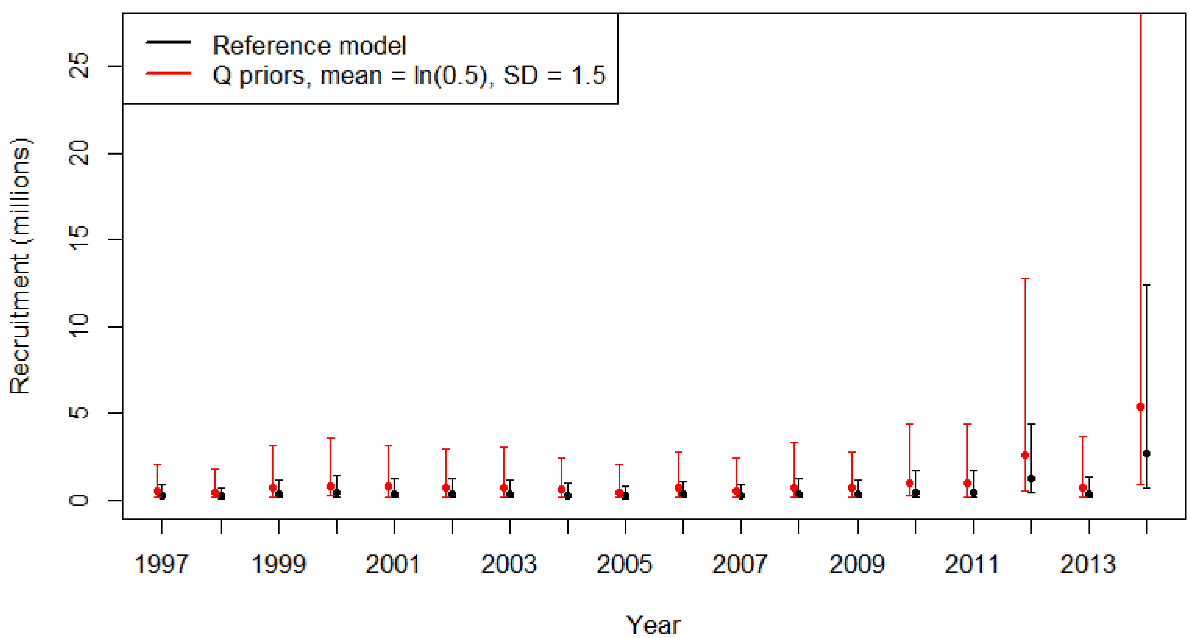


Figure 39. Estimated median recruitment with 95% credible intervals, for models examining sensitivity to the the catchability standard deviation parameter.

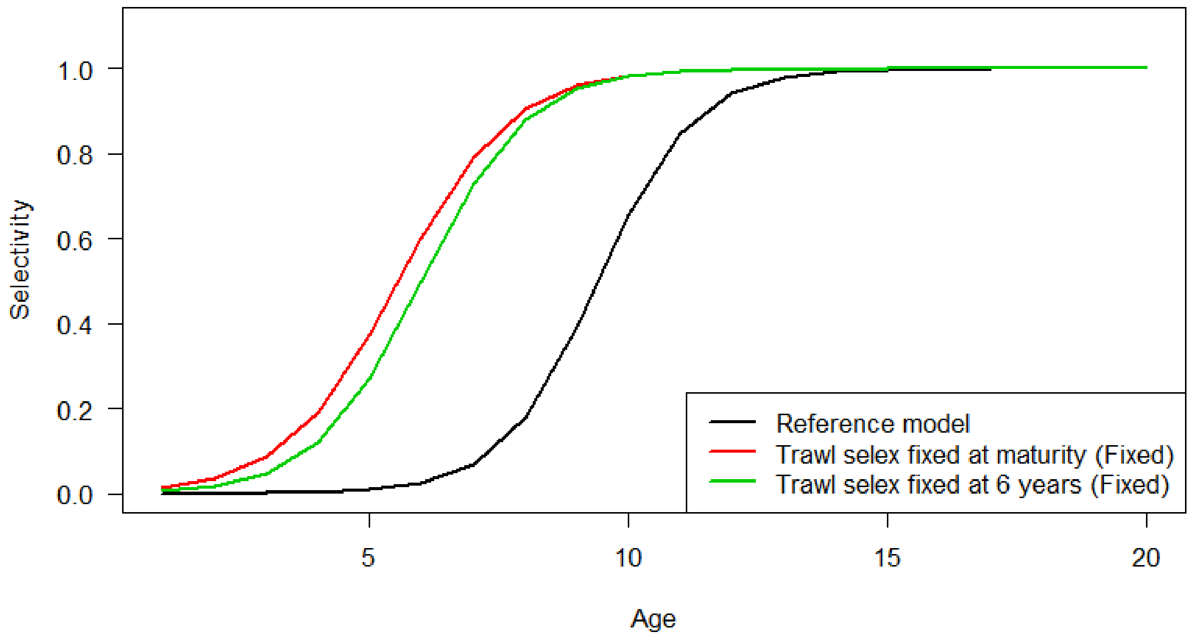


Figure 40. Trawl selectivity for models examining sensitivity to trawl selectivity.

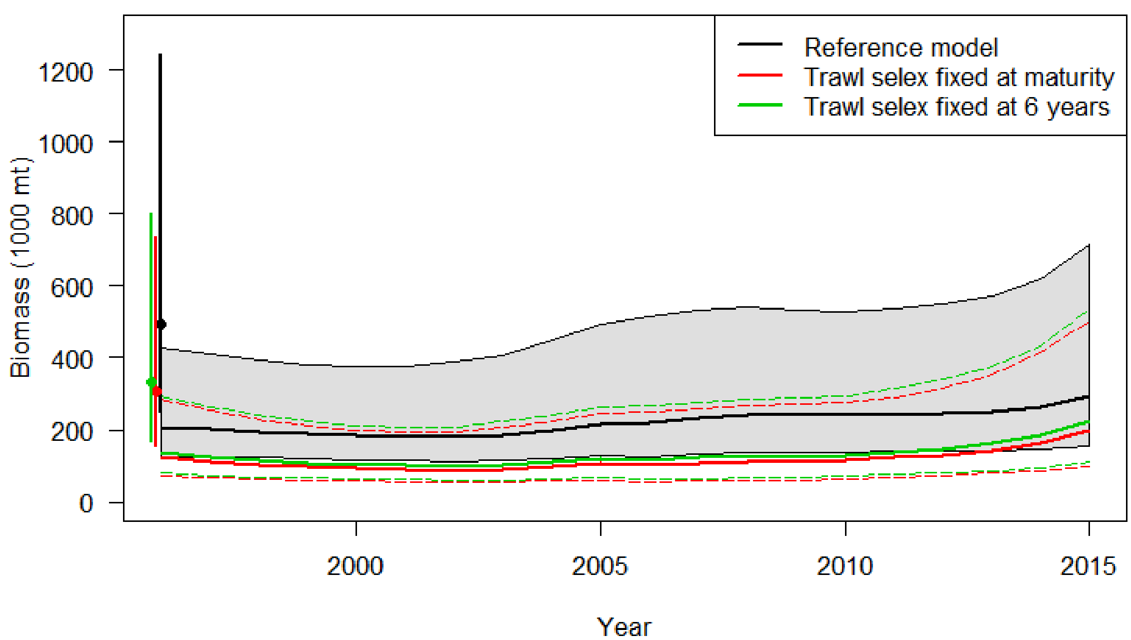


Figure 41. Estimated median spawning biomass with 95% credible intervals, for models examining sensitivity to trawl selectivity. Points and bars represent the estimates of B_0 with 95% credible interval.

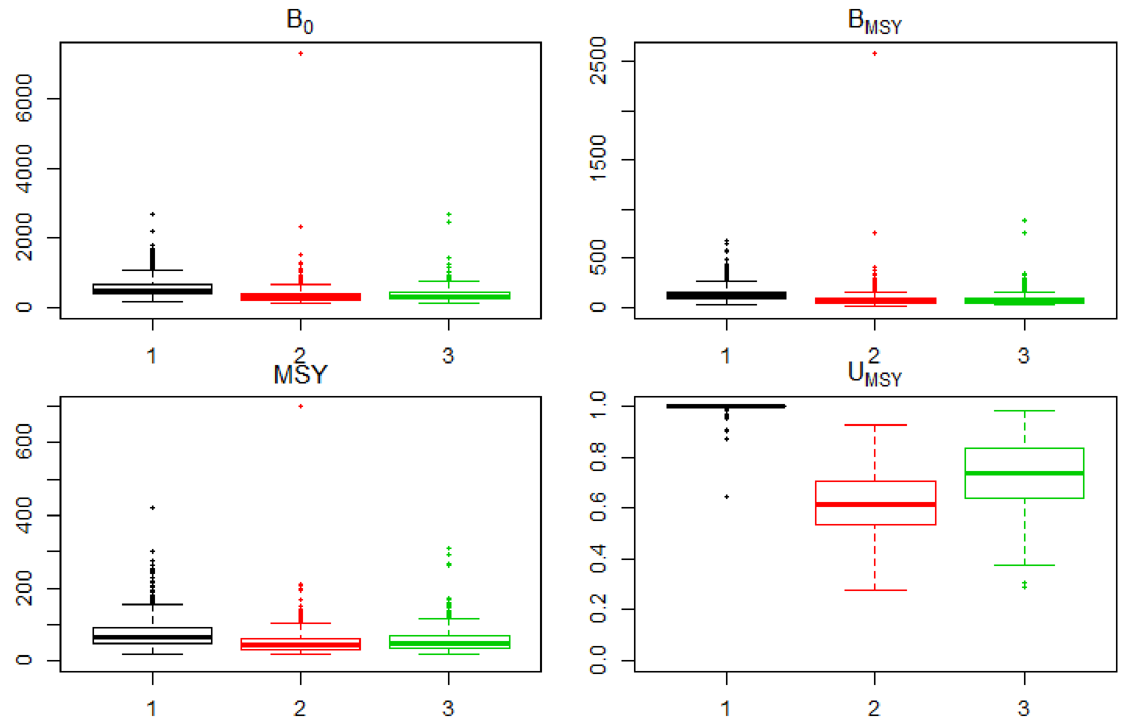


Figure 42. Posterior reference points for models examining sensitivity to trawl selectivity. Bars represent 95% credible intervals. 1 = Reference model, 2 = Trawl selex fixed at maturity, 3 = Trawl selex fixed at 6 years. MSY-based reference points are in thousands of tonnes.

APPENDIX A. BIOLOGICAL DATA

All biological parameters were estimated from survey data only. These data were aggregated from the four surveys used as indices of abundance in this assessment, the Queen Charlotte Syound Synoptic, Hecate Strait Multispecies Assemblage, Hecate Strait Synoptic, and the West Coast Vancouver Island survey.

A.1 LENGTH AND WEIGHT MODEL

All valid length/weight pairs of data were extracted based on the criteria shown in table A.1. The length-weight equation used was:

$$W_s = \alpha_s L_s^{\beta_s} \tag{A.1}$$

where α_s and β_s are parameters for sex s and L_s and W_s are paired length-weight observations.

We applied Eq. B.1 to survey observations for the four surveys used in this assessment, QCSSS, HSMAS, HSSS, and WCVISS (Survey series ID = 1,2,3,4) from PMFC areas 3CD and 5ABCDE combined (Table A.1).

A.2 VON-BERTALANFFY MODEL

We used the von-Bertalanffy function to estimate growth rates for Arrowtooth Flounder:

$$L_s = L_{\infty_s}(1 - e^{-k_s(a_s - t_{0_s})}) \tag{A.2}$$

where L_{∞_s}, k_s, and t_{0_s} are parameters specific to sex s and L_s and a_s are paired length-age observations.

We applied Eq. A.2 to survey observations for the four surveys used in this assessment, QCSSS, HSMAS, HSSS, and WCVISS (Survey series ID = 1,2,3,4) from PMFC areas 3CD and 5ABCDE combined (Table A.1).

A.3 MATURITY-AT-AGE MODEL

The maturity-at-age model used for Arrowtooth Flounder estimates age-at-50% maturity and standard deviation of age-at-50% maturity as follows:

$$P_{a_s} = \frac{1}{1 + e^{-\frac{a_s - a_{s_{50\%}}}{\sigma_{a_{s_{50\%}}}}}} \tag{A.3}$$

where P_{a_s} is the observed proportion mature at age a_s for sex s.

We applied Eq. A.3 to survey observations for the four surveys used in this assessment, QCSSS, HSMAS, HSSS, and WCVISS (Survey series ID = 1,2,3,4) from PMFC areas 3CD and 5ABCDE combined (Table A.1).

A.4 TABLES

Table A.1. Criteria for biological data extraction.

Criterion	Notes
Area	3CD and 5ABCDE combined
Survey series ID	1,2,3,4 (the four surveys used in this assessment)
Sample type = 1,2,6, or 7	only random or total samples
Sex	valid sex observation (1 or 2)

A.5 FIGURES

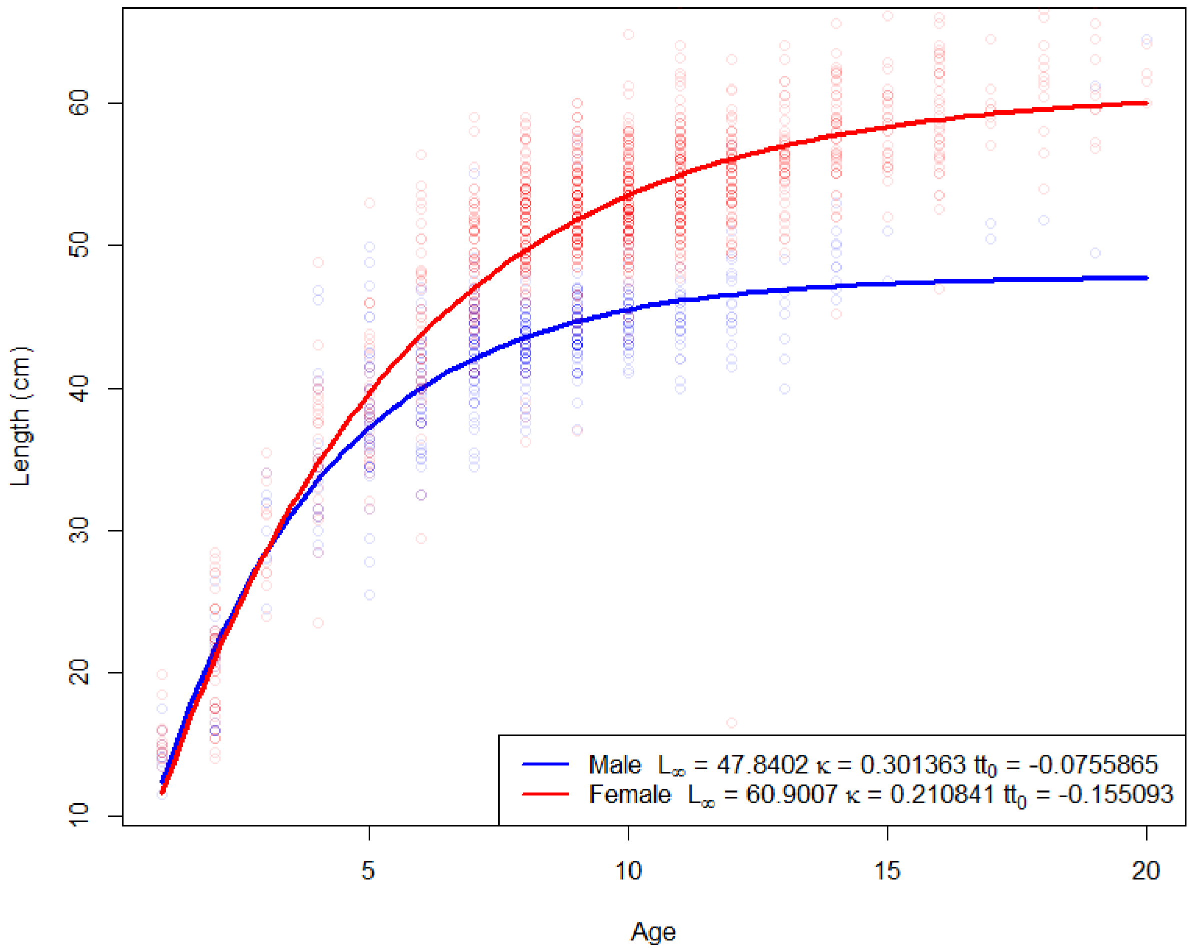


Figure A.1. Growth data and model fits for Arrowtooth Flounder. Estimated parameters L_∞, k, and t_0 are shown in the legend. See Eq. A.2.

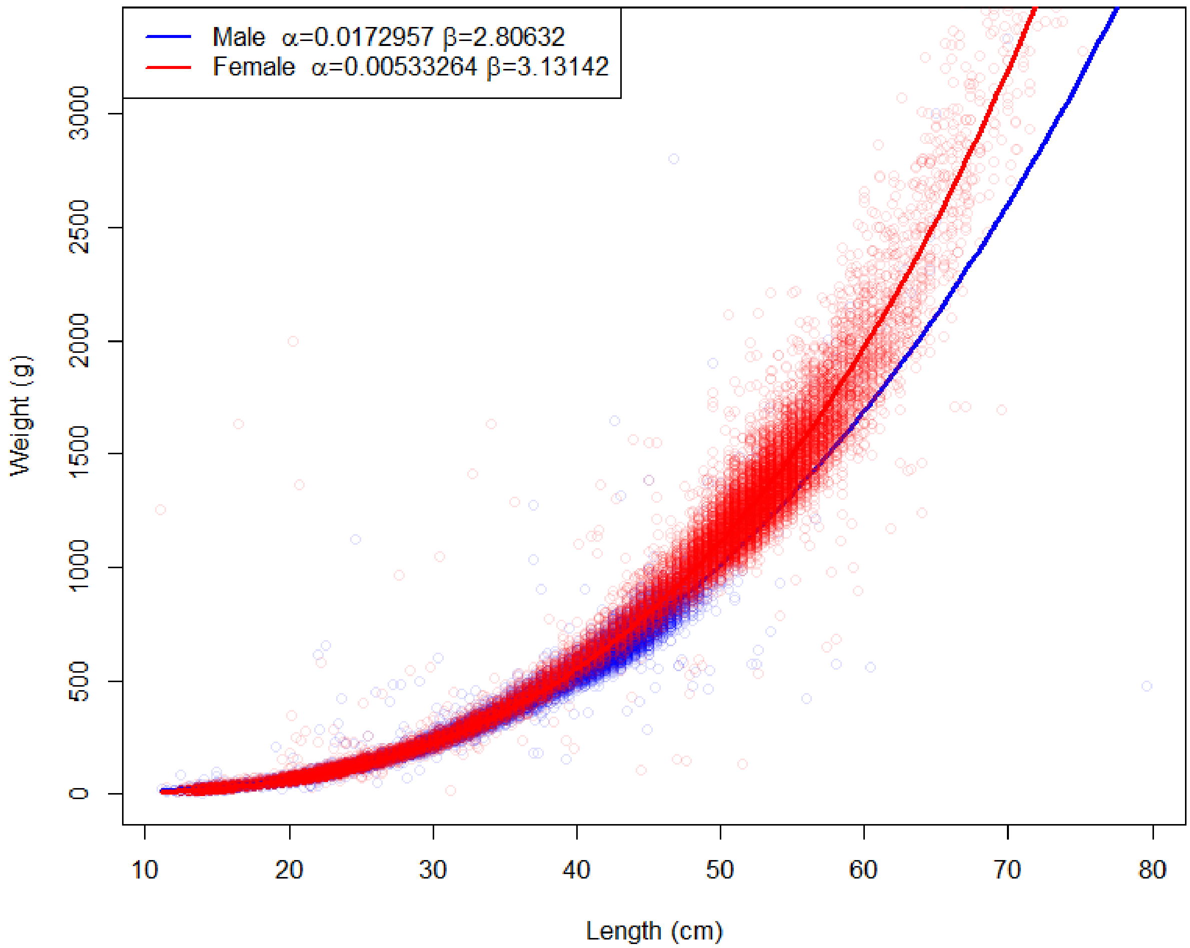


Figure A.2. Length/weight data and model fits for Arrowtooth Flounder. Estimated parameters α and β are shown in the legend. See Eq. B.1.

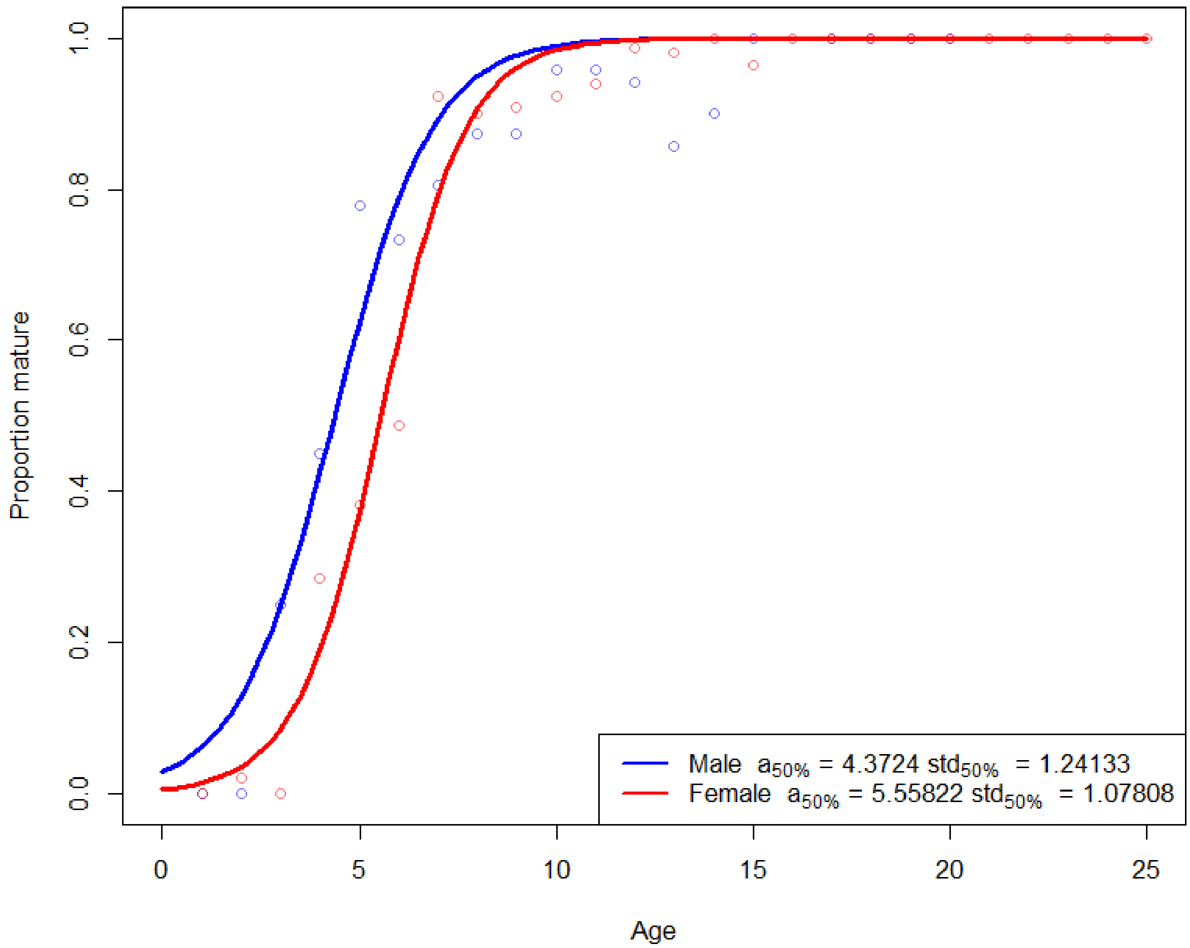


Figure A.3. Maturity data and model fits for Arrowtooth Flounder. Estimated parameters $a_{50\%}$ and $\sigma_{a_{50\%}}$ are shown in the legend. See Eq. A.3.

APPENDIX B. PROPORTION FEMALE ANALYSIS

B.1 INTRODUCTION

We elected to use a female-only stock assessment model because catch and survey data suggested the majority of the catch is female. Proportion of females in the fishery and surveys is quantified in this appendix. The weighting algorithm and proportion generation algorithm is similar to algorithm 2 in the 2014 Rock Sole assessment (Holt et al., 2014). The analysis presented here assumes a coastwide stock.

B.2 DATA SELECTION

Age data were selected based on the following attributes:

Trawl Fishery:
TRIP_SUB_TYPE_DESC equal to 1 or 4 (observed domestic or non-observed domestic)
MORPHOMETRICS_ATTRIBUTE_CODE equal to 1 or 2 or 4 or 10 (Fork length, Standard length, Total length, Whole round weight)

Surveys:
TRIP_SUB_TYPE_DESC equal to 2 or 3 (research or charter)
MORPHOMETRICS_ATTRIBUTE_CODE equal to 1 or 2 or 4 or 10 (Fork length, Standard length, Total length, Whole round weight)

Years:
Greater than or equal to 1996

Quarters of the year:
1 = Jan-Mar
2 = Apr-Jun
3 = Jul-Sep
4 = Oct-Dec

Areas:
3CD and 5ABCDE

Sex:
Male or female only, no unknowns or null fields

B.3 ALGORITHM

Pseudocode has been provided in Section B.3.4 to describe the weighting algorithm.

B.3.1 TRAWL FISHERY

Observations within a sample are likely to be correlated due to the small area which is trawled in a single fishing event. Also, trip samples are likely to be correlated due to the fact that it is the same vessel and captain. This algorithm calculates a sex-specific mean weight by trip, calculated from individual sex-specific length observations converted to weight using Eq. B.1, then uses Eqs. B.2–B.9 to estimate proportion of females. The pseudocode for the algorithm is provided in Section B.3.4.

B.3.2 SURVEYS

For surveys, the same algorithm is followed except that the quarter of the year is not included in the calculation. This is because the surveys are single events which occur linearly through a reletively short period of 1-2 months.

B.3.3 EQUATIONS

$$\hat{w}_{ijs} = \alpha_s l_{ijs}^{\beta_s} \tag{B.1}$$

where α_s and β_s are parameters for sex s and w_{ijs} and l_{ijs} are paired length-weight observations for specimen i in sample j.

$$W_{jst} = \sum_{i=1}^{N_{jst}} \hat{w}_{ijst} \tag{B.2}$$

where W_{jst} is the total weight for sample j, sex s, trip t, and N_{jst} is the number of specimens in sample j for sex s

$$W_{st} = \frac{\sum\limits_{j=1}^{K_t} W_{jst} S_{jt}}{\sum\limits_{j=1}^{K_t} S_{jt}} \tag{B.3}$$

where W_{st} is the mean weight for sex s and trip t, weighted by sample weight, where K_t is the number of samples in trip t, and S_{jt} is the sample weight for sample j from trip t.

$$C_t = \sum_{j=1}^{K_t} C_{jt} \tag{B.4}$$

where C_t is the total catch weight for sampled hauls for trip t, K_t is the number of samples in trip t, and C_{jt} is the catch weight associated with sample j and trip t.

$$W_{qs} = \frac{\sum_{t=1}^{T_q} W_{qst} R_{qt}}{\sum_{t=1}^{T_q} R_{qt}} \tag{B.5}$$

where W_{qs} is the total weight for sex s and quarter of year q, R_{qt} is the trip weight for all sampled trips in quarter q, and T_q is the number of sampled trips in quarter q.

$$C_q = \sum_{t=1}^{K_q} C_t \tag{B.6}$$

where C_q is the total catch weight for sampled hauls for quarter q, K_q is the number of trips in quarter q, and C_t is the catch weight associted with trip t.

$$W_{ys} = \frac{\sum_{q=1}^{4} W_{qys} C_{qy}}{\sum_{q=1}^{4} C_{qy}} \tag{B.7}$$

where W_{sy} is the total weight for year y, sex s, W_{qys} is the weight in quarter q of year y, and C_{qy} is the catch in quarter q of year y.

$$C_y = \sum_{q=1}^{4} C_{qy} \tag{B.8}$$

where C_y is the total catch weight for sampled hauls for year y, and C_{qy} is the catch weight associted with quarter q in year y.

$$P_y = \frac{W_{s=Female,y}}{W_{s=Female,y} + W_{s=Male,y}} \tag{B.9}$$

where P_y is the proportion female by weight for year y.

B.3.4 PSEUDOCODE

The following outlines the method used for calculating the proportion of female fish for each year.

Algorithm 1 Algortihm for calculating the proportion female

function PROPFEMALE(())
    $i \leftarrow$ Specimen
    $s \leftarrow$ Sex
    $j \leftarrow$ Sample number
    $t \leftarrow$ Trip number
    $q \leftarrow$ Quarter of year
    $y \leftarrow$ Year
    $l_{ijs} \leftarrow$ Specimen length measurement
    $w_{ijs} \leftarrow$ Specimen weight measurement
    $\hat{w}_{ijs} \leftarrow$ Specimen weight estimate
    for each specimen i where $w_{ijs} = NULL$ and $l_{ijs} <> NULL$ **do**
        apply the sex-specific length-weight relationship (Eq. B.1) to fill in the missing specimen weights w_{ijs} with estimates $\hat{w}_{ijs}$
    end for
    for each year y **do**
        for each quarter q in year y **do**
            for each trip t in quarter q **do**
                for each sample ID j in trip t **do**
                    Calculate the sex-specific sample weight W_{js} for sample j (Eq. B.2)
                    Extract the catch weight C_j associated with sample j
                end for
                Calculate the sex-specific total sample weight W_{st} for trip t (Eq. B.3)
                Calculate the sex-specific total catch weight C_t for trip t (Eq. B.4)
            end for
            Calculate the sex-specific total sample weight W_{qs} for quarter q (Eq. B.5)
            Calculate the sex-specific total catch weight C_q for quarter q (Eq. B.6)
        end for
        Calculate the sex-specific total sample weight W_{sy} for year y weighted by catch C_y (Eq. B.7)
        Calculate the proportion female for year y (Eq. B.9)
    end for
end function

B.3.5 RESULTS

The proportion of females resulting from this analysis are high, ranging from 0.606 for the 2010 WCVI trawl fishery to 0.950 for the 2000 QCS+HS trawl fishery (Table B.1).

Table B.1. Proportion of females for the trawl fishery and 4 surveys Coastwide.

Year	Fishery Coastwide	Fishery WCVI	Fishery QCS+HS	Survey QCSSS	Survey HSMAS	Survey HSSS	Survey WCVI
1996	0.85	0.86					
1997	0.90	0.79	0.90				
1998	0.78	0.64	0.79		0.71		
1999	0.83	0.81	0.79				
2000	0.83	0.79	0.95		0.91		
2001	0.88	0.71	0.94				
2002	0.86	0.87	0.85		0.83		
2003	0.75	0.79	0.80	0.82		0.84	
2004	0.87	0.85	0.87	0.81			0.84
2005	0.87	0.92	0.85	0.84		0.77	
2006	0.85	0.85	0.86				0.90
2007	0.84	0.78	0.83	0.76		0.78	
2008	0.91	0.92	0.92				0.82
2009	0.70	0.78	0.70	0.79		0.76	
2010	0.72	0.61	0.73				0.81
2011	0.74	0.81	0.71	0.75		0.80	
2012	0.83	0.83	0.85				0.79
2013	0.79	0.84	0.83	0.72		0.75	
2014	0.79	0.62	0.82				0.78

APPENDIX C. WEIGHTING OF AGE PROPORTIONS

This appendix summarizes a method for representing commercial and survey age structures for a given species through weighting observed age frequencies x_a or proportions x'_a by catch||density in defined strata. The methodology presented in this appendix is based on that presented by Holt et al. (2014) for Rock Sole.

Ideally, sampling effort would be proportional to the amount of the species caught, but this is not usually the case. Therefore, the stratified weighting scheme presented below attempts to adjust for unequal sampling effort among strata. For commercial samples, strata comprise quarterly periods within a year, while for survey samples, the strata are defined by longitude, latitude, and depth. Within each stratum, commercial ages are weighted by the catch weight (kg) of the species in tows that were sampled, and survey ages are weighted by the catch density (kg/km^2) of the species in sampled tows. A second weighting is then applied: quarterly commercial ages are weighted by the commercial catch weight of the species from all tows within each quarter; stratum survey ages are weighted by stratum areas (km^2) in the survey. Throughout this section, we use the symbol '||' to delimit parallel values for commercial and survey analyses, respectively, as the mechanics of the weighting procedure are similar for both.

For simplicity we illustrate the weighting of age frequencies x_a, unless otherwise specified. The weighting occurs at two levels: h (quarters for commercial ages, strata for survey ages) and i (years if commercial, surveys in series if survey). Notation is summarised in Table C.1.

*Table C.1. Equations for weighting age frequencies or proportions for Arrowtooth Flounder. (**c**) = commercial, (**s**) = survey*

Symbol	Description
	Indices
a	age class (1 to A, where A is an accumulator age-class)
d	(**c**) trip IDs as sample units
	(**s**) sample IDs as sample units
h	(**c**) quarters (1 to 4), 91.5 days each
	(**s**) strata (area-depth combinations)
i	(**c**) calendar years (1977 to present)
	(**s**) survey IDs in survey series (e.g., QCS Synoptic)
	Data
x_{adhi}	observations-at-age a for sample unit d in quarter||stratum h of year||survey i
x'_{adhi}	proportion-at-age a for sample unit d in quarter||stratum h of year||survey i
C_{dhi}	(**c**) commercial catch (kg) of a given species for sample unit d in quarter h of year i
	(**s**) density (kg/km^2) of a given species for sample unit d in stratum h of survey i
C'_{dhi}	C_{dhi} as a proportion of total catch||density $C_{hi} = \sum_d C_{dhi}$
y_{ahi}	weighted age frequencies at age a in quarter||stratum h of year||survey i
K_{hi}	(**c**) total commercial catch (kg) of species in quarter h of year i
	(**s**) stratum area (km^2) of stratum h in survey i
K'_{hi}	K_{hi} as a proportion of total catch||area $K_i = \sum_h K_{hi}$
p_{ai}	weighted frequencies at age a in year||survey i
p'_{ai}	weighted proportions at age a in year||survey i

For each quarter||stratum h we weight sample unit frequencies x_{ad} by sample unit catch||density of the assessment species. For commercial ages, we use trip as the sample unit, though at times one trip may contain multiple samples. In these instances, multiple samples from a single trip will be merged into a single sample unit. Within any quarter||stratum h and year||survey i there is a set of sample catches||densities C_{dhi} that can be transformed into a set of proportions:

$$C'_{dhi} = \frac{C_{dhi}}{\sum_d C_{dhi}} \tag{C.1}$$

The proportion C'_{dhi} is used to weight the age frequencies x_{adhi} summed over d, which yields weighted age frequencies by quarter||stratum for each year||survey:

$$y_{ahi} = \sum_d C'_{dhi} x_{adhi} \tag{C.2}$$

This transformation reduces the frequencies x from the originals, and so we rescale (multiply) y_{ahi} by the factor

$$\frac{\sum_a x_{ahi}}{\sum_a y_{ahi}} \tag{C.3}$$

to retain the original number of observations.

At the second level of stratification by year||survey i, we calculate the the annual proportion of quarterly catch (t) for commercial ages or the survey proportion of stratum areas (km^2) for survey ages

$$K'_{hi} = \frac{K_{hi}}{\sum_h K_{hi}} \tag{C.4}$$

to weight y_{ahi} and derive weighted age frequencies by year||survey:

$$p_{ai} = \sum_h K'_{hi} y_{ahi} \tag{C.5}$$

Again, if this transformation is applied to frequencies, it reduces them from the original, and so we rescale (multiply) p_{ai} by the factor

$$\frac{\sum_a y_{ai}}{\sum_a p_{ai}} \tag{C.6}$$

to retain the original number of observations.

Finally, we standardise the weighted frequencies to represent proportions-at-age:

$$p'_{ai} = \frac{p_{ai}}{\sum_a p_{ai}} \tag{C.7}$$

If initially we had used proportions x'_{adhi} instead of frequencies x_{adhi} , the final standardisation would not be necessary. However, its application does not affect the outcome.

The choice of data input (frequencies x *vs.* proportions x') can sometimes matter: the numeric outcome can be very different, especially if the input samples comprise few observations. Theoretically, weighting frequencies emphasises our belief in individual observations at specific ages while weighting proportions emphasises our belief in sampled age distributions. Neither method yields inherently better results. However, if the original sampling methodology favoured sampling few fish from many tows rather than sampling many fish from few tows, then weighting frequencies probably makes more sense than weighting proportions. In this assessment, we weight age frequencies x.

APPENDIX D. MODEL DESCRIPTION

D.1 INTRODUCTION

Stock Assessment modelling was done using the Integrated Statistical Catch Age Model (iSCAM), developed by S. Martell (Martell et al., 2011). iSCAM is written in AD Model Builder and the source code and documentation for both are available online. iSCAM uses a statistical catch-at-age model implemented in a Bayesian estimation framework.

Running of iSCAM and compilation of results figures was streamlined using the iscam-gui software package developed at the Pacific Biological Station. iscam-gui is written in the statistical language R, and provides a graphical user interface that allows users to run and show output of multiple iSCAM model scenarios in a comparative fashion.

D.2 MODEL DESCRIPTION

This section contains the documentation in mathematical form of the underlying iSCAM age-structured model, its steady state version that is used to calculate reference points, the observation models used in predicting observations, and the components of the objective function that formulate the statistical criterion used to estimate model parameters. A documented list of symbols used in model equations is given in Table D.1. The documentation presented here is a revised version of the iscam user guide available online. Much of the text and many of the equations have been taken directly from the original iSCAM user guide.

Note that all the model equations are presented for a sex structured model with S sexes. Models can therefore be constructed with data for females only, for males and females, or with unsexed data. This Arrowtooth Flounder assessment is a female only model with $S = 1$.

D.3 ANALYTIC METHODS: EQUILIBRIUM CONSIDERATIONS

D.3.1 A STEADY-STATE AGE-STRUCTURED MODEL

For the steady-state conditions represented in Table D.2, we assume the parameter vector Θ in Eq. D.12 is unknown and would be estimated by fitting iSCAM to data. For a given set of sex-specific growth parameters and maturity-at-age parameters defined by Eq. D.13, growth is assumed to follow von Bertalanffy (Eq. D.14), mean weight-at-age is given by the allometric relationship in Eq. D.15, and the age and sex-specific vulnerability is given by an age-based logistic function (Eq. D.16). The terms vulnerability and selectivity are used interchangeably throughout this document, although, technically, selectivity refers to the fishing gear, while vulnerability refers to all processes affecting the availability of fish to the fishery. Selectivity parameters can be fixed or estimated.

Survivorship for unfished and fished populations is defined by Eqns. D.18 and D.19, respectively. It is assumed that all individuals ages A and older (i.e., the plus group) have the same total mortality rate. The incidence functions refer to the life-time or per-recruit quantities such as spawning biomass per recruit (ϕ_E, Eq. D.20) or vulnerable biomass per recruit (ϕ_B, Eq. D.21). Note that upper and lower case subscripts denote unfished and fished conditions, respectively. Unfished spawning biomass is given by Eq. D.23 and the recruitment compensation ratio (Myers et al., 1999) is given by Eq. D.24. The steady-state equilibrium recruitment for a given fishing mortality rate F_e is given by Eq. D.25. Note that we assume that recruitment follows a Beverton-Holt stock recruitment model of the form shown in Eq. D.38, where the maximum juvenile survival rate s_o is given by:

$$s_o = \frac{\kappa}{\phi_E},$$

and the density-dependent term is given by:

$$\beta = \frac{\kappa - 1}{R_o \phi_E}$$

which simplifies to Eq. D.25.

The equilibrium yield C_e for a given fishing mortality rate is given by Eq. D.26. These steady-state conditions are critical for determining various reference points such as F_{MSY} and B_{MSY}.

D.3.2 MSY-BASED REFERENCE POINTS

When defining reference points for this assessment, only the commercial trawl fishery was used to calculate MSY quantities. In the case of a single fishery, iSCAM calculates F_{MSY} by finding the value of F_{e} that results in the zero derivative of Eq. D.26. This is accomplished numerically using a Newton-Raphson method where an initial guess for F_{MSY} is set equal to M. Given an estimate of F_{MSY}, other reference points such as MSY and B_{MSY} are calculated using the equations in Table D.2.

D.4 ANALYTIC METHODS: STATE DYNAMICS

The estimated parameter vector in iSCAM is defined in Eq. D.27 of Table D.3. The estimated parameters R_0, h, and M, are the leading population parameters that define the overall scale and productivity of the population.

Variance components of the model were partitioned using an errors in variables approach. The key variance parameter is the inverse of the total variance ϑ^2 (i.e., total precision). This parameter can be fixed or estimated, and was fixed for this model. The total variance is partitioned into observation and process error components by the model parameter ρ, which represents the proportion of the total variance that is due to observation error (Eq. D.28, (Punt and Butterworth, 1999; Deriso et al., 2007)).

The unobserved state variables in Eq. D.29 include the numbers-at-age in year t of sex s ($N_{t,a,s}$), the spawning stock biomass in year t of sex s ($B_{t,s}$), and the total age- and sex-specific total mortality rate ($Z_{t,a,s}$). The initial numbers-at-age in the first year (Eq. D.30) and the annual recruits (Eq. D.31) are treated as estimated parameters and used to initialize the numbers-at-age array.

Vulnerability-at-age is here assumed time-invariant and is modelled using a two-parameter logistic function (Eq. D.32). The annual fishing mortality for each gear k in year t is the exponent of the estimated vector $\Gamma_{k,t}$ (Eq. D.33). The vector of log fishing mortality rate parameters $\Gamma_{k,t}$ is a bounded vector with a minimum value of -30.0 and an upper bound of 3.0. In arithmetic space this corresponds to a minimum value of $9.36e^{-14}$ and a maximum value of 20.01 for annual fishing mortality rates. In years where there are zero reported catches for a given fleet, no corresponding fishing mortality rate parameter is estimated and the implicit assumption is there was no fishery in that year.

State variables in each year are updated using Eqns. D.34–D.37, where the spawning biomass is the product of the numbers-at-age and the mature biomass-at-age (Eq. D.34). The total mortality rate is given by Eq. D.35, and the total catch (in weight) for each gear is given by Eq. D.36, assuming that both natural and fishing mortality occur simultaneously throughout the year. The sex-specific numbers-at-age are propagated over time using Eq. D.37, where members of the plus group (age A) are all assumed to have the same total mortality rate. Recruitment to age k is assumed to follow a Beverton-Holt model for Arrowtooth Flounder (Eq. D.38) where the maximum juvenile survival rate (s_o) is defined by $s_o = \kappa/\phi_E$. For the Beverton-Holt model, β is derived by solving Eq. D.38 for β conditional on estimates of h and R_o.

D.5 RESIDUALS, LIKELIHOODS, AND OBJECTIVE FUNCTION VALUE COMPONENTS

The objective function contains five major components:

1. The negative log-likelihood for the catch data
2. The negative log-likelihood for the relative abundance data
3. The negative log-likelihood for the age composition data
4. The prior distributions for model parameters
5. Three penalty functions that are invoked to regularize the solution during intermediate phases of the non-linear parameter estimation. The penalty functions:
   a. constrain the estimates of annual recruitment to conform to a Beverton-Holt stock-recruit function
   b. weakly constrain the log recruitment deviations to a normal distribution
   c. weakly constrain estimates of log fishing mortality to a normal distribution ($\sim N(\ln(0.2), 4.0)$) to prevent estimates of catch from exceeding estimated biomass.

Tests showed the model was insensitive to changes in the penalty function parameters, indicating that the other likelihood components and prior probability distributions were the most important contributors to the objective function.

The objective function components are discussed in more detail in the following sections.

D.5.1 CATCH DATA

It is assumed that the measurement errors in the catch observations are log-normally distributed, and the residuals given by:

$$\eta_{k,t} = \ln(C_{k,t} + o) - \ln(\hat{C}_{k,t} + o) \tag{D.1}$$

where o is a small constant (e^{-10}) to ensure the residual is defined in the case of a zero catch observation. The residuals are assumed to be normally distributed with a user-specified standard deviation σ_C. At present, it is assumed that observed catches for each gear k have the same standard deviation. The negative loglikelihood (ignoring the scaling constant) for the catch data is given by:

$$\ell_C = \sum_k [T_k \ln(\sigma_C) + \frac{\sum_t (\eta_{k,t})^2}{2\sigma_C^2}] \tag{D.2}$$

where T_k is the total number of catch observations for gear type k.

D.5.2 RELATIVE ABUNDANCE DATA

The relative abundance data are assumed to be proportional to biomass that is vulnerable to the sampling gear:

$$V_{k,t} = \sum_a N_{t,a} e^{-\lambda_{k,t} Z_{t,a}} v_{k,a} w_a \tag{D.3}$$

where $v_{k,a}$ is the age-specific selectivity of gear k, and w_a is the mean-weight-at-age. A user specified fraction of the total mortality $\lambda_{k,t}$ adjusts the numbers-at-age to correct for survey timing. The residuals between the observed and predicted relative abundance index is given by:

$$\epsilon_{k,t} = \ln(I_{k,t}) - \ln(q_k) + \ln(V_{k,t}) \tag{D.4}$$

where $I_{k,t}$ is the observed relative abundance index, q_k is the catchability coefficient for index k, and $V_{k,t}$ is the predicted vulnerable biomass at the time of sampling. The catchability coefficient q_k is evaluated at its conditional maximum likelihood estimate:

$$q_k = \frac{1}{N_k} \sum_{t \in I_{k,t}} \ln(I_{k,t}) - \ln(V_{k,t})$$

where N_k is the number of relative abundance observations for index k (see Walters and Ludwig, 1994, for more information). The negative loglikelihood for relative abundance data is given by:

$$\ell_I = \sum_k \sum_{t \in I_{k,t}} \ln(\sigma_{k,t}) + \frac{\epsilon_{k,t}^2}{2\sigma_{k,t}^2} \tag{D.5}$$

where

$$\sigma_{k,t} = \frac{\rho\varphi^2}{\omega_{k,t}}$$

where $\rho\varphi^2$ is the proportion of the total error that is associated with observation errors, and $\omega_{k,t}$ is a user specified relative weight for observation t from gear k.

The $\omega_{k,t}$ terms allow each observation to be weighted relative to the total error $\rho\varphi^2$; for example, to omit a particular observation, set $\omega_{k,t} = 0$, or to give 2 times the weight, then set $\omega_{k,t} = 2.0$. To assume all observations have the same variance then simply set $\omega_{k,t} = 1$. Note that if $\omega_{k,t} = 0$ then Eq. D.5 is undefined; therefore, iSCAM adds a small constant to $\omega_{k,t}$ (e^{-10}, which is equivalent to assuming an extremely large variance) to ensure the likelihood can be evaluated. In this assessment, values for $\omega k, t$ were set to inverse of the annual CVs from the survey (Table 3)

D.5.3 AGE COMPOSITION DATA

Sampling theory suggest that age composition data are derived from a multinomial distribution (Fournier and Archibald, 1982). However, iSCAM assumes that age-proportions are obtained from a multivariate logistic distribution (Schnute and Richards, 1995; Richards et al., 1997). iSCAM departs from the traditional multinomial model due to choices regarding weighting of the age-composition data in the objective function. First, the multinomial distribution requires the specification of an effective sample size. This weighting may be done arbitrarily or through iterative re-weighting (McAllister and Ianelli, 1997; Gavaris and Ianelli, 2002), and in the case of multiple and potentially conflicting age-proportions this procedure may fail to converge properly. The assumed effective sample size can have a large impact on the overall model results.

A feature of the multivariate logistic distribution is that the age-proportion data can be weighted based on the conditional maximum likelihood estimate of the variance in the age-proportions. Therefore, the contribution of the age-composition data to the overall objective function is “self-weighting” and is conditional on other components in the model. Ignoring the subscript for gear type for clarity, the observed and predicted proportions-at-age must satisfy the constraint:

$$\sum_{a=1}^{A} p_{t,a} = 1$$

for each year. The residuals between the observed ($p_{t,a}$) and predicted proportions ($\hat{p}_{t,a}$) is given by:

$$\eta_{t,a} = \ln(p_{t,a}) - \ln(\hat{p}_{t,a}) - \frac{1}{A}\sum_{a=1}^{A}\left[\ln(p_{t,a}) - \ln(\hat{p}_{t,a})\right] \qquad \text{(D.6)}$$

The conditional maximum likelihood estimate of the variance is given by

$$\hat{\tau}^2 = \frac{1}{(A-1)T}\sum_{t=1}^{T}\sum_{a=1}^{A}\eta_{t,a}^2$$

and the negative loglikelihood evaluated at the conditional maximum likelihood estimate of the variance is given by:

$$\ell_A = (A-1)T\ln(\hat{\tau}^2). \tag{D.7}$$

In short, the multivariate logistic likelihood for age-composition data is just the log of the residual variance weighted by the number observations over years and ages.

D.5.4 STOCK RECRUITMENT

This stock assessment assumes Beverton-Holt recruitment. Annual recruitment and the initial age-composition are treated as latent variables in iSCAM, and residuals between estimated recruits and the deterministic stock-recruitment models are used to estimate unfished spawning stock biomass and recruitment compensation. The residuals between the estimated and predicted recruits is given by:

$$\delta_t = \ln(\bar{R}e^{w_t}) - R_t) \tag{D.8}$$

where R_t is given by Eq. D.38, and k is the age at recruitment. Note that a bias correction term for the lognormal process errors is included in Eq. D.38.

The negative log likelihood for the recruitment deviations is given by the normal density (ignoring the scaling constant):

$$\ell_\delta = n\ln(\tau) + \frac{\sum_{t=1+k}^{T}\delta_t^2}{2\tau^2} \tag{D.9}$$

Eqs. D.8 and D.9 are key for estimating unfished spawning stock biomass and recruitment compensation via the recruitment models. The relationship between (s_o, β) and (B_o, κ) is defined as:

$$s_o = \frac{\kappa}{\phi_E} \tag{D.10}$$

$$\beta = \frac{\kappa - 1}{B_o} \quad (Beverton - Holt) \tag{D.11}$$

where s_o is the maximum juvenile survival rate, and β is the density effect on recruitment.

D.6 TABLES

Table D.1. A list of symbols, constants and description for variables used in iSCAM.

Symbol	Value	Description
Indices		
s		Index for sex
a		Index for age
t		Index for year
k		Index for gear
Model dimensions		
S	1	Number of sexes
$\acute{a}, A$	$1, 20$	Youngest and oldest age class (A is a plus group)
$\acute{t}, T$	$1996, 2014$	First and last year of catch data
K	5	Number of gears including survey gears
Observations (data)		
$C_{k,t}$		catch in weight by gear k in year t
$I_{k,t}$		relative abundance index for gear k in year t
Fixed parameters		
ρ		Fraction of the total variance associated with observation error
ϑ^2		Total precision (inverse of variance) of the total error
Estimated parameters		
R_o		Age-$\acute{a}$ recruits in unfished conditions
h		Steepness of the stock-rectruitment relationship
$\bar{R}$		Average age-$\acute{a}$ recruitment from year $\acute{t}$ to T
$\bar{R}_{init}$		Average age-$\acute{a}$ recruitment in year $\acute{t}-1$
M_s		Instantaneous natural mortality rate
$\hat{a}_k, \hat{\gamma}_k$		Selectivity parameters for gear k
$\Gamma_{k,t}$		Logarithm of the instantaneous fishing mortality for gear k in year t
ω_t		Age-$\acute{a}$ deviates from $\bar{R}$ for years $\acute{t}$ to T
$\omega_{init,t}$		Age-$\acute{a}$ deviates from $\bar{R}_{init}$ for year $\acute{t}$
q_s		Catchability parameter for survey k
Standard deviations		
σ		Standard deviation for observation errors in survey index
τ		Standard deviation in process errors (recruitment deviations)
σ_C		Standard deviation in observed catch by gear
Residuals		
δ_t		Annual recruitment residual
η_t		Residual error in predicted catch
Fixed Growth & maturity parameters		
$l_{\infty s}$		Asymptotic length in mm sex s
$\acute{k}_s$		Brody growth coefficient sex s
t_{os}		Theoretical age at zero length sex s
$\acute{a}_s$		Scalar in length-weight allometry for sex s
$\acute{b}_s$		Power parameter in length-weight allometry for sex s
$\dot{a}_s$		Age at 50% maturity for sex s
$\dot{\gamma}_s$		Standard deviation at 50% maturity for sex s

Table D.2. Steady-state age-structured model assuming unequal vulnerability-at-age, age-specific fecundity and Ricker type recruitment.

Parameters

$$\Theta = (R_o, h, M)\,; \quad R_o > 0; \quad 0.2 \leq h < 1.0; \quad M > 0 \tag{D.12}$$

$$\Phi = (l_{\infty,s}, \acute{k}_s, t_{o,s}, \acute{a}_s, \acute{b}_s, \dot{a}_s, \dot{\gamma}_s, \hat{a}_k, \hat{\gamma}_k) \tag{D.13}$$

Age-schedule information

$$l_{a,s} = l\left(1 - e^{(-k_s(a - t_{o,s}))}\right) \tag{D.14}$$

$$w_{a,s} = \acute{a}_s(l_{a,s})^{\acute{b}_s} \tag{D.15}$$

$$v_a = \left(1 + e^{\left(\frac{-(\hat{a}-a)}{\hat{\gamma}}\right)}\right)^{-1} \tag{D.16}$$

$$f_{a,s} = w_{a,s}\left(1 + e^{\left(\frac{-(\dot{a}_s - a_s)}{\dot{\gamma}_s}\right)}\right)^{-1} \tag{D.17}$$

Survivorship

$$\iota_a = \begin{cases} \frac{1}{S}, & a = 1 \\ \iota_{a-1}e^{-M}, & a > 1 \\ \frac{\iota_{a-1}}{(1-e^{-M})}, & a = A \end{cases} \tag{D.18}$$

$$\iota_a = \begin{cases} \frac{1}{S}, & a = 1 \\ \hat{\iota}_{a-1,s}e^{-M-F_e v_{a-1,s}}, & a > 1 \\ \frac{\hat{\iota}_{a-1,s}e^{-M-F_e v_{a-1,s}}}{(1-e^{-M-F_e v_{a,s}})}, & a = A \end{cases} \tag{D.19}$$

Incidence functions

$$\phi_E = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \iota_a f_{a,s}, \qquad \phi_e = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \hat{\iota}_{a,s} f_{a,s} \tag{D.20}$$

$$\phi_B = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \iota_a w_{a,s} v_{a,s}, \quad \phi_b = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \hat{\iota}_{as} w_{a,s} v_{a,s} \tag{D.21}$$

$$\phi_q = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \frac{\hat{\iota}_{a,s} w_{a,s} v_{a,s}}{M + F_e v_{a,s}}\left(1 - e^{(-M-F_e v_{a,s})}\right) \tag{D.22}$$

Steady-state conditions

$$B_o = R_o \phi_B \tag{D.23}$$

$$\kappa = \frac{4h}{1-h} \tag{D.24}$$

$$R_e = R_o \frac{\kappa - \frac{\phi_E}{\phi_e}}{\kappa - 1} \quad (Beverton - Holt) \tag{D.25}$$

$$C_e = F_e R_e \phi_q \tag{D.26}$$

Table D.3. Statistical catch-age model using Baranov catch.

Estimated parameters

$$\Theta = (R_0, h, M, \overline{R}, \overline{R}_{init}, \vartheta^2, \rho, \Gamma_{k,t}, \{\omega_t\}_{\acute{t}=1-A}^{\acute{t}=T}, \{\omega_{init,t}\}_{t=\acute{t}-A}^{t=\acute{t}-1}) \quad \text{(D.27)}$$

$$\sigma = \sqrt{\frac{\rho}{\vartheta}}, \quad \tau = \frac{(1-\rho)^{1/2}}{\vartheta} \quad \text{(D.28)}$$

Unobserved states

$$N_{t,a,s},\ B_t, s,\ Z_{t,a,s} \quad \text{(D.29)}$$

Initial states

$$N_{t,a,s} = \frac{1}{S}\overline{R}_{init} e^{\omega_{init,t}} e^{-M(a-1)}; \quad (\acute{t} - A) < t < 1; \quad 2 \leq a \leq A \quad \text{(D.30)}$$

$$N_{t,a,s} = \frac{1}{S}\bar{R}e^{\omega_t}; \quad 1 \leq t \leq T; \quad a = 1 \quad \text{(D.31)}$$

$$v_{k,a} = \frac{1}{1 + e^{-\frac{(a-\hat{a}_k)}{\hat{\gamma}_k}}} \quad \text{(D.32)}$$

$$F_{k,t} = e^{\Gamma_{k,t}} \quad \text{(D.33)}$$

State dynamics ($t > 1$)

$$B_{t,s} = \sum_a N_{t,a,s} f_{a,s} \quad \text{(D.34)}$$

$$Z_{t,a,s} = M + \sum_k F_{k,t} v_{k,t,a,s} \quad \text{(D.35)}$$

$$\hat{C}_{k,t} = \sum_s \sum_a \frac{N_{t,a,s} w_{a,s} F_{k,t} v_{k,t,a,s} (1 - e^{-Z_{t,a,s}})}{Z_{t,a,s}}^{\eta_t} \quad \text{(D.36)}$$

$$N_{t,a,s} = \begin{cases} \frac{s_o E_{t-1}}{1+\beta E_{t-1}} e^{(\omega_t - 0.5\tau^2)} & a = 1 \\ N_{t-1,a-1,s} e^{(-Z_{t-1,a-1,s})} & a > 1 \\ N_{t-1,a,s} e^{(-Z_{t-1,a,s})} & a = A \end{cases} \quad \text{(D.37)}$$

Recruitment model

$$R_t = \frac{s_o B_{t-k}}{1 + \beta B_{t-k}} e^{\delta_t - 0.5\tau^2} \quad (Beverton - Holt) \quad \text{(D.38)}$$