Working paper for the 18th Session of the Working Party on Tropical Tunas

Indian Ocean Tuna Commission (IOTC)

Victoria, Seychelles, 5-10 November 2016

Stock assessment of Indian Ocean bigeye tuna (*Thunnus obesus*) using Age-Structured Assessment Program (1979-2015)

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Jiangfeng Zhu

College of Marine Sciences, Shanghai Ocean University, Shanghai, China;
Key Laboratory of Sustainable Exploitation of Oceanic Fisheries Resources (Shanghai Ocean University), Ministry of Education, China

Email: jfzhu@shou.edu.cn

November 2016

Summary

This paper conducted a stock assessment for Indian Ocean bigeye tuna (*Thunnus obesus*) using Age Structured Assessment Program (ASAP), based on fishery-specific catch and catch-at-age data. The assessment considered that the bigeye tuna stock were subject to 7 fisheries, i.e., Deep longline fishery (LL), Purse seine fishery of free-school (PSFS), Purse seine fishery of associated-school (PSLS), Pole-and-line and small seine fisheries (BB), Fresh longline fishery (FL), Line fishery (LINE), and Other fishery (OTHER). The stock was modeled on yearly basis from 1979 to 2015. The catch-per-unit-effort (CPUE) standardized using joint fishery data from the main longline fleets were used as abundance indices for tuning the model. Key sources of uncertainty were considered to be from steepness (h = 0.7, 0.8, and 0.9 assumed) of Beverton-Holt stock-recruitment relationship, natural mortality (M, high and low levels), and weighting schemes for area-specific abundance indices. Models were run considering combinations of these uncertainties. The assessment results, including MSY and related biological reference points, were sensitive to the assumed values of h and M. In particular, models with low M assumptions resulted in unrealistic estimates of model parameters and were not used for justifying stock status. Overall, the current stock of BET in the Indian Ocean is not overfished, and slight overfishing is occurring at the beginning of 2015. The stock status was more optimistic under the assumptions of higher steepness parameter. The impact of CPUE weighing factors on stock status was neglectable, which is mostly because of the consistent trends of the indices series.

1 Introduction

Bigeye tuna, *Thunnus obesus* (Lowe, 1839), is a large epi- and mesopelagic fish distributed in tropical and subtropical waters of Indian Ocean. The bigeye tuna (BET) resource was initially harvested by longlines since the 1950s and now is one of the main economic tuna recourses in the Indian Ocean. They are currently caught by longliners (deep-freezing and fresh-tuna longliners), purse seiners (free-school and associated school), pole and line, and other small fleets as well.

Stock assessments of BET in the Indian Ocean have been conducted using Virtual population analysis (Nishida and Takeuchi, 1999), Stock Synthesis (Shono et al., 2009; Kolody et al., 2010; Langley et al., 2013), and age-structured production model (Nishida and Rademeyer, 2011). These assessments suggested there was a low probability that the Indian Ocean BET stock has been overfished and overfishing was probably not occurring (Kolody et al., 2010; Nishida and Rademeyer, 2011; Langley et al., 2013). However, it should be cautious that the BET assessments were associated with many uncertainties according to explorations of extensive sensitivity analysis (Kolody et al., 2010; Langley et al., 2013).

Following the uncertainty remaining in the assessments carried out from the previous Working Party on Tropical Tunas (WPTT) meetings in 2010, 2011, and 2013, the WPTT recommended that bigeye tuna would be the priority species for stock assessments in 2016 (IOTC–WPTT17, 2015).

This working paper presented a stock assessment of Indian Ocean BET for 1979-2015 with Age Structured Assessment Program (ASAP, Version 3; NOAA Fisheries Toolbox, 2013), using stock assessment data sets provided by the IOTC secreatarity for the WPTT. ASAP is a formal stock assessment model and has been used for assessing many commercially exploited stocks, e.g., red grouper, yellowtail flounder, Pacific sardine, Greenland halibut, Gulf of Maine cod, Florida lobster (see NOAA Fisheries Toolbox at http://nft.nefsc.noaa.gov).

The present assessment included a base case model and sensitivity analyses designed for the consideration of key assumptions regarding population dynamics (i.e., the steepness parameter of the stock-recruitment relationship and natural mortality), and weighting scheme for the abundance indices being used to tune the model. Stock status was evaluated based on fishing mortality and spawning stock biomass based reference points. Kobe plots were presented to show historical trends in stock status, as recommended by the Scientific Committe.

During the 18th WPTT meeting, it was informed that after this assessment report had been submitted the catch-at-age data was actually revised to remove a few of unexpected behaviour for some fisheries. Therefore, the assessment models were rerun during the meeting with the revised catch-at-data and the present report was also revised accordingly.

2 Biological parameters and assumptions

2.1 Stock structure

Genetic studies have suggested that there is only one population of bigeye tuna in the Inidan Ocean (Appleyard et al., 2002; Chiang et al., 2008). Thus, a single stock was assumed for the present assessment. Movement was not considered since the ASAP does not allow movement to be modelled.

2.2 Growth and maturity

Previous study used classical Von Bertalanffy growth function to model BET growth (see Shono et al., 2009). However, recent studies demonstrated that young bigeye tunas may growth in linear-like pattern. Therefore, Von Bertalanffy growth model described in Laslett et al. (2008) (see IOTC-2008-WPTT-09) and W-L relationship were used for sexes combined **(Table 1, Figure 1)**. Aging error was not considered.

Maturity-at-length model was adopted as in Shono et al. (2009). Maturity-at-length data (proportion of fish mature at length) was converted into maturity-at-age (proportion of fish mature at age) using von Bertalanffy growth model **(Figure 1)**. The proportion of fishing mortality that occurs before spawning was assumed to be 0.0, i.e., spawning occurring at the beginning of Jan 1st.

2.3 Natural mortality

Natural mortality (M) for young fish was belived to be higher than adult fish. Thus, a linear decreasing natural mortality pattern was assumed for fish of age class 0+ through 2+, and constant natural mortality was assumed for fish of age class 3+ through 9+. Since natural mortality might be an important parameter influencing assessment results, two levels of natural mortality values were considered for the current assessment, i.e., the higher level was assumed for the base case model, and the lower level for the sensitivity analysis (**Figure 2**).

3 Fisheries data

3.1 Fishery history and definition of fisheries in model

Bigeye tuna have been caught by industrial longline fleets since the early 1950's, but before 1970 they only represented an incidental catch. After 1970, the introduction of fishing practices that improved catchability of the bigeye tuna resource, combined with the emergence of a sashimi market, lead bigeye tuna to become a primary target species for the main industrial longline fleets (Herrera et al., 2012). Total annual catches have increased steadily since the start of the fishery, reaching the 100,000 t level in 1993 and peaking at 150,000 t in 1999 **(Figure 3)**. Catches dropped since then to 120,000–140,000 t (2000–2007), further dropping to under 90,000 t in 2010–2011. The most recent catch estimate for 2015 was 92,736 t. The Scientific Commitee believes that the recent drop in catches could be related, at least in part, with the expansion of piracy in the northwest Indian Ocean, which has led to a marked drop in the levels of longline effort in the core fishing area of these species (Herrera et al., 2012).

Ideally, the fisheries for stock assessment should be defined to have selectivity and catchability characteristics that do not vary greatly over time, however, defining too many fisheries may cause stock assessment model instability owing to lack of long term data to support parameter estimates. For the present assessment, Indian Ocean BET are assumed to be subject to 7 fisheries, i.e., Deep longline fishery (LL), Purse seine fishery of free-school (PSFS), Purse seine fishery of associated-school (PSLS), Pole-and-line and small seine fisheries (BB), Fresh longline fishery (FL), Line fishery (LINE), and Other fishery (OTHER), according to the available datasets provided by the IOTC Secretariat for 18th WPTT. The historical catch for each fishery was shown in **Figure 3**. Historically, deep longline fishery contributed most of the total catch, followed by fresh longline and log-associated purse seine fishery. The purse fisheries started in 1978, and fresh longline fishery started in 1973. It was also noted that the catches from pole-and-line and small seine fisheries (BB), and Other fishery before 1978 were very low. To decrease the number of model parameters and increase the model converging ability, we developed the BET assessment model on yearly basis from 1979 to 2015 (covering 37 years).

3.2 Total catch and catch-at-age data

Fleet-specific catch and catch-at-age for January 1979 through December 2015 (**Figures 3 and 4**), estimated and provided by the IOTC Secretariat, were used as basic fishery data for conducting the present stock assessment of BET in the Indian Ocean.

3.3 Indices of abundance

The catch-per-unit-effort (CPUE; number of fish caught per 1000 hooks) standardized using joint fishery data from the main longline fleets were used as abundance indices for fitting the model (Hoyle et al., 2016). Five abundance indices series were avaialbe, i.e., the index series for northwest (R1), northeast (R2), southwest (R3), southeast (R4) waters in the Indian Ocean, and the index series for the tropical northern Indian Ocean (R1R2) (**Figure 5**). Four weighing schemes (lamda in the objective function) were examined with respect to these indices in tuning the assessment model. For the indices in the tropical area, either R1 and R2 or R1R2 considered used when setting up the model scenarios (**Table 2**).

4 Stock assessment

4.1 Model configulations

The ASAP uses forward computations assuming separability of fishing mortality into year and age components to estimate population sizes given observed catches, catch-at-age, and indices of abundance. Technical details of the ASAP model can be found in NOAA Fisheries Toolbox (2013).

The objective function in ASAP is the sum of a number of model fits and two penalties. There are two types of error distributions in the calculation of the objective function: lognormal and multinomial. Multinomial distribution is assumed for catch-at-age data, with effective sample size iteratively adjusted based on initial model runs. The lognormal error distribution is assumed for total catch (in weight), abundance indices and stock-recruitment relationship (recruitment deviation).

The CV for annual catch in initial model run was assumed to be 0.1 for each of seven fisheries and constant for the whole time period. Adjustment was made according to the diagnostic results for the residual pattern and root mean square error (RMSE).

Since there was no strong prior evidence supporting which index is more reliable than others, the weighting factor for the five indices was systematically examined (**Table 2**). The CV=0.1 was assumed for initial runs and adjusted based on diagnostics.

Beverton-Holt stock recruitment (S-R) model was assumed in the current assessment, as in previous assessments (Shono et al., 2009; Kolody et al., 2010). Steepness was regarded as most important parameter influencing stock assessment results. The steepness (h) for BET model was assumed at 0.7, 0.8, and 0.9. The h=0.8 assumption was considered for the base case, and h=0.7 and 0.9 for sensitivity analysis.

Combining steepness, natural mortality, and abundance index weighting assumptions produced 24 model cases which were used to examine the population dynamics and define the stock status of bigeye tuna **(Table 2)**.

4.2 Parameter estimate

The following parameters are assumed to be known for the present BET stock assessment in the Indian Ocean:

1. Length-at-age and weight-at-age;
2. Age-specific maturity;
3. Age-specific natural mortality rates;
4. The deviation for indices of abundance;
5. The steepness of the stock-recruitment relationship.

The following parameters are to be estimated in the present BET stock assessment in the Indian Ocean:

1. Recruitment in each year from 1979 through 2015 (CV=0.6 for log-tranformed recruitment deviations);
2. Catchability coefficients (q, constant over time) for the abundance indices;
3. Selectivity curves for the 7 fisheries. The selectivity curves for LL and FL were assumed to be Single Logistic (two parameters). The selectivity curves for PSFS, PSLS, and LINE was assumed to be Double Logistic (four parameters). Age-specific parameters were defined for BB and OTHER, but selectivity for

age 0 was fixed at 1.0 as these two fisheries seem catching high proportion of juveniles. This assumption is arbitrary, but fixing at least one parameter at 1.0 is required by the ASAP model configulation.

(4) Effective sample size (ESS) for catch-at-age for each fishery;
(5) Initial population size and age structure;
(6) Fully recruited fishing mortality (*F*mult) for each fleet for the first year, and deviations for *F*mult for the remaining years.

4.3 Management quantities

The program computes a number of biological reference points (BRPs) based on the estimated selectivity pattern, weights at age, natural mortality, and relative fishing intensity among fleets in the terminal year of the assessment (i.e., 2015). The reference points computed are MSY, $C_{current}$/MSY, F_{MSY}, $F_{current}/F_{MSY}$, SSB_{MSY}, $SSB_{current}/SSB_{MSY}$, and $SSB_{current}/SSB_0$. The term “current” means the terminal year in the model (i.e., 2015).

4.4 Stock assessment results

The assessment results presented in the following sections are likely to change in future assessments because (1) future data may provide evidence contrary to these results, and (2) the assumptions and constraints used in the assessment model may change. Most assessment results are presented only for the base case, while the BRPs and Kobe plots were presented for both the base case and sensitivity cases.

4.4.1 Model fit diagnostics

Convergence was the first step to perceive if the model might be misspecified. The model was then diagnosed by looking at the residual pattern in fitting abundance indices, catch, and age composition data. The diagnostics is also made by checking the root mean square error (RMSE) computed for each set of residuals. Ideally, an infinite sample drawn from N (0, 1) distribution has RMSE equal to one. However, when sample sizes are limited, RMSE values drawn from a true N (0, 1) distribution can have a relatively wide range. The input CV can be adjusted based on the RMSE values. The effective sample size (ESS) for the age compositon data can be adjusted based on the Francis (2011) approach, however, this adjustment was not accepted for the current assessment due to unrealistic results produced. Likelihood profile with regard to natural mortality and steepness parameter assumptions are plot. Retropective analysis was also conducted to diagnose the model misspecifcation.

The model fits to the catch data closely as shown in **Figure 6**. The model fits to the abundance index data are shown in **Figure 7**. Overall, the model fits the longline CPUE observations closely, except for a few years in the early period. The input and estimated effective sample size for the age composition of catch are shown in **Figure 8**. The initial ESS input for each fishery was set at 50, and the ESS was adjusted by replacing the inputs using the estimated ESS (conducted only once). The model fits to the age composition data are shown in **Figure 9**. Visual inspection indicates that the model estimates follow the main pattern of the varation in the observations. But the model did not estimate age compositon very well for a few age classes for the BB and OTHER fisheies, which is mostly because the selectivity-at-age 0 was fixed at 1 (ages 0, 1, 2, … are corresponding to ages 1, 2, 3, … in the ASAP model outputs).

Figure 10 showed the likelihood conponents of the base case model fit, indicating that the most majority of the likelihood are contributed by age composition and catch data. Among the 24 models configured, Models 5-8, Models 13-16 and Models 21-24 with low natural mortality resulted in unrealistically pessimistic stock staus (**Tables 2, 3**). In addition, the likelihood profile for natual mortality supported that the model preferred a higher natural mortality (**Figure 11**). Therefore, the models with low M assumption are considered to be significantly biased and not used for futher analysis. In terms of steepness, there was not strong indication that the likelihood prefers h=0.8 or higher steepness values (**Figure 12**), in contrast to lower steepness (0.7). However, to be conservative, lower steepness assumption was kept. Retrospective analysis showed that the retrospective error assocated with the SSB and fishing mortality estimates are considered to be low (**Figure 13**).

4.4.2 Fishery and population dynamics

The selectivity-at-age for each fishery was shown in **Figure 14**. The selecvitivity curve for fishery PSFS is more like dome-shaped than the PSLS, consistent with the the obseravation that more large fish are captured in the free school purse fishery. The selectivity curves of BB fishery and OTHER fishery were not smooth, which is mostly related to the fixing of selectivity equal to 1 for age 0. The catchability coefficients for the the four abundance indices (R1, R2, R3, R4) in base case are shown in **Figure 15**.

The fully recruited fishing mortality for 1979-2015 was shown in **Figure 16.** The fishing mortality increased gradually from 1979 to early 1990s, followed by a steep increase during the mid- and late 1990s. The fishing mortality since 2000 stays at a relative high level, with slight annual varations. In contrast to the fishing mortality trend, the spawning stock biomass (SSB) has been declining since 1980s, although there was a short-term increase from 1979 to the mid-1980s.

The stock abundance was stable at about 250 millions fish from 1979 to 1994, then increase towards 320 millions at 1998. The stock abundance was rapidly decreasing from 1999 to 2005, followed by a short increase (**Figure 17**). Since 2007, the recruitment was decreasing (**Figures 17 and 18**). In ASAP, the recruits were defined as the fish of first age class, i.e., the age 0 class for BET. The estimated stock-recruitment curve was shown in **Figure 18**.

4.4.3 Biological reference points

The biological referent points (BRPs) for all model cases are listed in **Table 3**. Diagnostics showed that the models with low natural mortality may not be realistic, in that the models seemed to systematically bias the estimates of fishing mortality or biomass. The reason needs to be futher investigated. It was noted that MSY-related BRPs were more sensitive to the steepness parameters than the weighting factors. The impact of weighting factor on BRPs was neglectable. This is partially because the joint CPUE indices from different areas show consistent trends. The uncertainties of BRPs for the base case model estimated from the MCMC procedure in ASAP (100 iterations, thinning per 500 iterations) was shown in **Table 4**, resulting in relative narrow variations.

5 Status of the stock

As mentioned above, models assuming lower natural mortality were dropped and not used for justifying stock status. The ratio of current fishing mortality compared with the fishing mortality at MSY (F_{curr}/F_{MSY}) was slightly higher than one for models with lower and medium steepness (Models 1-4 and 9-12; **Table 3**), indicating that overfishing is occurring. However, the models with higher steepness resulted in F_{curr}/F_{MSY} slightly lower than one (Models 17-20).

The ratio of current spawning stock biomass compared with the level corresponding to MSY (SSB_{curr}/SSB_{MSY}) was higher than one for all the models with high natural mortality (Models 1-4, 9-12, and 17-20). Thus, the current stock of BET is not overfished. In addition, the stock status was more optimistic under the assumptions of higher steepness parameter. The impact of CPUE weighing factors on stock status was neglectable.

The Kobe plots reflecting the historical change in the stock status are shown in **Figure 19**, including the models resulted in unrealistically pessimesstic stock status. The plausible models (Models 1-4, 9-12, 17-20) suggest that the histocal stock status did not experience overfishing for the most of years.

6. Projection and risk assessment

The base case model was used to project for short-term (3 years) and medium-term (10 years) considering nine constant catch strategies (**Table 5**). The ASAP itself does not incorporate projection component; however, its MCMC procedure can be used to sample model parameters from the uncertainty distribution and generate multiple realizations of number-at-age for starting the projection. An independent stock projection program AgePro (NOAA Fisheries Toolbox, 2011) was then used to conduct projection.

For the present projection of BET, 100 iterations from MCMC with each generating 100 simulations in AgePro produced a total of 10,000 projections, which was used to calculate the risk of violating performance measure. The results were shown as Kobe II Strategy Matrix in **Table 5**. The current catch level will be resulting in a high probability (percentage) of violating the F-based target BRP, but low probability of violating the SSB-based target BRPs. The current catch level will result in low probability of violating both F- and SSB-based limit BRPs. It should be noted that projection is based on the current biological assumptions, fishery selectivities, and Stock-recruitment relationship for driving recruitments, which might be changing in the future.

Ackowledgements

Thanks are given to the IOTC Secretariat for developing stock assessment data sets and WPTT participants for providing comments and suggestions which improved this work. This study was supported by the Project of GaoFeng Discipline of Fishery Science, International Center for Marine Studies and National Engineering Research Center for Oceanic Fisheries at Shanghai Ocean University, China.

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Table 1 Bigeye tuna model parameters for use in base case and sensitivity cases of stock assessment

Biological parameters	**Values for assessments**
Sex ratio	1:1
Age (longevity)	10 age classes (age 0 through 9+)
Natural mortality	Age specific, linearly decreases for younger fish (ages 0+ through 2+), constant for larger fish (ages 3+ through 9+). Higher M for base case and lower M for sensitivity cases. Common to sex.
Growth formula	VB log k model (Laslett, Eveson and Polacheck method, IOTC-2008-WPTT-09).
Weight-length allometry	$W=aL^b$ with $a= 3.661*10^{-5}$ and $b=2.901$ common to sex
Maturity	Age-specific (50% mature at length 110.9 cm)
Stock-recruitment	B&H, h=0.8 for base case (h= 0.7 and 0.9 for sensitivity cases), CV_R=0.6
Other parameters	
Fisheries	7 fisheries, i.e., Deep longline fishery (LL), Purse seine fishery of free-school (PSFS), Purse seine fishery of associated-school (PSLS), Pole-and-line and small seine fisheries (BB), Fresh longline fishery (FL), Line fishery (LINE), and Other fishery (OTHER)
Abundance indices	Joint CPUE, five index series (R1, R2, R1+R2, R3, R4). Equal weight for base case, and higher weight for R1 and R2 for sensativity cases.
Selectivity	Fishery specific, age based. Single Logistic (two parameters) for LL and FL; Double Logistic (four parameters) for PSFS, PSLS, and LINE; age-specific parameters for BB and OTHER

Table 2 Base case (model 9) and sensitivity analysis for BET assessment, defined by different steepness, natural mortality levels, and weighting of CPUE indices in the objective function

Model	*h*	*M*	weighting (lamda) for joint CPUE indices					Note
	0.7, 0.8, 0.9	high, low	R1	R2	R1+R2	R3	R4	
Model 1	0.7	high	1	1	0	1	1	R1+R2 not used
Model 2	0.7	high	2	2	0	1	1	R1+R2 not used
Model 3	0.7	high	0	0	1	1	1	
Model 4	0.7	high	0	0	2	1	1	
Model 5	0.7	low	1	1	0	1	1	R1+R2 not used
Model 6	0.7	low	2	2	0	1	1	R1+R2 not used
Model 7	0.7	low	0	0	1	1	1	
Model 8	0.7	low	0	0	2	1	1	
Model 9*	**0.8**	**high**	**1**	**1**	**0**	**1**	**1**	R1+R2 not used
Model 10	0.8	high	2	2	0	1	1	R1+R2 not used
Model 11	0.8	high	0	0	1	1	1	
Model 12	0.8	high	0	0	2	1	1	
Model 13	0.8	low	1	1	0	1	1	R1+R2 not used
Model 14	0.8	low	2	2	0	1	1	R1+R2 not used
Model 15	0.8	low	0	0	1	1	1	
Model 16	0.8	low	0	0	2	1	1	
Model 17	0.9	high	1	1	0	1	1	R1+R2 not used
Model 18	0.9	high	2	2	0	1	1	R1+R2 not used
Model 19	0.9	high	0	0	1	1	1	
Model 20	0.9	high	0	0	2	1	1	
Model 21	0.9	low	1	1	0	1	1	R1+R2 not used
Model 22	0.9	low	2	2	0	1	1	R1+R2 not used
Model 23	0.9	low	0	0	1	1	1	
Model 24	0.9	low	0	0	2	1	1	

* Base case

Table 3 Management related quantities derived from base case assessment model and sensitivity analyses for Indian Ocean BET

Model	MSY	C_{curr}/ MSY	F_{MSY}	F_{curr}/ F_{MSY}	SSB_{MSY}	SSB_{curr}/ SSB_{MSY}	SSB_0	SSB_{curr}/ SSB_0
Model 1	76,907	1.21	0.12	1.29	519,343	1.14	1,600,080	0.37
Model 2	74,963	1.24	0.12	1.34	511,080	1.15	1,577,840	0.37
Model 3	78,183	1.19	0.12	1.28	526,457	1.12	1,620,740	0.36
Model 4	76,245	1.22	0.12	1.33	519,804	1.13	1,604,260	0.37
Model 5	89,835	1.03	0.10	3.78	928,153	0.28	2,676,500	0.10
Model 6	100,248	0.93	0.10	4.10	1,109,660	0.22	3,189,240	0.08
Model 7	109,675	0.85	0.10	3.79	1,157,870	0.22	3,328,310	0.08
Model 8	102,241	0.91	0.10	4.04	1,104,590	0.22	3,175,840	0.08
Model 9*	82,559	1.12	0.14	1.09	452,855	1.30	1,539,060	0.38
Model 10	80,592	1.15	0.14	1.13	445,759	1.31	1,519,350	0.39
Model 11	83,794	1.11	0.14	1.08	458,574	1.29	1,556,810	0.38
Model 12	81,931	1.13	0.14	1.13	453,244	1.30	1,544,240	0.38
Model 13	84,220	1.10	0.11	3.40	773,241	0.32	2,380,310	0.10
Model 14	81,843	1.13	0.11	3.53	766,802	0.32	2,361,480	0.10
Model 15	86,441	1.07	0.11	3.26	774,185	0.33	2,383,590	0.11
Model 16	83,049	1.12	0.11	3.49	761,505	0.32	2,345,710	0.11
Model 17	88,401	1.05	0.16	0.92	388,933	1.52	1,497,980	0.39
Model 18	86,395	1.07	0.16	0.96	382,518	1.53	1,479,800	0.40
Model 19	89,625	1.03	0.16	0.91	393,698	1.50	1,513,930	0.39
Model 20	87,803	1.06	0.16	0.95	388,921	1.51	1,503,740	0.39
Model 21	76,213	1.22	0.13	2.96	597,297	0.42	1,986,950	0.13
Model 22	74,651	1.24	0.13	3.08	596,351	0.41	1,985,410	0.12
Model 23	77,722	1.19	0.13	2.84	594,949	0.43	1,978,710	0.13
Model 24	75,577	1.23	0.13	3.04	592,260	0.42	1,971,710	0.13

Unit for catch and biomass: metric ton.

Table 4 Summary of key management quantities from the base case model

Management quantity	Estimates
Most recent catch estimate (t) (2015)	92,736
Mean catch over last 5 years (t) (2011–2015)	101,513
h (steepness)	Base=0.8
MSY (1,000 t) (80% CI)	82.3 (80.4-84.1)
Data period (catch)	1979–2015
CPUE series/period	4/1979–2015
F_{MSY} (80% CI)	0.139 (0.132-0.146)
SB_{MSY} (1,000 t) (80% CI)	453.4 (432.7-474.1)
F_{2015}/F_{MSY} (80% CI)	1.118 (1.058-1.177)
B_{2015}/B_{MSY} (80% CI)	n.a.
SB_{2015}/SB_{MSY} (80% CI)	1.317 (1.256-1.377)
B_{2015}/B_{1950} (80% CI)	n.a.
SB_{2015}/SB_{1950} (80% CI)	n.a.
$SB_{2015}/SB_{current,\ F=0}$ (80% CI)	0.381 (0.377-0.385)

n.a. = not available

Table 5 Bigeye tuna: ASAP base case assessment Kobe II Strategy Matrix. Probability (percentage) of violating the MSY-based target (top) and limit (bottom) reference points for nine constant catch projections (average catch level from 2015 (92,736 t), ± 10%, ± 20%, ± 30% ± 40%) projected for 3 and 10 years.

Reference point and projection timeframe	**Alternative catch projections (relative to the average catch level from 2015) and probability (%) of violating MSY-based target reference points ($SB_{targ} = SB_{MSY}$; $F_{targ} = F_{MSY}$)**								
	60%	70%	80%	90%	100%	110%	120%	130%	140%
	55,642	64,915	74,189	83,463	**92,736**	######	######	120,557	129,831
$SB_{2018} < SB_{MSY}$	0	0	0	0	0	0	0	0	0
$F_{2018} > F_{MSY}$	0	0	11	45	76	93	97	99	100
$SB_{2025} < SB_{MSY}$	0	0	0	1	3	5	8	11	16
$F_{2025} > F_{MSY}$	3	9	20	34	49	63	74	83	89

Reference point and projection timeframe	**Alternative catch projections (relative to the average catch level from 2015) and probability (%) of violating MSY-based limit reference points ($SB_{lim} = 0.5SB_{MSY}$; $F_{lim} = 1.3F_{MSY}$)**								
	60%	70%	80%	90%	100%	110%	120%	130%	140%
	55,642	64,915	74,189	83,463	**92,736**	######	######	120,557	129,831
$SB_{2018} < SB_{lim}$	0	0	0	0	0	0	0	0	0
$F_{2018} > F_{lim}$	0	0	0	0	3	19	47	71	87
$SB_{2025} < SB_{lim}$	0	0	0	0	0	0	0	0	1
$F_{2025} > F_{lim}$	0	1	4	9	18	29	42	33	66

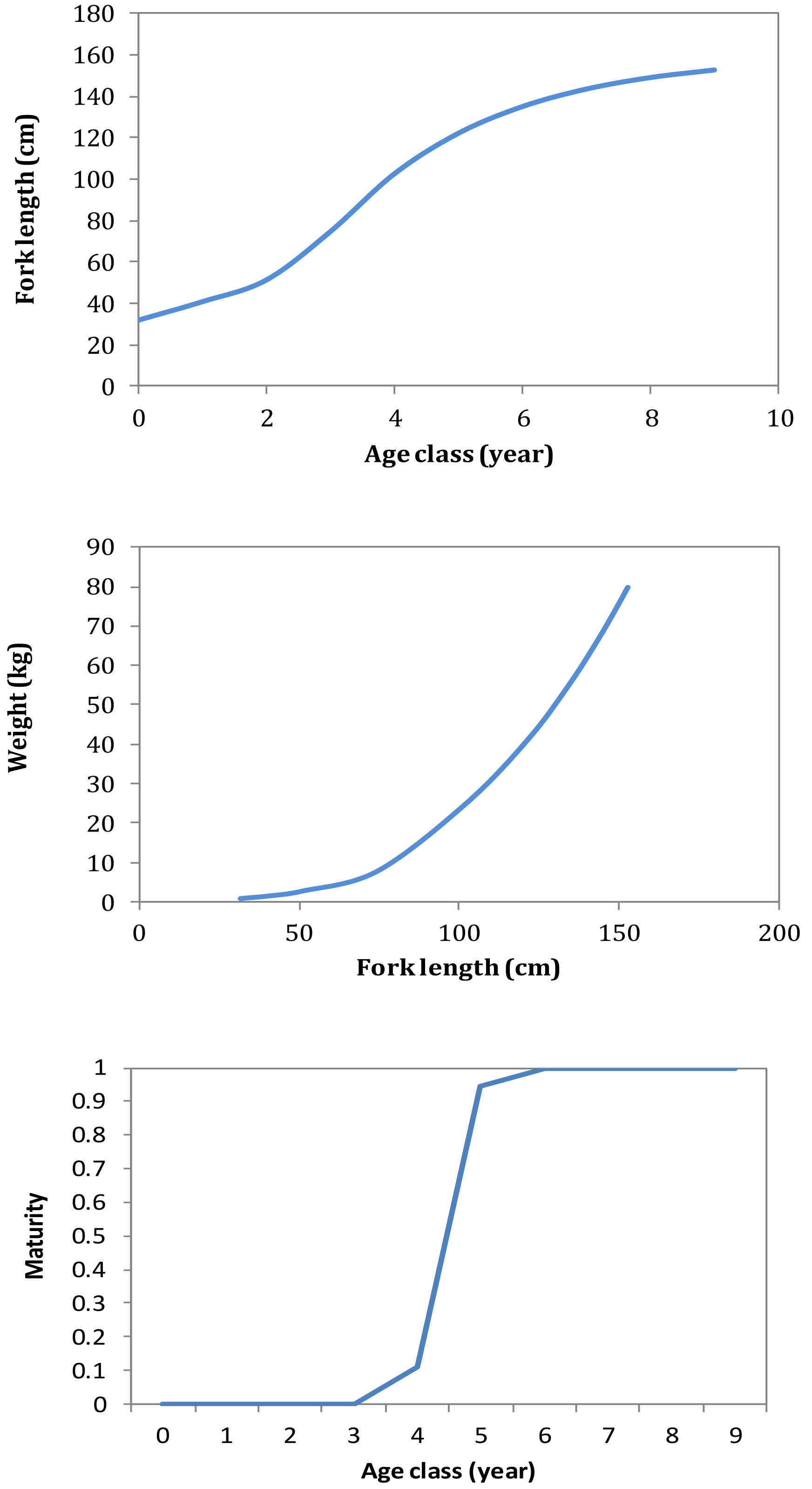


Figure 1 Growth and maturity curves used for the BET assessment

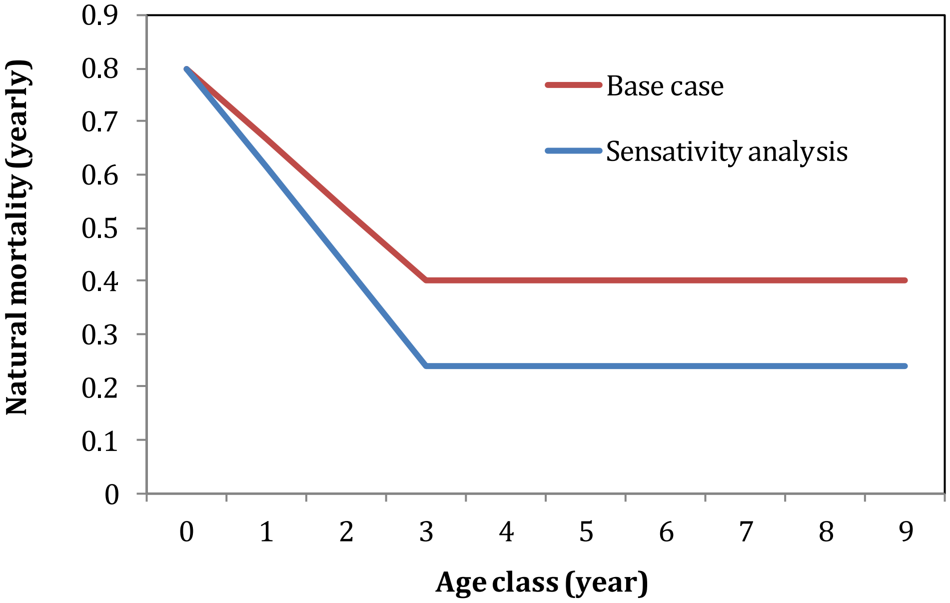


Figure 2 Natural mortality used for the BET assessment

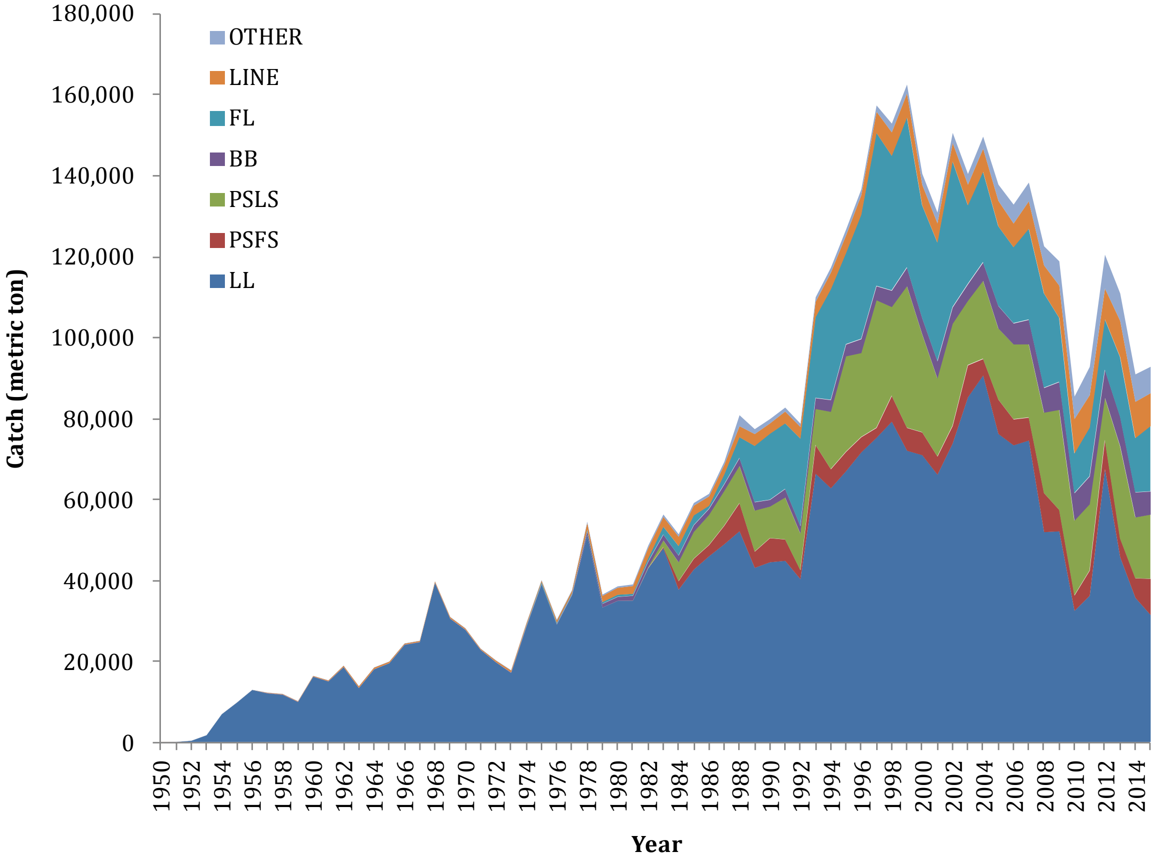
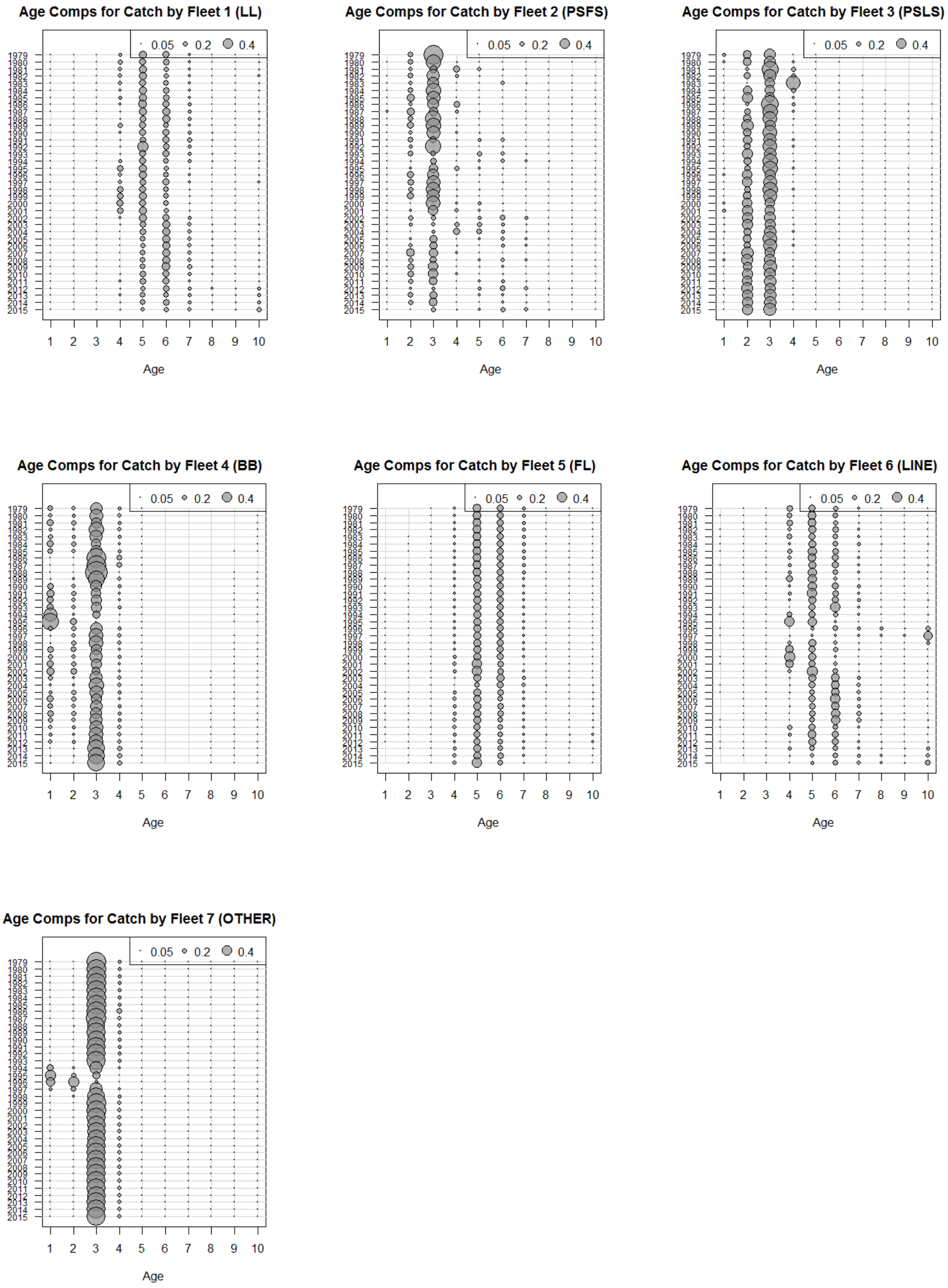


Figure 3 Fleet-specific historical catch of BET in Indian Ocean


Age Comps for Catch by Fleet 1 (LL)

Age Comps for Catch by Fleet 2 (PSFS)

Age Comps for Catch by Fleet 3 (PSLS)

Age Comps for Catch by Fleet 4 (BB)

Age Comps for Catch by Fleet 5 (FL)

Age Comps for Catch by Fleet 6 (LINE)

Age Comps for Catch by Fleet 7 (OTHER)

Figure 4 Fleet-specific age composition data of BET in Indian Ocean

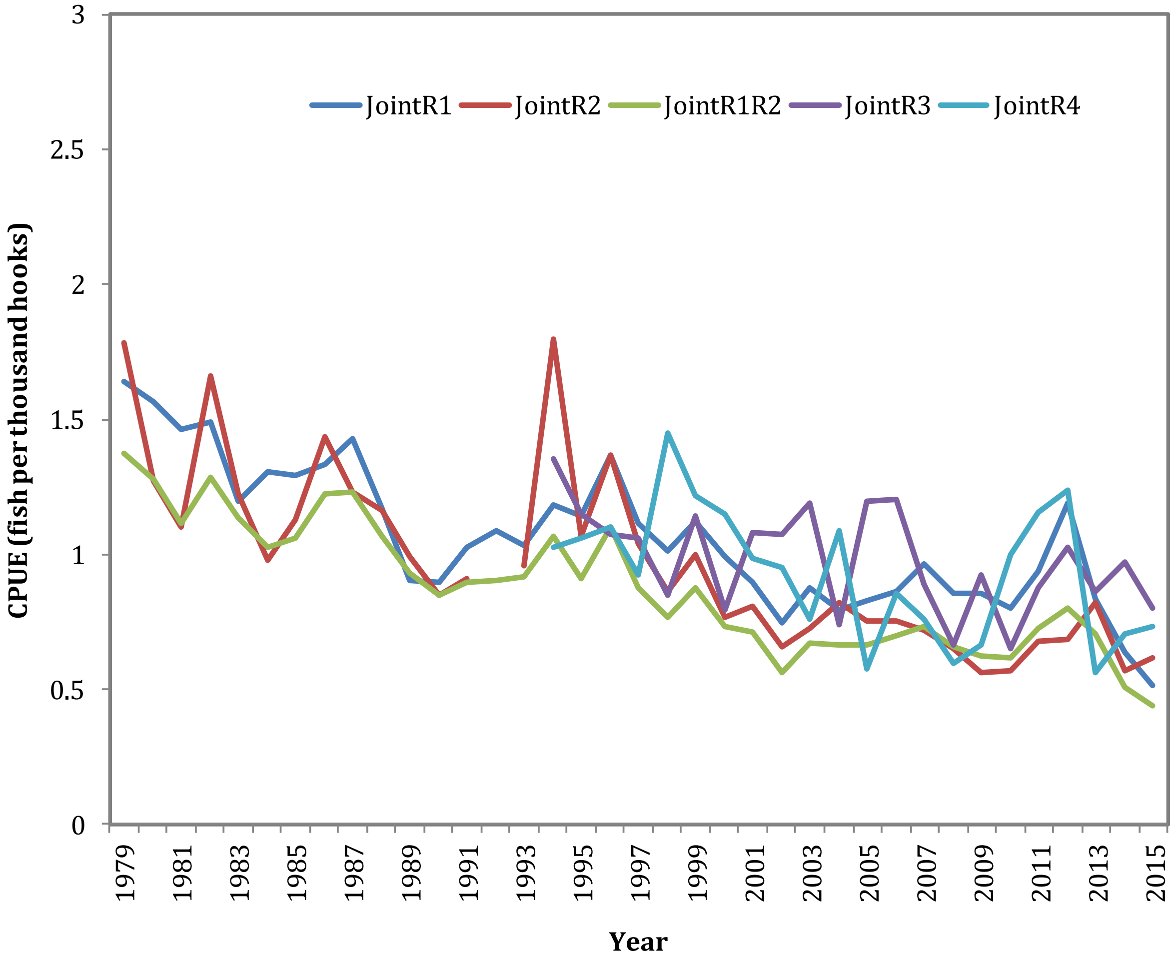


Figure 5 Standardized BET CPUEs in different areas using joint operational catch and effort data of the main longline fleets

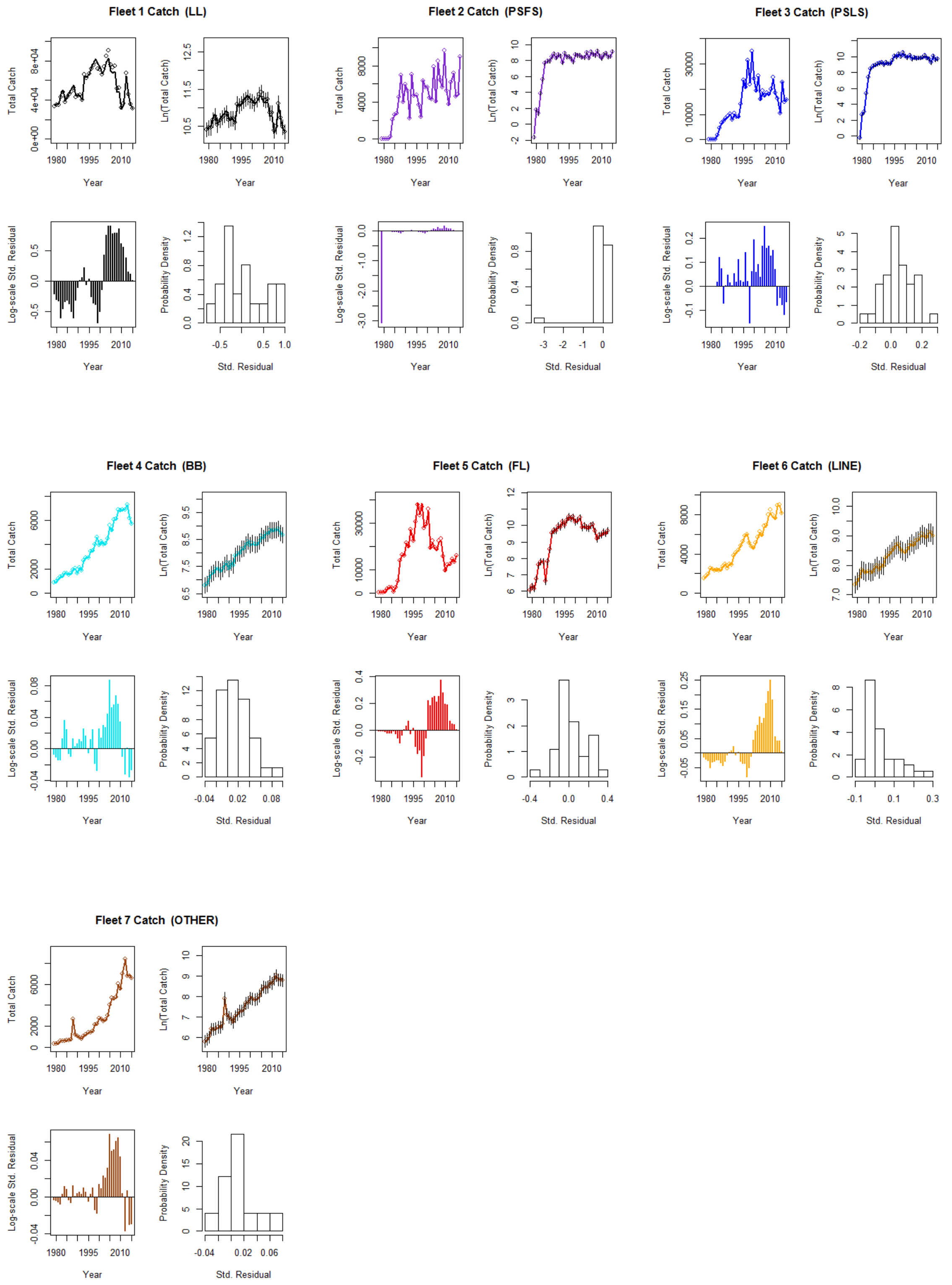


Figure 6 Model fits for annual catch data (base case)

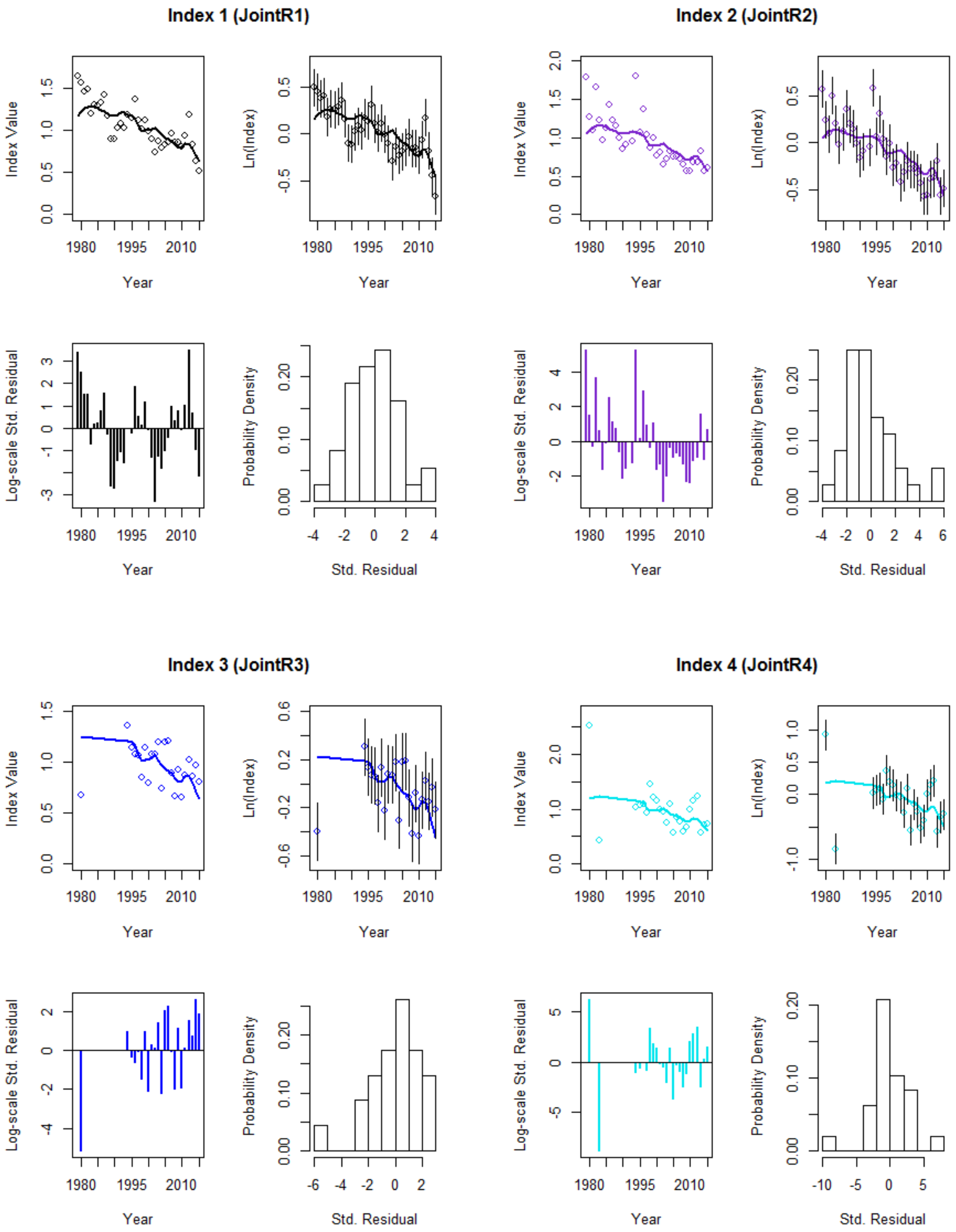


Figure 7 Model fits for the abundance indices (base case)

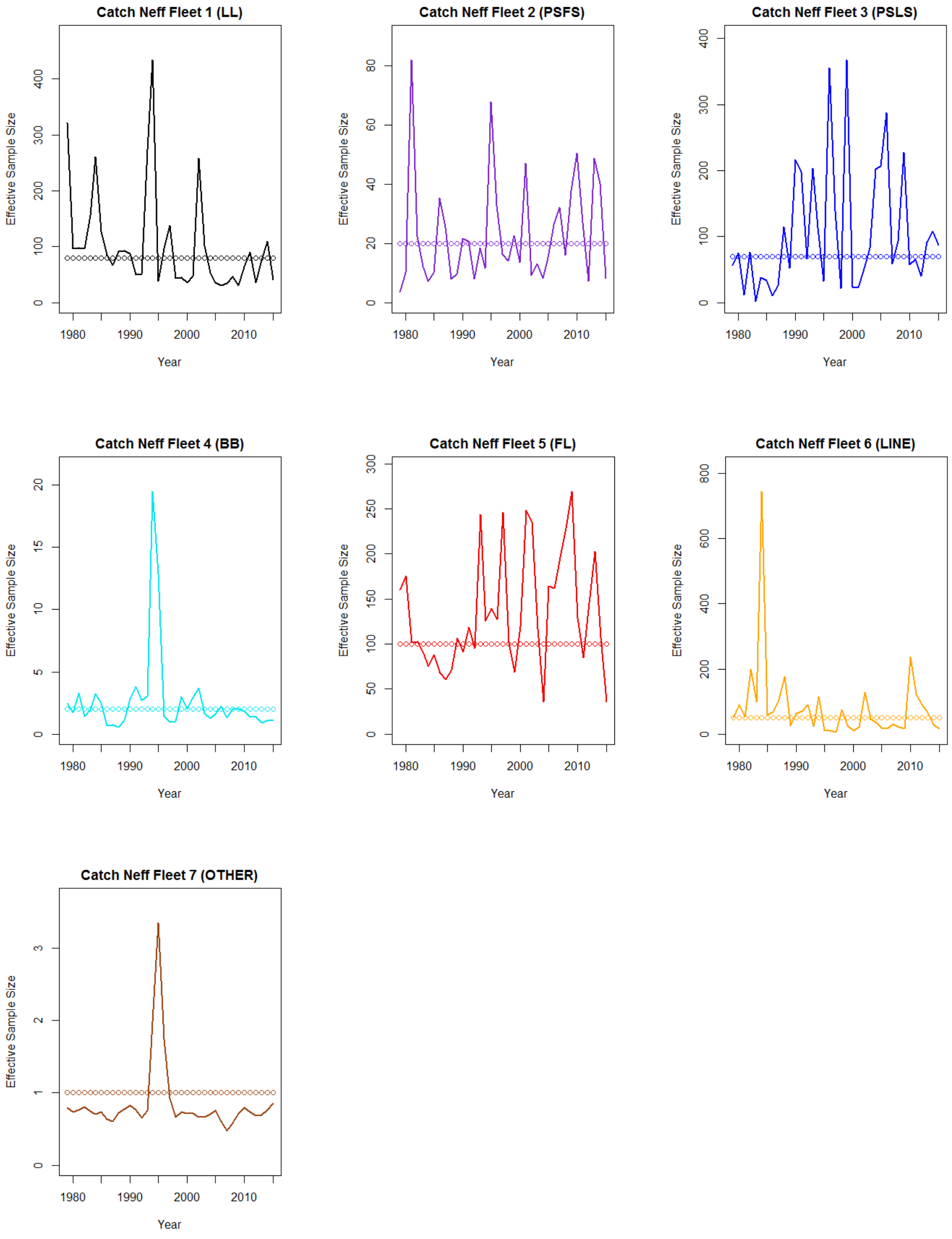


Figure 8 Model fits to the effective sample size for the age composition data of catch (base case)

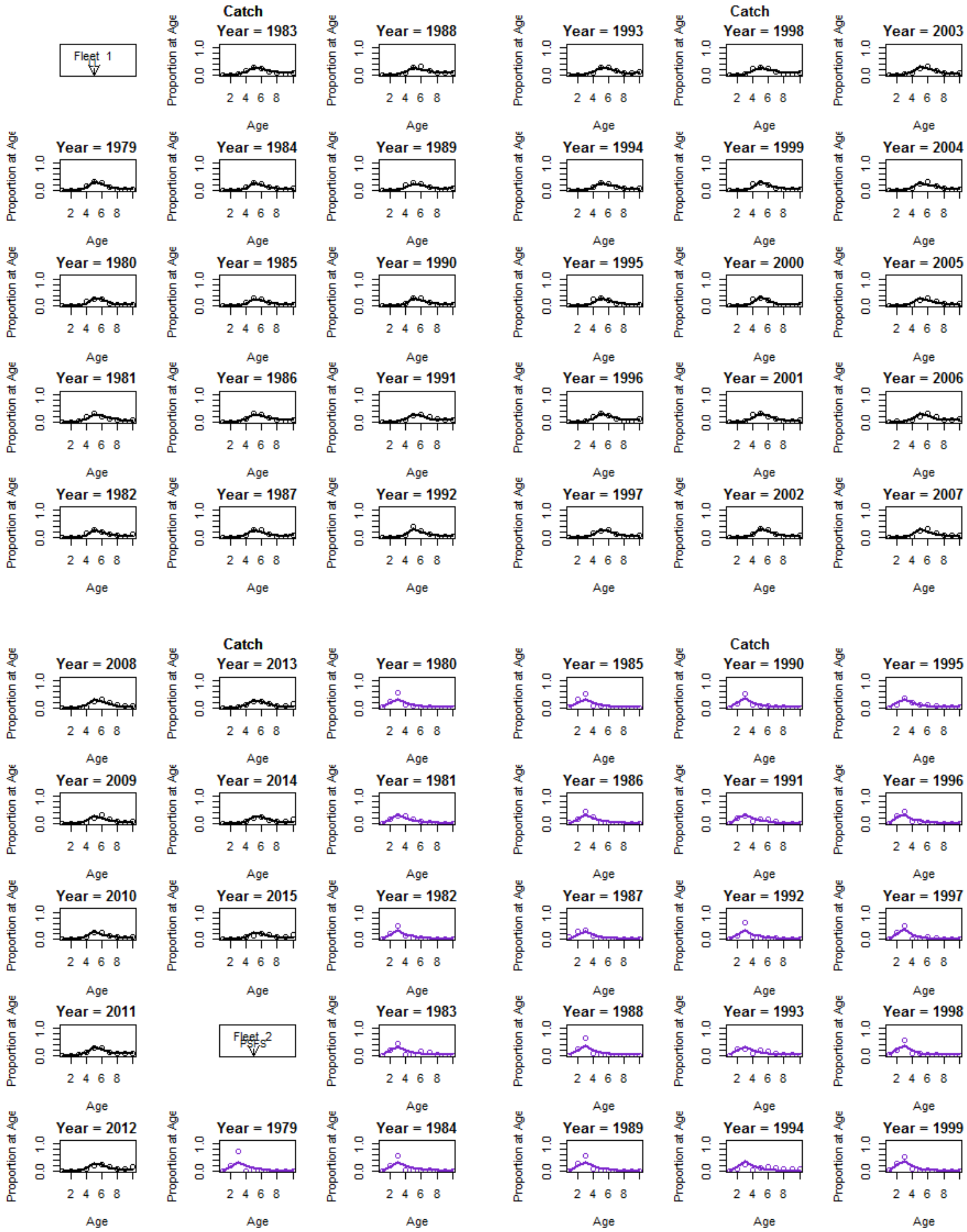


Figure 9 Model fits to age composition data for each fishery

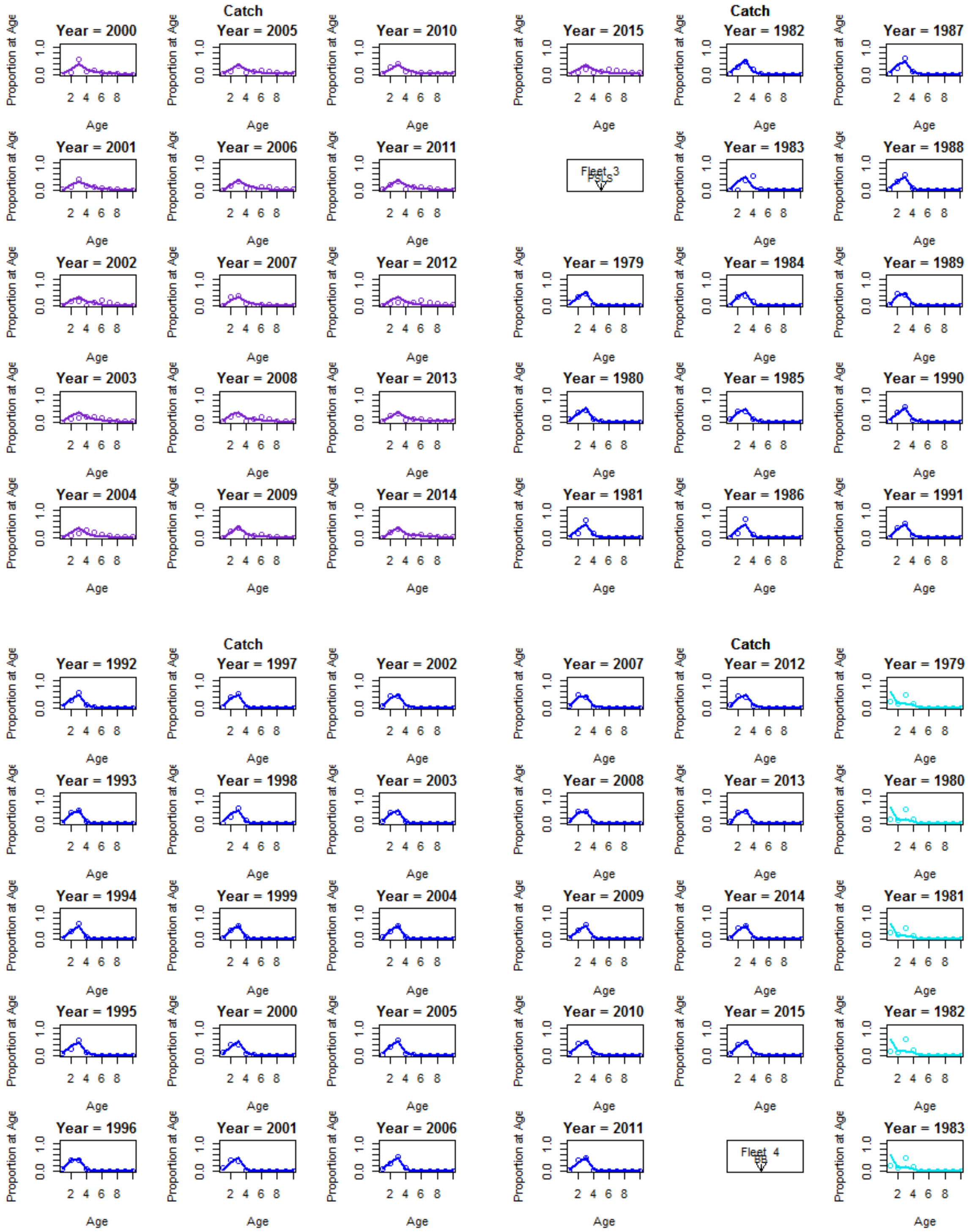


Figure 9 Continued.

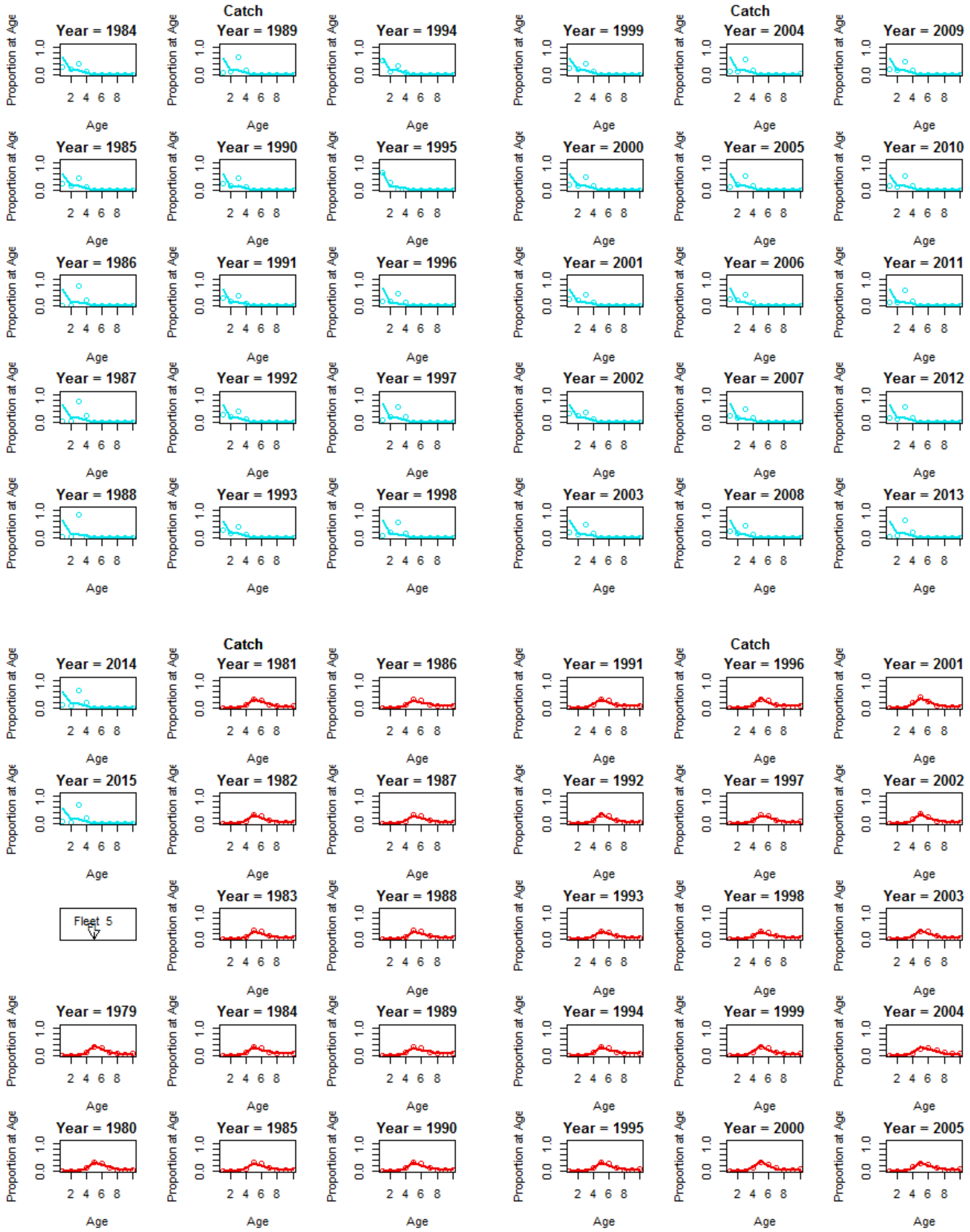


Figure 9 Continued.

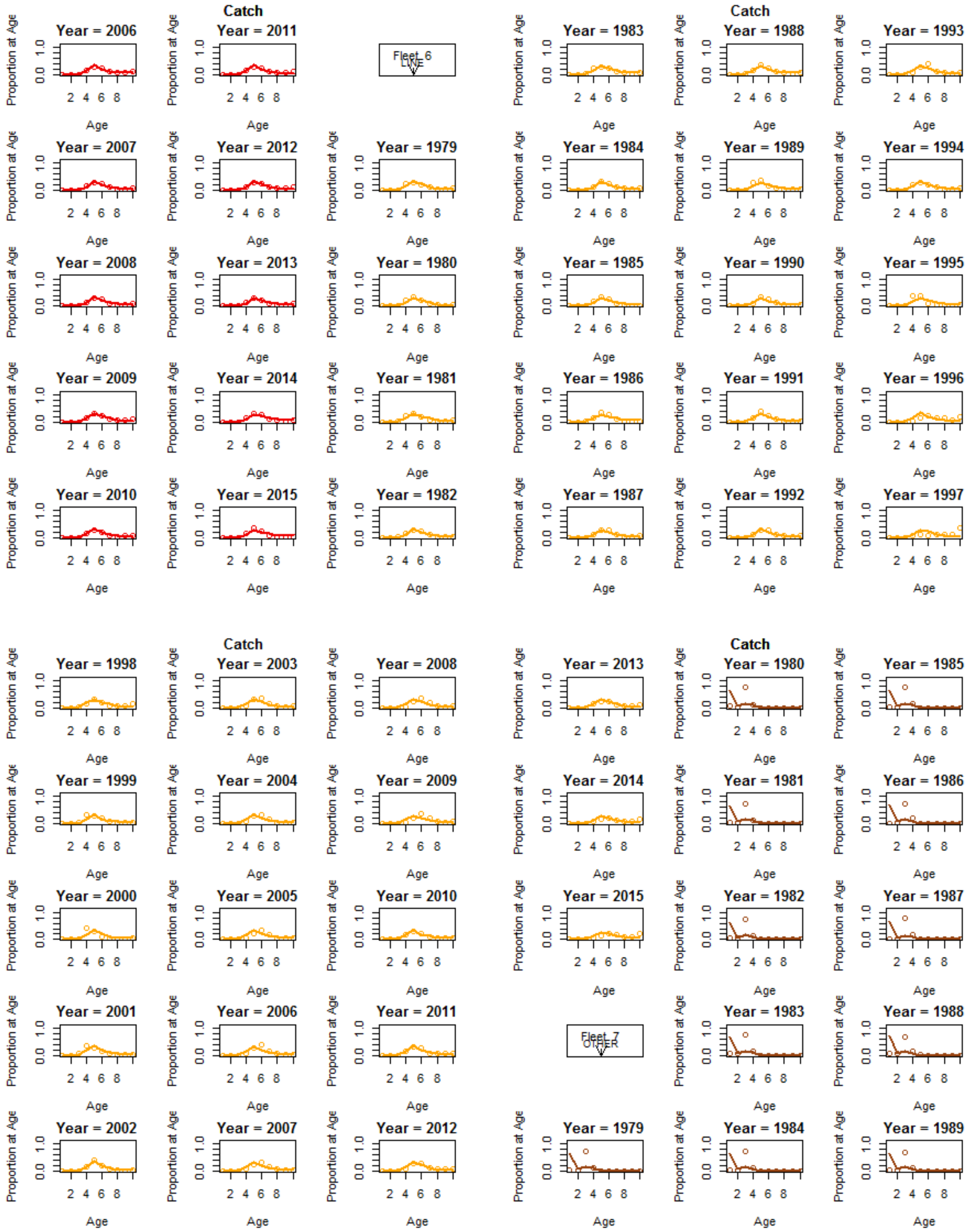


Figure 9 Continued.

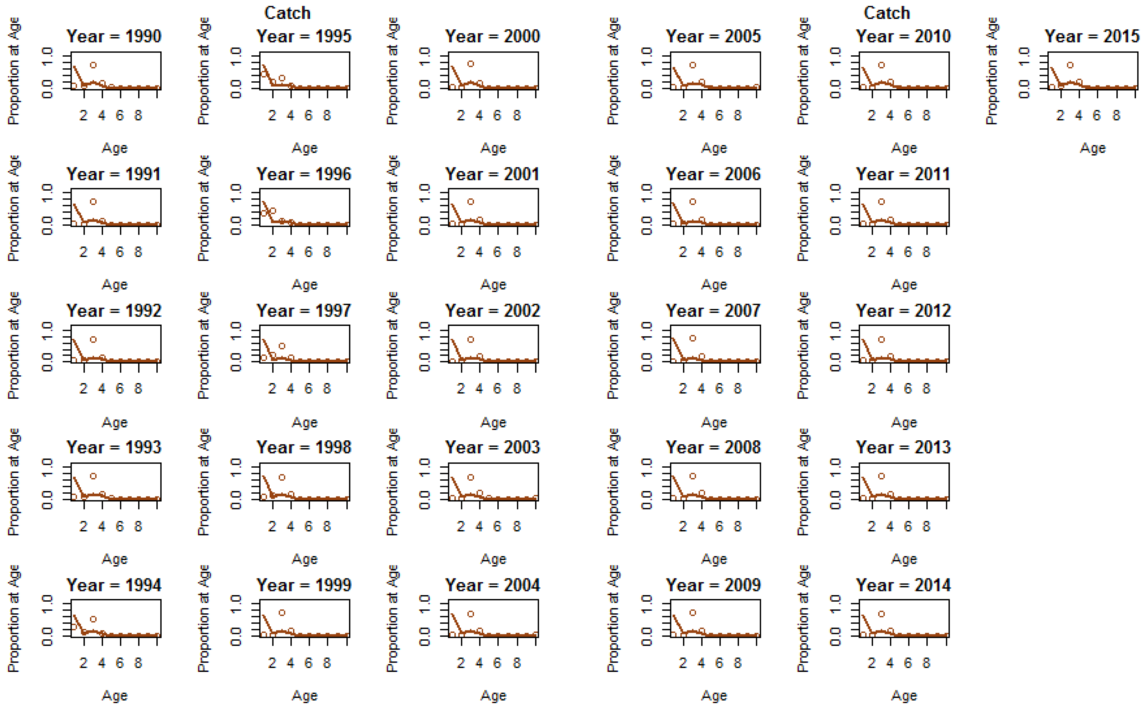


Figure 9 Continued.

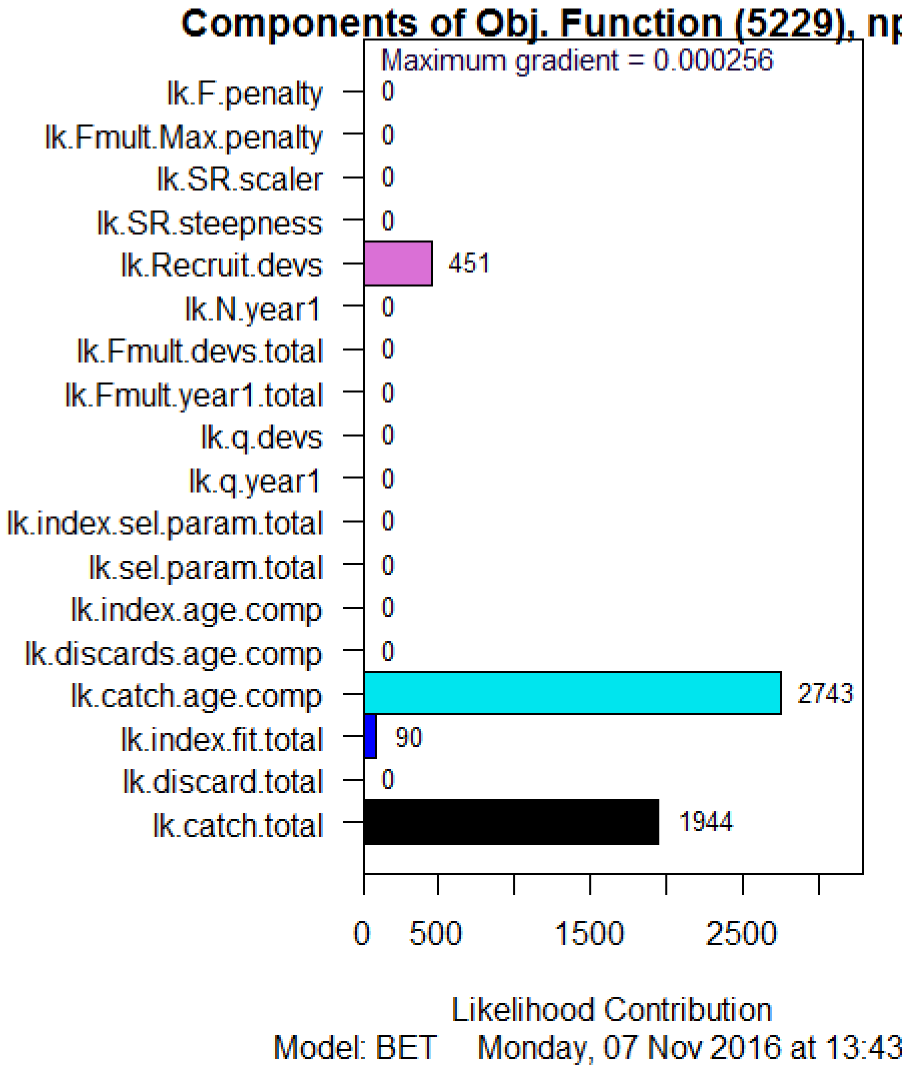


Figure 10 Likelihood conponents of the base case model fit for BET

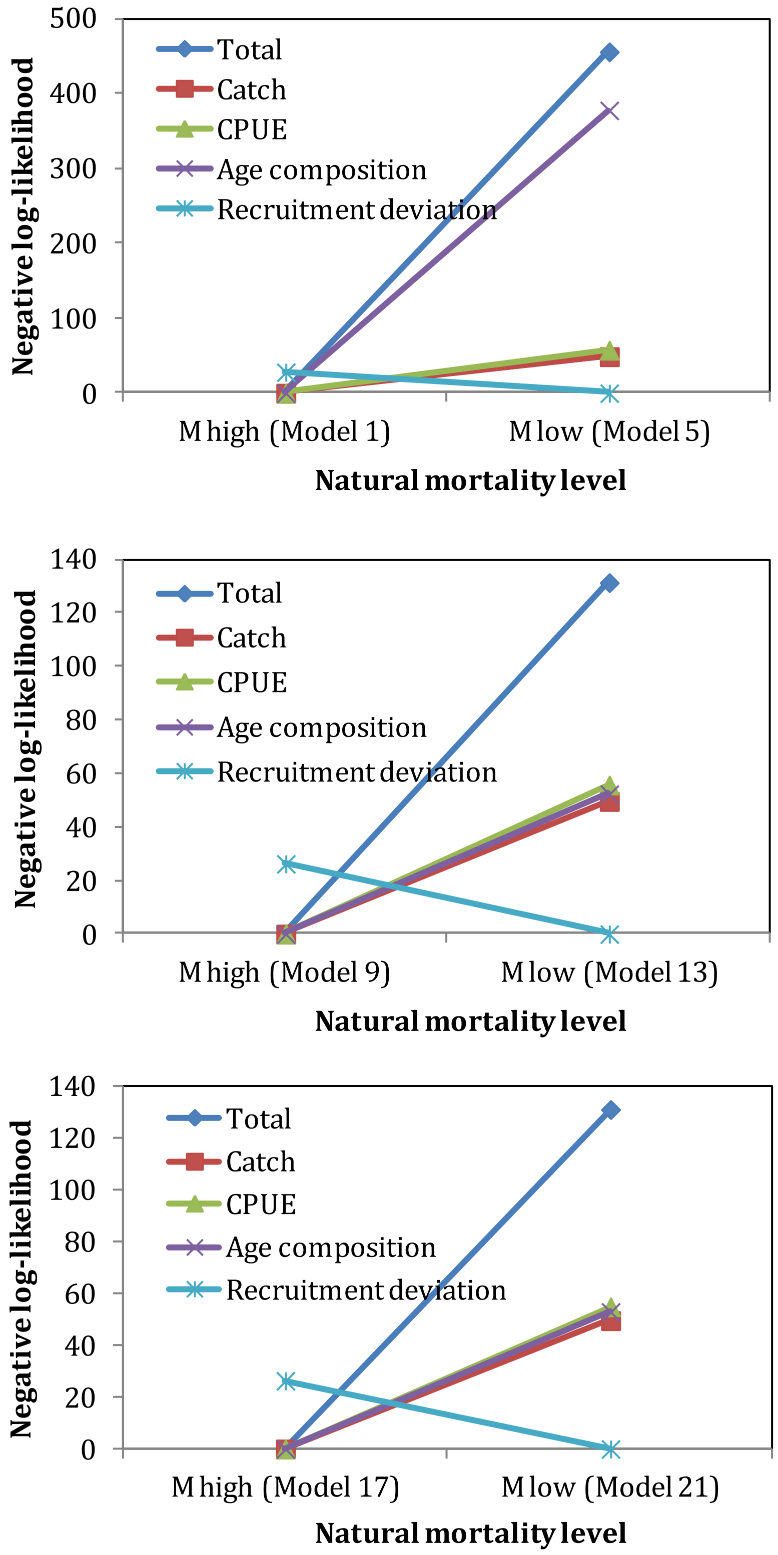


Figure 11 Likelihood profile on the natural mortality in the model for BET. The negative log-likelihood values were rescaled by subtracting the lowest value for each data component.

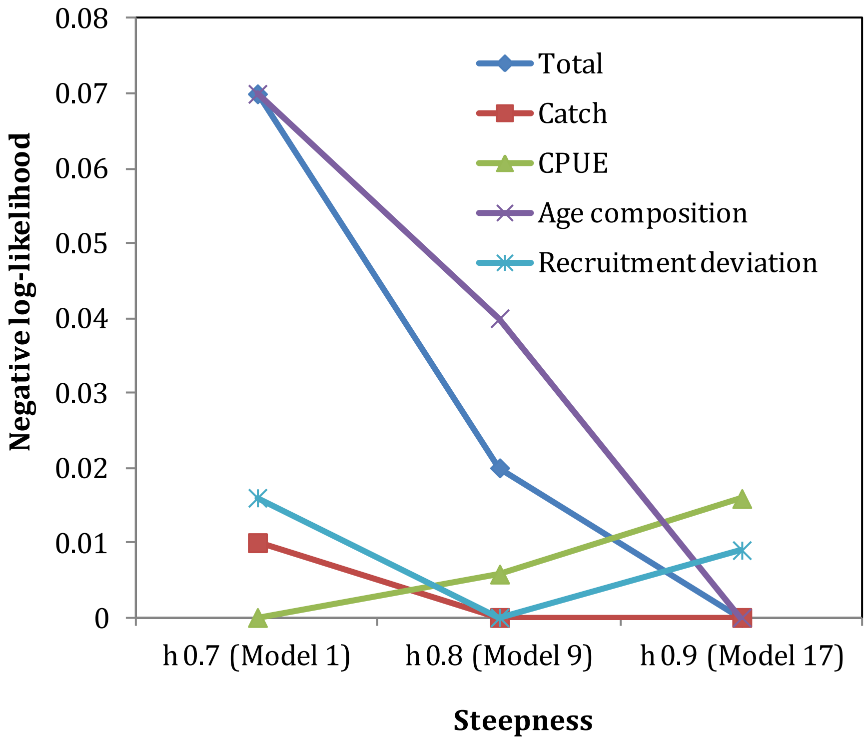
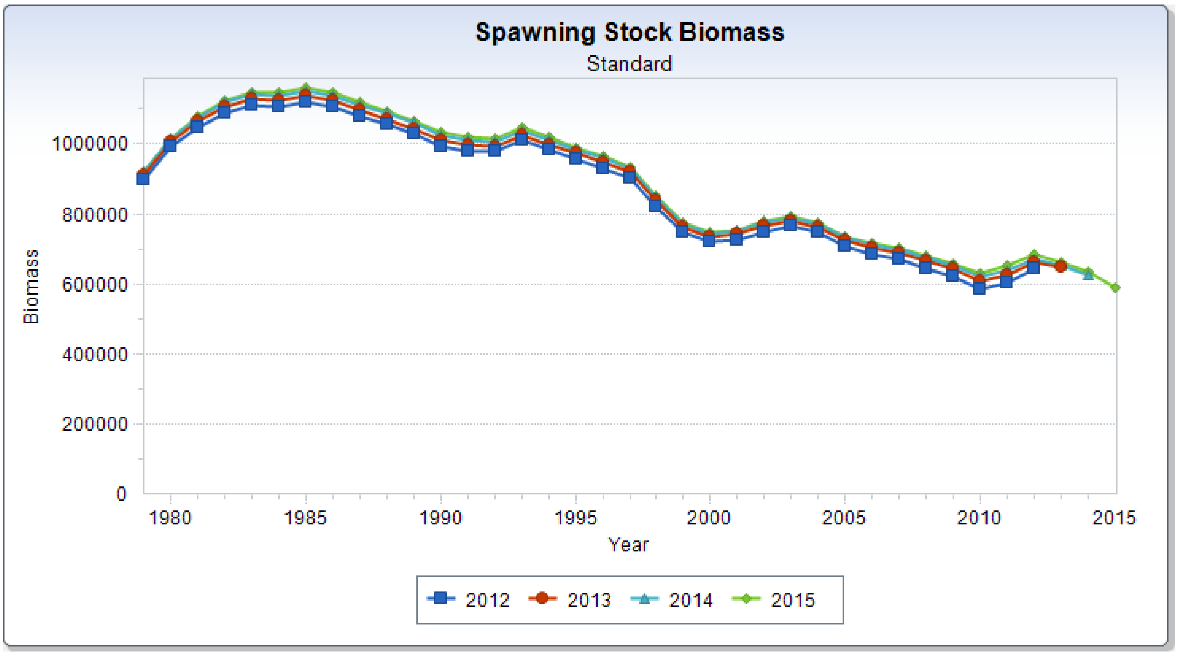


Figure 12 Likelihood profile on the steepness in the model for BET. The negative log-likelihood values were rescaled by subtracting the lowest value for each data component.



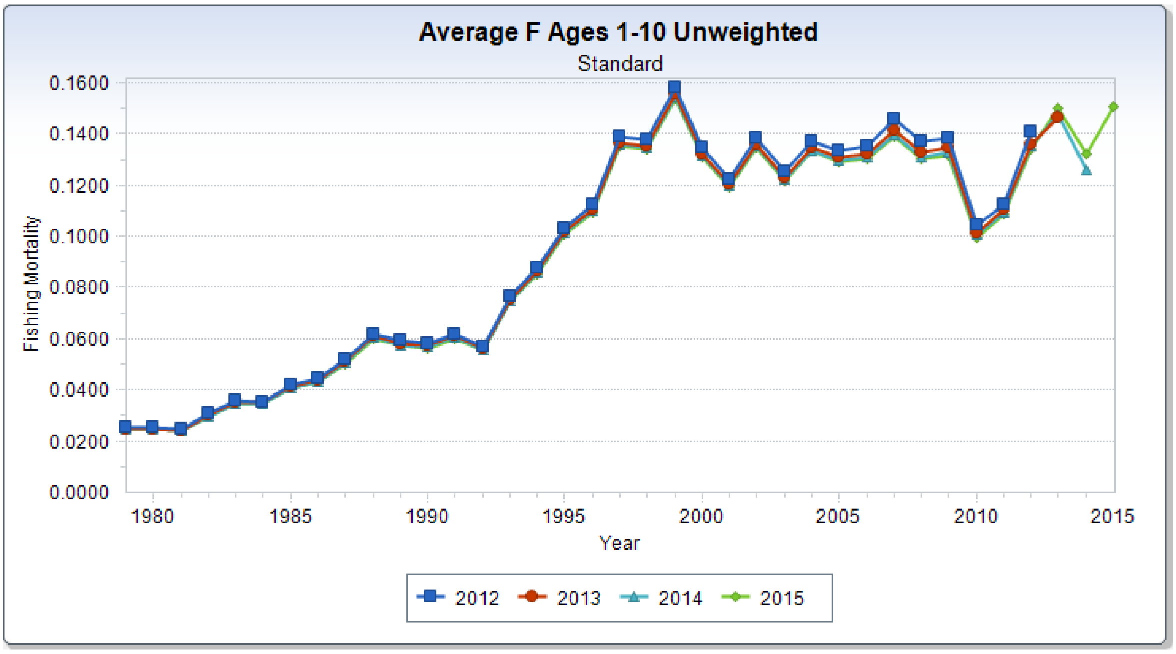


Figure 13 Retropective pattern of the base case model fit for BET

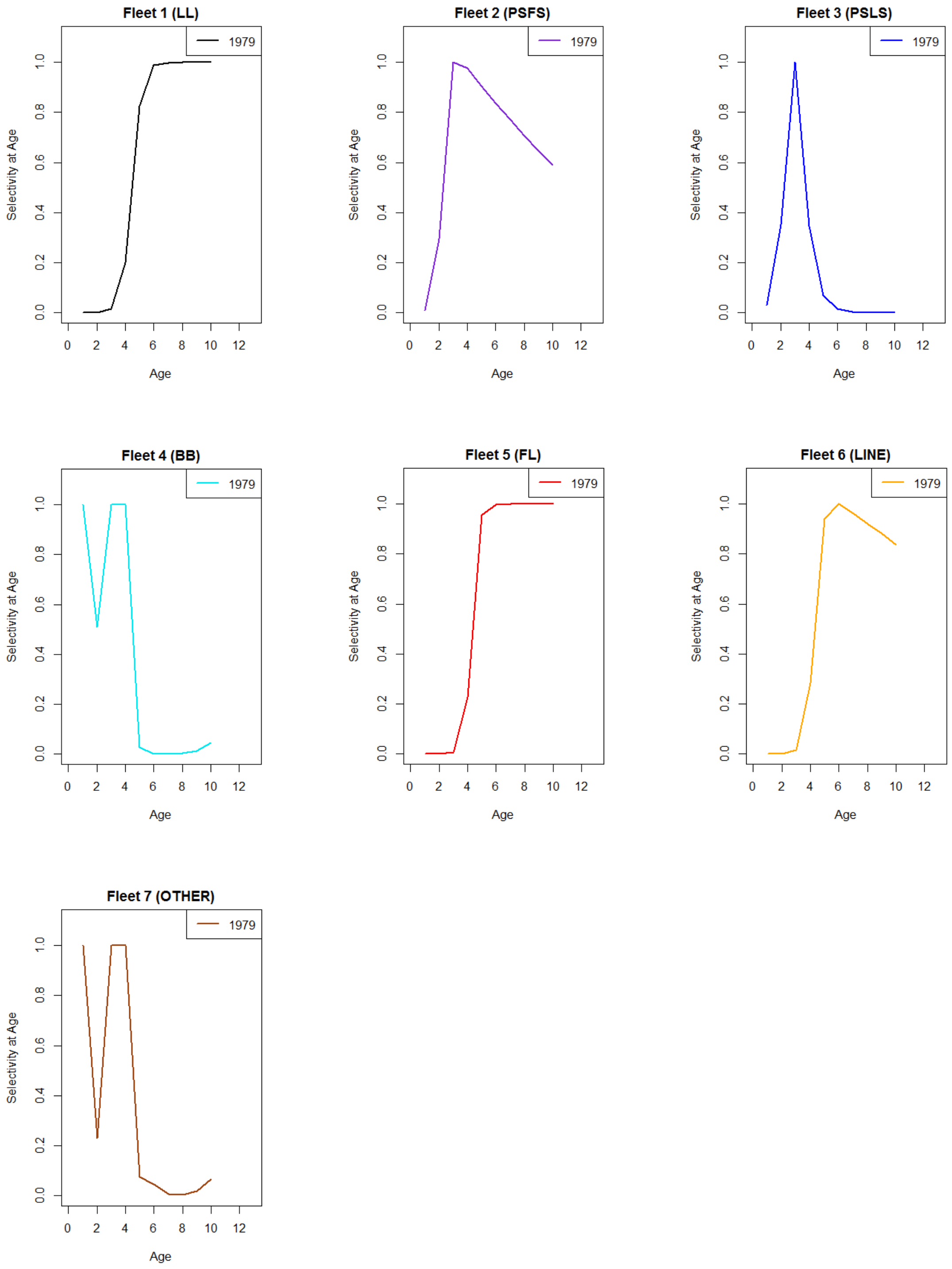


Figure 14 Selectivity curve for each fishery for the first model year (constant during 1979-2015) (base case)

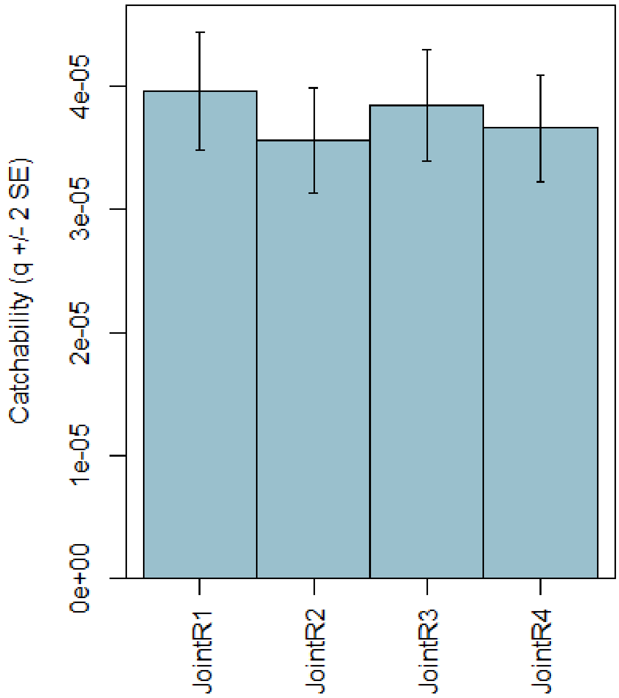


Figure 15 Catchability estimates of abundance indices (base case)

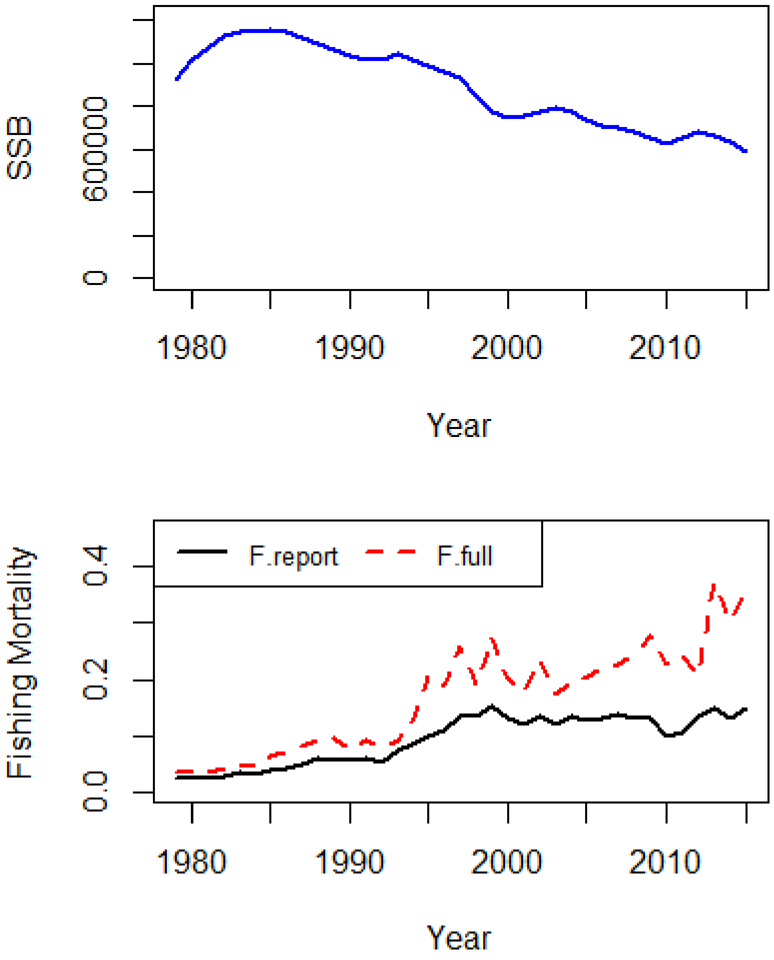


Figure 16 Trends of spawning biomass (metric ton) and fishing mortality for BET in the Indian Ocean (base case)

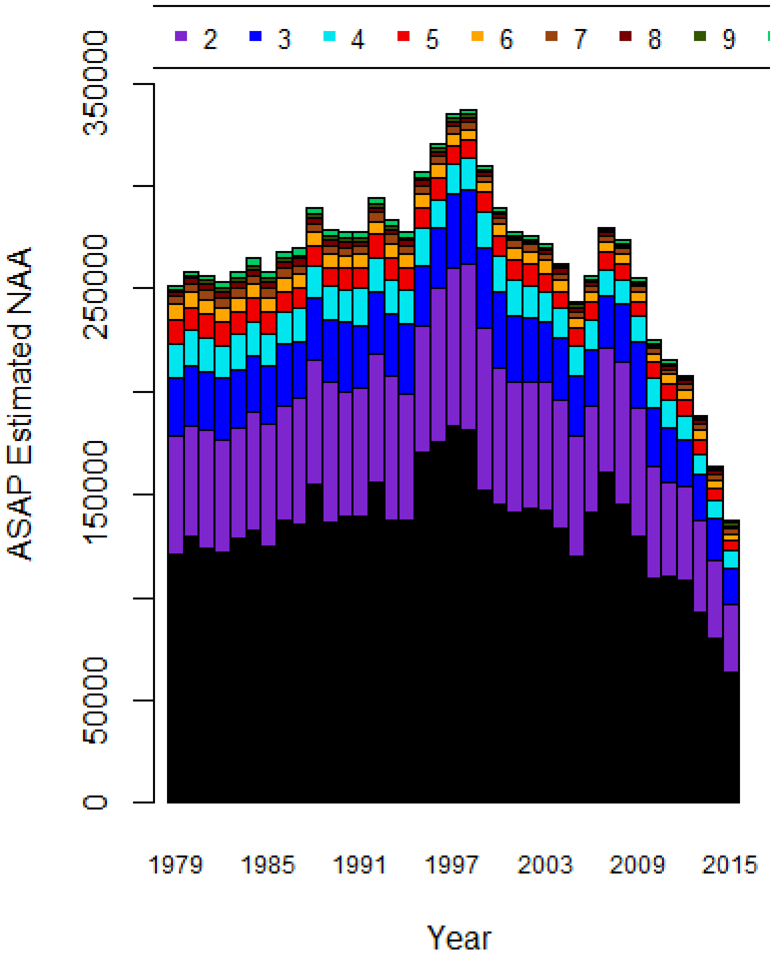


Figure 17 Estimated stock abundance (thousand fish) for BET in the Indian Ocean (base case).

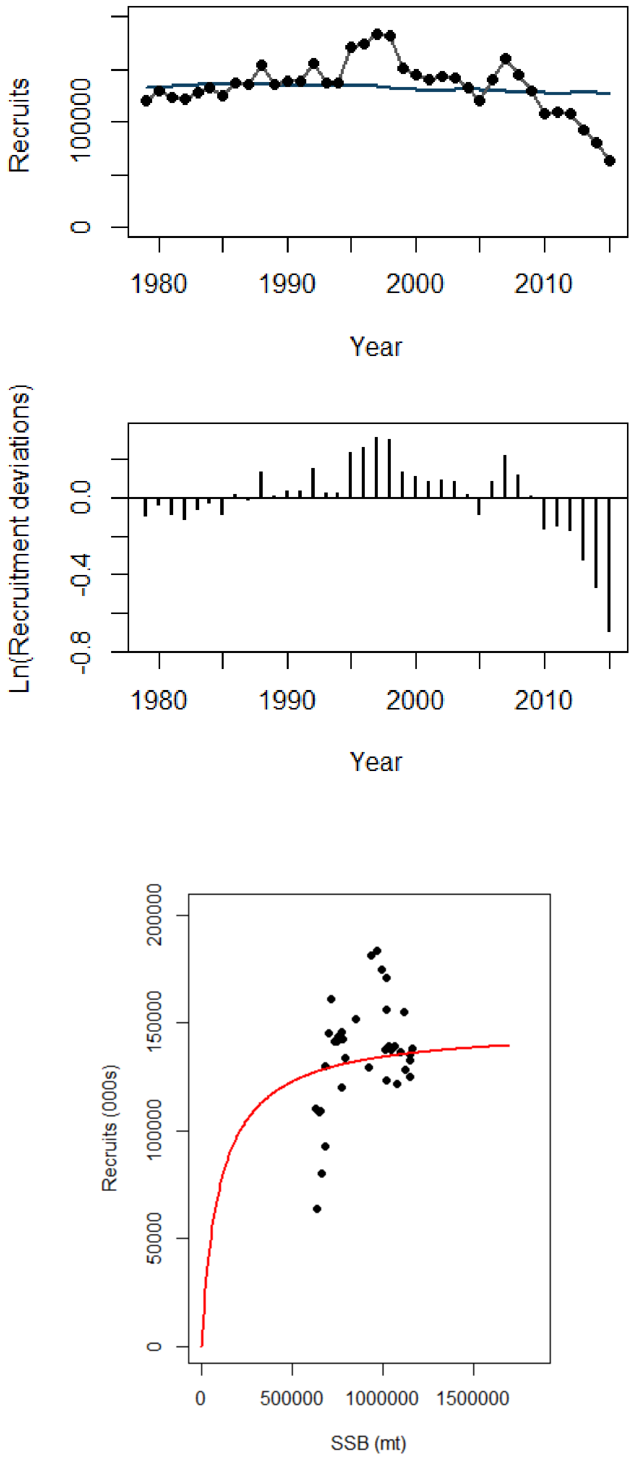
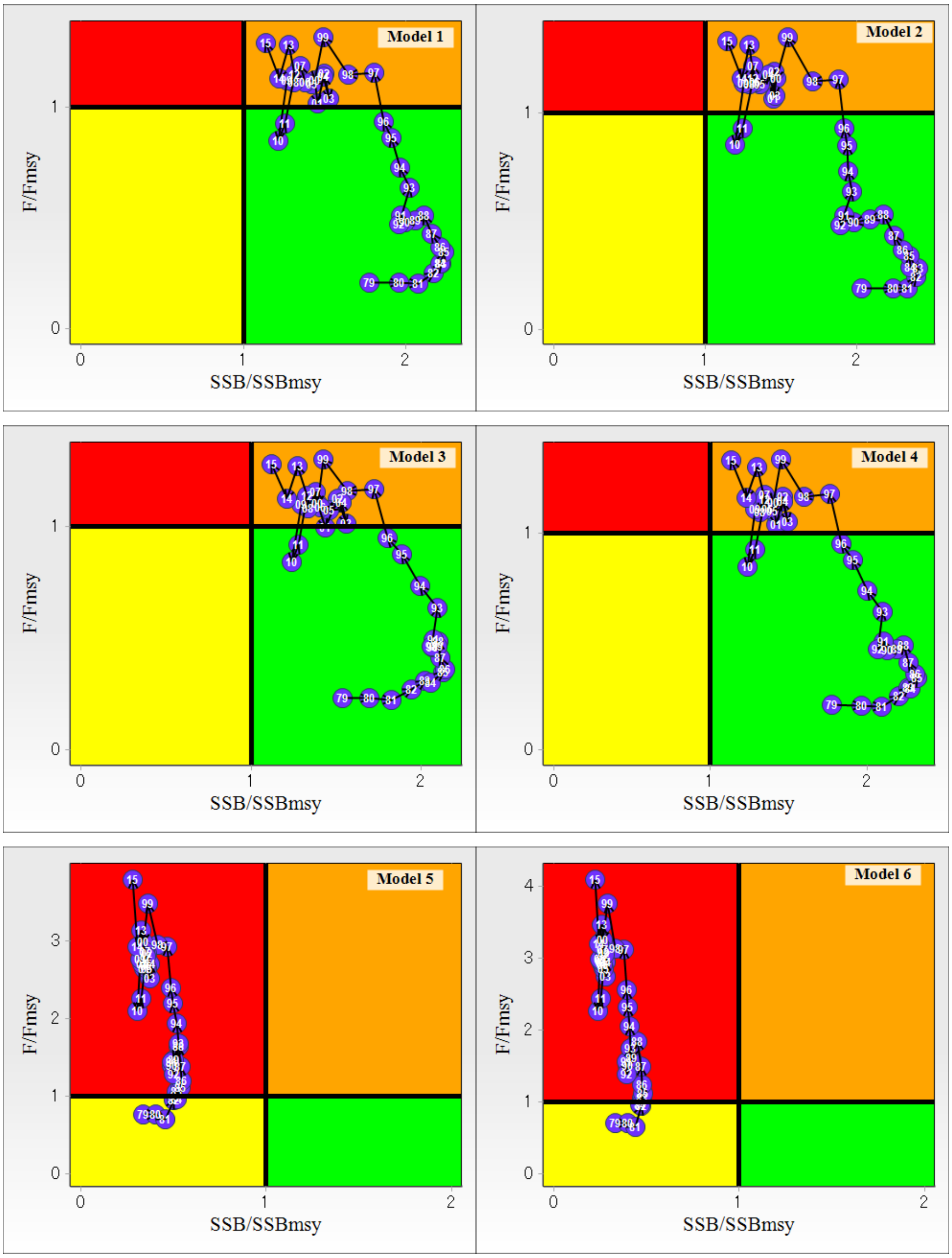
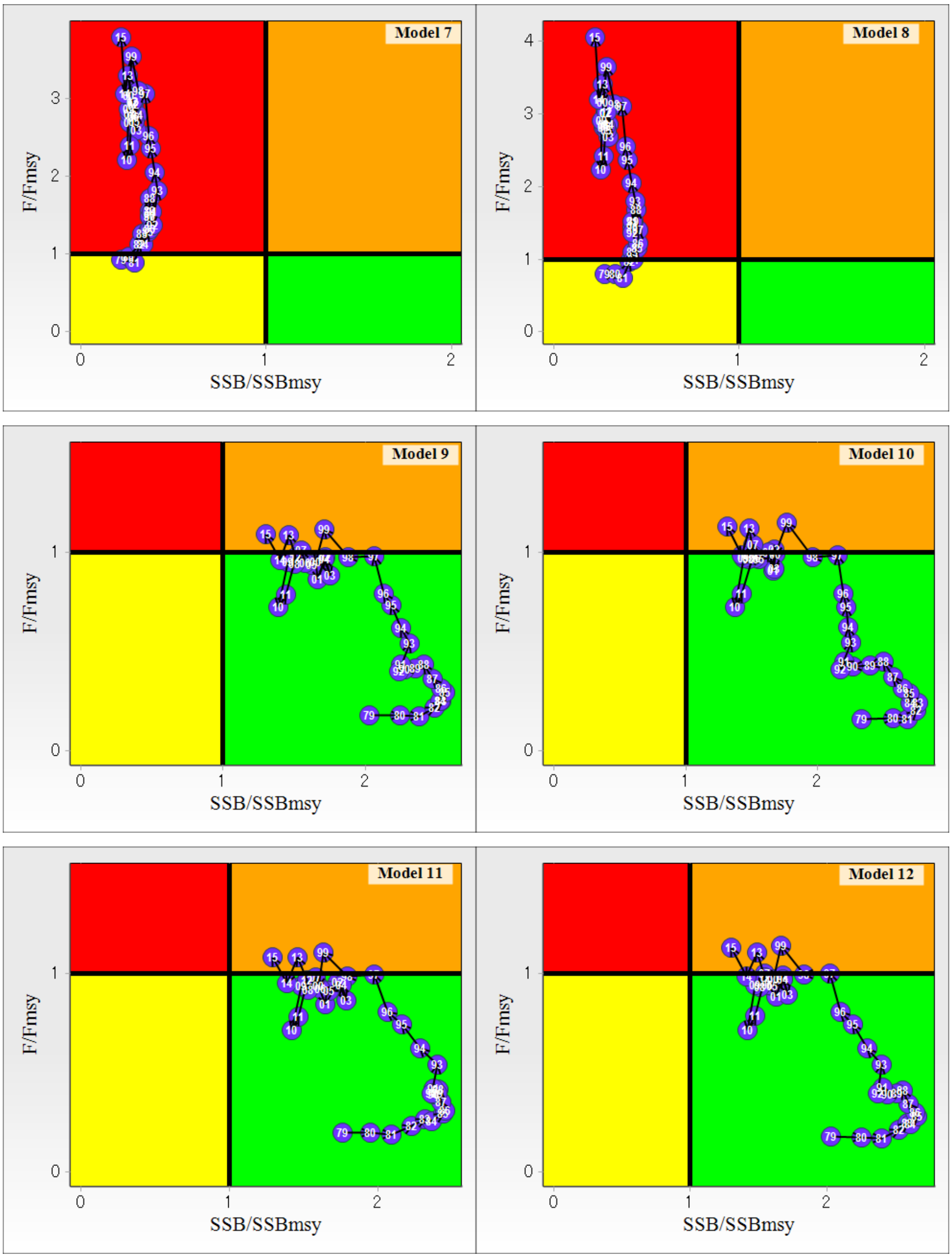


Figure 18 Estimated recruitments (1000 fish), recruitment variations, and stock-recruitment curve for the base case BET assessment in the Indian Ocean


Model 1
Model 2
Model 3
Model 4
Model 5
Model 6
F/Fmsy
SSB/SSBmsy
0
1
2
3
4


Model 7
F/Fmsy
SSB/SSBmsy
0
1
2
3
15
99
13
10
11
94
93
88
79
81
Model 8
4
15
99
13
97
96
95
94
93
10
11
Model 9
15
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01
03
Model 10
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Model 11
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Model 12
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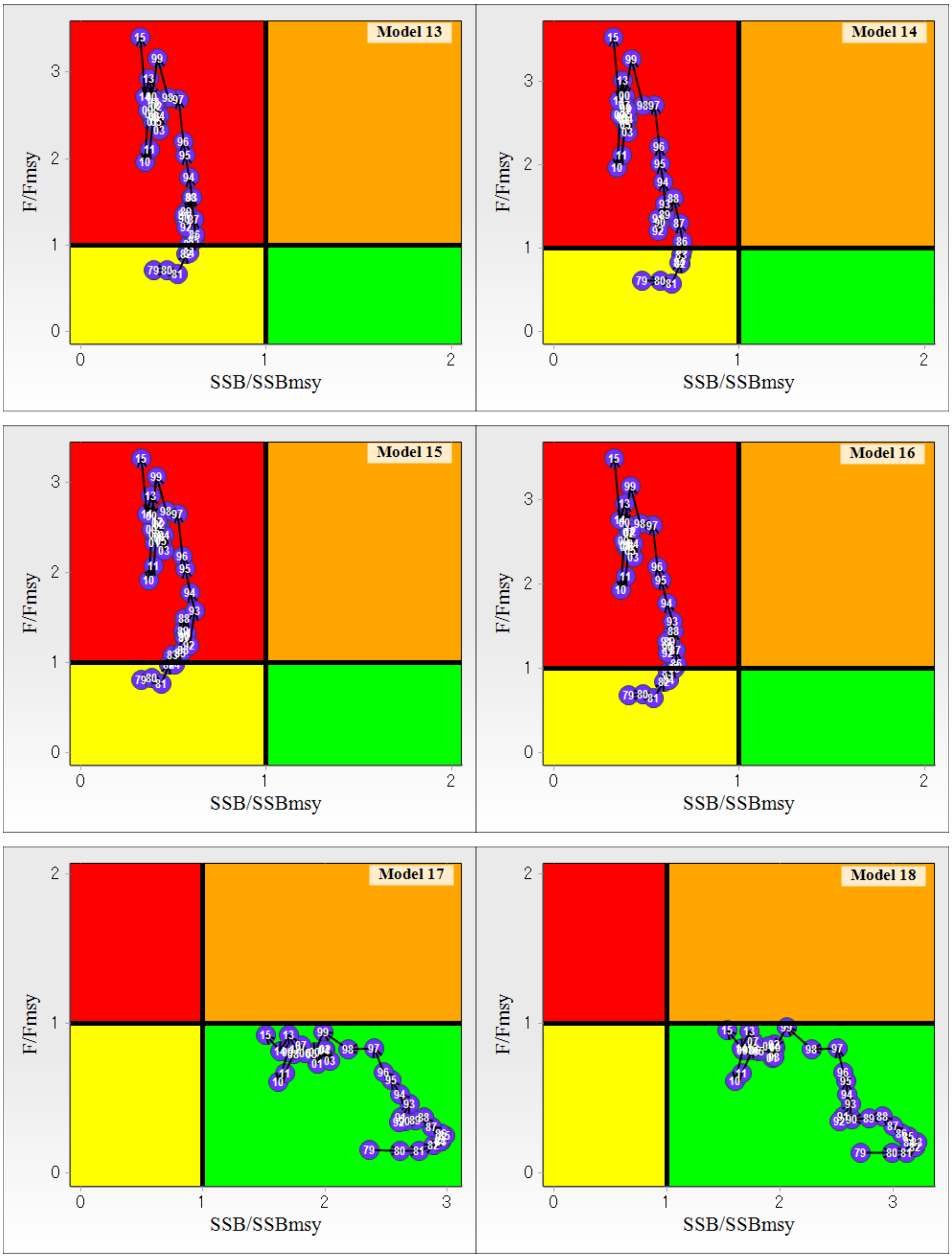
Model 13
Model 14
Model 15
Model 16
Model 17
Model 18
F/Fmsy
SSB/SSBmsy
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98

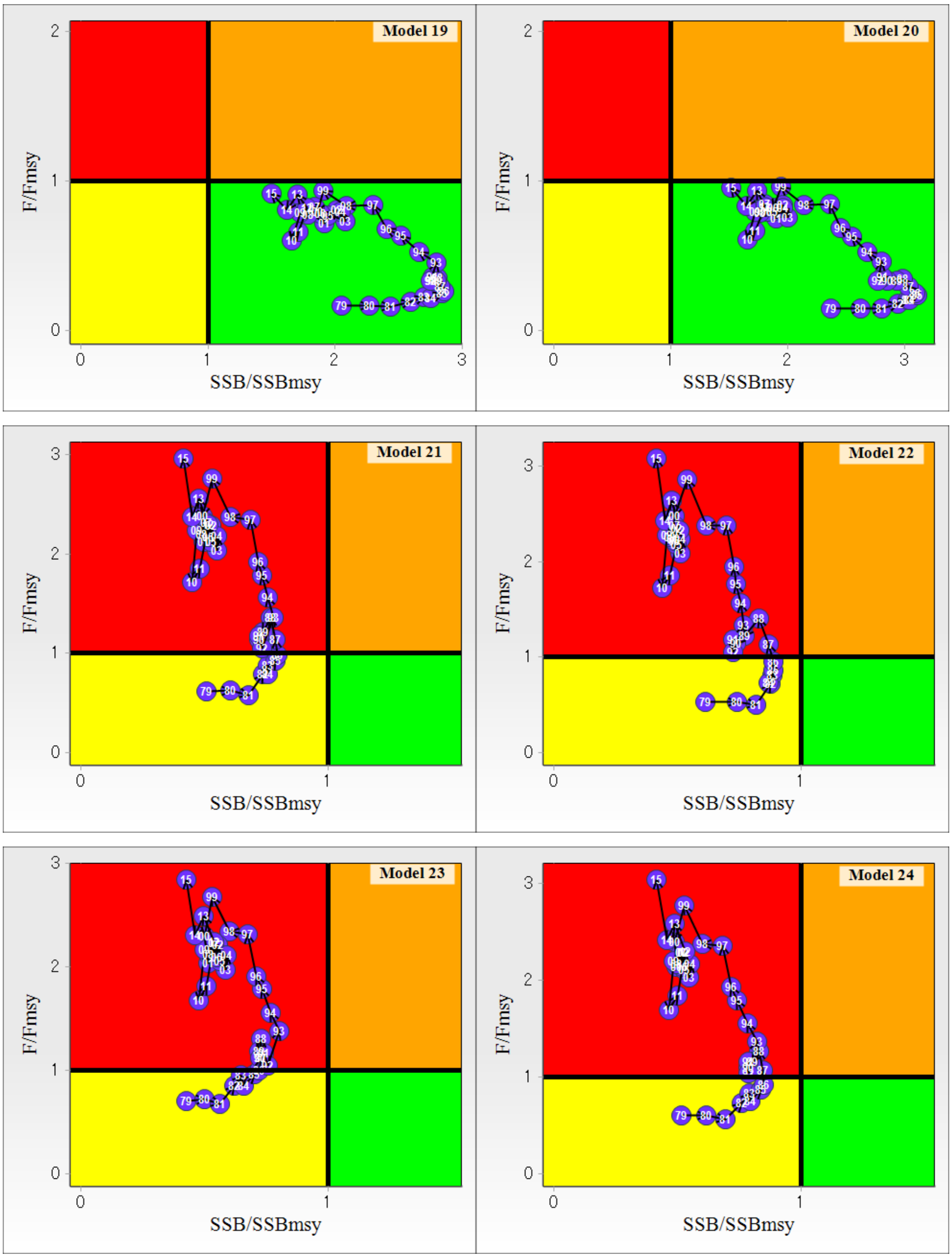

Figure 19 Kobe plots for the BET assessment in the Indian Ocean