Stock assessment of blue marlin (*Makaira nigricans*) in the Indian Ocean using Stock Synthesis

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ABSTRACT

In this study, Stock Synthesis (SS) was adopted to conduct the stock assessment for blue marlin in the Indian Ocean by incorporating historical catch, CPUE and length-frequency data. Although the model estimates were sensitive to the assumptions related to life-history parameters and selectivity functions, the results of all sensitivity scenarios indicated that the current stock status of blue marlin in the Indian may be not overfished but be overfishing already. In addition, there are high risks of spawning biomass dropping blow the MSY level and fishing mortality exceeding the MSY level if future catches are not reduced.

1. INTRODUCTION

Blue marlin is considered to be a non-target species of industrial and artisanal fisheries. Longline catches account for around 69% of total catches in the Indian Ocean, followed by gillnets (28%), with remaining catches recorded under troll and handlines. The catches were mainly made by Taiwan (longline, 33%), Indonesia (fresh longline, 28%), Pakistan (gillnet, 14%), Iran (gillnet, 7%), and Sri Lanka (7%). Catches reported by drifting longliners were more or less stable until the late 1970s, at around 3,000 t to 4,000 t, and have steadily increased since then to reach values between 8,000 t and to over 10,000 t since the early 1990's. The highest catches reported by longliners have been recorded since 2012, and are likely to be the consequence of higher catch rates by some longline fleets which appear to have resumed operations in the western tropical Indian Ocean (IOTC, 2015).

The stock status of blue marlin has been evaluated using A Stock-Production Model Incorporating Covariates (ASPIC), Bayesian State Space production model and Stock Reduction Model (Andrade, 2013; Sharma, 2013; Wang et al., 2013). The stock was determined to be not overfished and not subject to overfishing. However, the uncertainty in the data available for assessment purposes and the CPUE series suggests that the advice should be interpreted with caution as the stock may still be in an overfished state (IOTC, 2013).

Since historical length-frequency data and parts of auxiliary information, such as life-history parameters, were available for blue marlin in the Indian Ocean, the integrated stock assessment approach can be applied to evaluate the stock status. Therefore, this study attempt to conduct the stock assessment for blue marlin in the Indian Ocean using Stock Synthesis (SS, Methot and Wetzel, 2013).

2. MATERIALS AND METHODS

2.1 Fishery definition

Blue marlin was mainly exploited by longline fleets (Taiwan, Japan and Indonesia) and gillnet fleets (Pakistan, Iran, and Sri Lanka). Except for catch data, however, long-term CPUE series and length-frequency data were only available for Taiwanese and Japanese fleets although length-frequency data were also available in recent years for some other fleets. Therefore, the fleets operated in the Indian Ocean were simply aggregated into the 3 fleets (JPN: Japanese longline; TWN: Taiwanese longline; OTH: Other fleets).

2.2 Data used

The historical catches in weight and length-frequency data from for all fleets were provided by Indian Ocean Tuna Commission (IOTC). Fig. 1 shows the trends of catches for three fleets. The total catch obviously increased since early 1990s and the increase in catch mainly contributed from OTH.

The length data of blue marlin in the Indian Ocean were mainly collected by Japanese and Taiwanese longline fleets. Although the data also collected by other fleets, such as Korea, Sri Lanka, EU countries and China, the time series of data were not generally short or incomplete. All of the length-frequency data were converted into the measurement of eye fork length (EFL) and aggregated into 3 cm length interval. The relative abundance indices used in this study were based on the standardized CPUE of Taiwanese and Japanese longline fleets (Wang 2016; Yokoi et al., 2016).

Fig. 2 shows the data presence by year for each fleet used in the stock assessment of blue marlin in the Indian Ocean, including catch, length-frequency and CPUE data.

2.3. Life-history parameters

Growth of blue marlin has been known to be sexual dimorphic and females grow faster than males (e.g. Lee et al., 2013; 2014). SS provides three growth models as options, including von Bertalanffy growth curve, Schnute's generalized growth curve (aka Richards curve) and von Bertalanffy growth curve with age-specific deviations for growth coefficient (K). In this study, the standard von Bertalanffy growth curve was used and it was parameterized as:

$$L_2 = L_\infty + (L_1 - L_\infty)e^{-K(A_2 - A_1)}$$

where L_1 and L_2 are the sizes associated with ages near the youngest A_1 and oldest A_2 ages in the data, K is the growth coefficient, and L_∞ is the theoretical maximum length which can be solved based on the values other three parameters. In this study, growth parameters were estimated by SS.

Setyadji et al. (2014) provided a relationship for blue marlin in the Indian. However, EFL data can be converted into unreasonable high weights for fishes with large lengths when relationship of Setyadji et al. (2014) was used. Therefore, the length-weight relationship used in the assessment for blue marlin in the Pacific Ocean (Lee et al., 2013; 2014) was adopted in this study.

There is little information about natural mortality (M) for blue marlin in the Indian. Lee et al. (2013, 2014) used sex- and age-specific natural mortality for the assessment of blue marlin in the Pacific Ocean. Based on the age-specific natural mortality used in Lee et al. (2013, 2014), the values were fixed as 0.42 year^{-1} for age 0, 0.37 year^{-1} for age 1, 0.32 year^{-1} for age 2, 0.27 year^{-1} for age 3, and 0.22 year^{-1} for age above 4 for female and 0.42 year^{-1} for age 0, 0.37 year^{-1} for age above 1 for male. In this study, the values for adult fishes were used as the base-case (0.22 year^{-1} for female and 0.37 year^{-1} for male).

The maturity ogive of Sun et al. (2009) was used in this study. The value of length at 50% maturity was 179.76 cm and slope of the logistic function was -0.2039.

The standard Beverton-Holt stock-recruitment relationship was used in this study. There is also little information about the parameters of the stock-recruitment relationship (steepness, *h*), which represented the productivity of the fish. Therefore, the assumption used in Lee et al. (2013, 2014) was adopted in this study and value of *h* was assumed to be 0.87.

The values of life-history parameters used in this study are listed in Table 1 and these values were used as the base-case.

2.4 Model structure and assumption

In this study, the population structure was sex-specific although sex specific data were not available but the model population age structure can be differentiated by sex.

The maximum age used in the model was 40 years. The time period of assessment model was from 1950 to 2015 along with 10-years projection. Sex ratio of female was assumed to be 0.5.

Recruitment was estimated as deviates from the Beverton-Holt stock recruitment relationship and was assumed to follow a lognormal distributed deviates with zero mean and standard deviation (σ_R). In this study, the σ_R was assumed to be 0.4, which was commonly adopted in previous stock assessment for tunas and billfishes. Recruitment deviations were assigned and estimated for 1960-2014 in the model and deviates for other years were fixed at zero.

Selectivity curves were length-based and modeled using double normal functions because the length-frequency compositions tended to concentrate at specific ranges for fleets. In addition, selectivity was time-invariant for all fleets.

Catchability was estimated assuming that survey indices are proportional to vulnerable biomass with a scaling factor of catchability. It was assumed that catchability was constant over time for all indices (Lee et al. 2013). As Methot (2012) recommended, fishing mortality (F) was modelled using continuous F as full parameters.

Stock Synthesis version 3.24f (Methot, 2012) was used in this study. Equal weightings were assigned to all data components. The Markov Chain Monte Carlo (MCMC) method was used to develop Bayesian posterior distributions for the parameters of the model and the key quantities of management interests. The posterior distributions were constructed based on samples generated by conducting 510,000 cycles of the MCMC algorithm, ignoring the first 10,000 cycles as the burn in" period, and selecting every 1000th parameter vector thereafter.

2.5 Sensitivity analysis

Life-history parameters and model structure assumed above were treated as base-case in this study. Sensitivity analysis was conducted to explore the influence of model assumptions on model estimations using various values of steepness (*h*) and natural mortality (*M*), selectivity functions and growth parameters.

Two values of steepness (*h*) were adopted to examine model estimations under the assumptions of higher (h=0.99, Case "hhigh") and lower (h=0.75, Case "hlow") productivity. Female natural mortality (*M*) was increased to 0.37 year^{-1} for the high M assumption (Case "Mhigh"), while male M was decreased to 0.22 year^{-1} for low M assumption (Case "Mlow). To examine the influence of selectivity assumption, selectivity functions were changed to be asymptotic for Japanese and Taiwanese longline fleets (Case "Seldome"). In addition, the growth parameters were fixed to be values used in Lee et al. (2013, 2014) (Case "FixG"). The cases conducted for sensitivity analysis are also shown in Table 2.

3. RESULTS AND DISCUSSIONS

3.1 Base-case assessment

The model generally fitted to the JPN and TWN CPUE series after the mid-1990s, while CPUE series in early years cannot be appropriately fitted by the model (Fig. 4). The CPUE series in early years were obviously higher than those after about the early 1990s. Assuming a time-variant catchability may be helpful to improve the model fits to CPUE series, but this may cause obviously different assessment results for management advice and more evidence of changes in fishing operations should be necessary to support this assumption (Wang et al., 2015).

The length-frequency data generally can be fitted by the model for JPN and TWN fleets and for most years (Fig. 5). However, the model fits to the length-frequency data were obviously deteriorated for JPN data after 2003 and most of OTH data due to the small amount of samples. In addition, the model cannot fit to the high proportions of samples with lengths less than 100 cm, which were observed for TWN fleet, especially for the 1990s and early 2000s (Figs. 5 and 6). However, this cannot be identified by comparing TWN data with JPN data because all of catches caught by JPN were larger than 100 cm.

The model estimated selectivity curves are shown in Fig. 7. TWN obviously tended to select the smaller fishes than those of JPN and OTH, while JPN tended to select more large fishes than TWN and OTH.

Time trajectories of total fishing mortality, recruitment and spawning biomass estimated by the model (maximum likelihood estimates with 95% confidence intervals) are shown in Figs. 8-10. Fishing mortality gradually increased since the early 1990s when the catches substantially increased, and this resulted in the substantial declines in recruitment and spawning biomass (Figs. 1 and 8). Although strong recruitments occurred in 2008 and 2009 and spawning biomass slightly recovered in following few years, spawning biomass decreased again in recent years due to the substantial increases in catch and fishing mortality, even though strong recruitments were observed in 2014 and 2015.

Time trajectories of the fishing mortality and spawning biomass as a ratio of that at which MSY is achieved are shown in Figs. 11 and 12. The results indicated that the current spawning biomass was still higher than its MSY level, while the fishing mortality has exceeded its MSY level since the mid-2000s. Kobe plot reveals that current stock status was not overfished but subject to overfishing (Fig. 13). The estimates of quantities of management interest based on the base-case are summarized in Table 3.

Table 4 shows the Kobe II Strategy Matrix, which represents probability (percentage) of violating the MSY-based reference points for nine constant catch projections (average catch level from 2013–15 (15,400 t), ± 10%, ± 20%, ± 30% and ± 40%) projected for 3 and 10 years (2018 and 2025). The results indicate that there are high risks of spawning biomass dropping blow the MSY level and fishing mortality exceeding the MSY level if future catches will be higher than 70% current level.

3.2 Sensitivity analysis

Table 5 shows the estimates of the management quantities and values of negative log-likelihood for the CPUE, and the length–frequency data and total negative log-likelihood based on different cases. The model estimates were not unreasonable when high values of steepness and natural mortality were assumed, and thus the results of these cases were ignored. The results indicated that the model estimates were sensitive to the assumptions of life-history parameters and selectivity. The most pessimistic stock status occurred when steepness and natural mortality were assumed to be lower than base-case, while the most optimistic stock status was obtained when fixing the growth parameters by the values of blue marlin in the Pacific Ocean. However, fixing growth parameters obviously deteriorated the model fits to length-frequency data, while the model fits to CPUE data were deteriorated when selectivity curves were assumed to be asymptotic for JPN and TWN longline fleets. Overall, the results of all cases indicated that current stock status of blue marlin in the Indian Ocean may be not overfished but be overfishing already.

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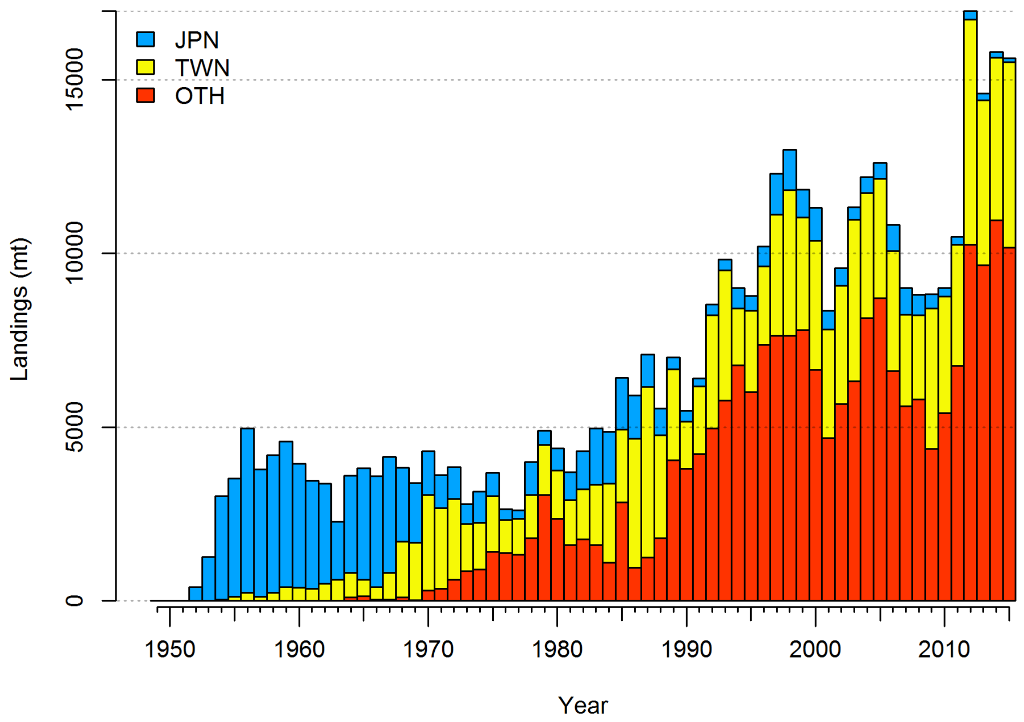


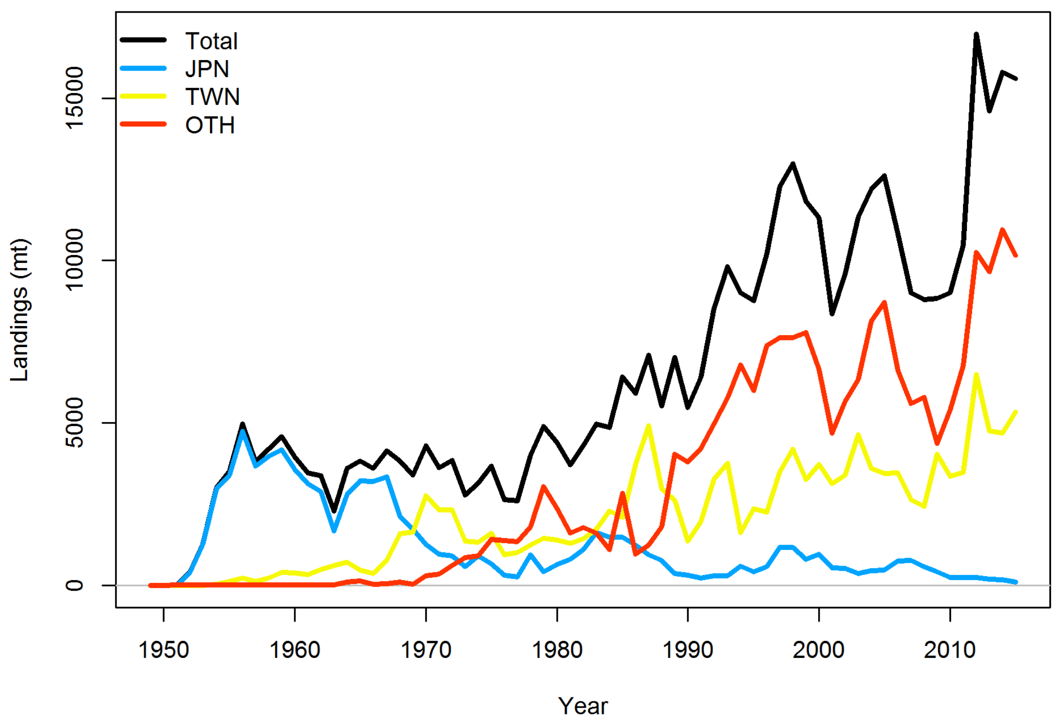


Fig. 1. Annual catches of blue marlin in the Indian Ocean by fleets.

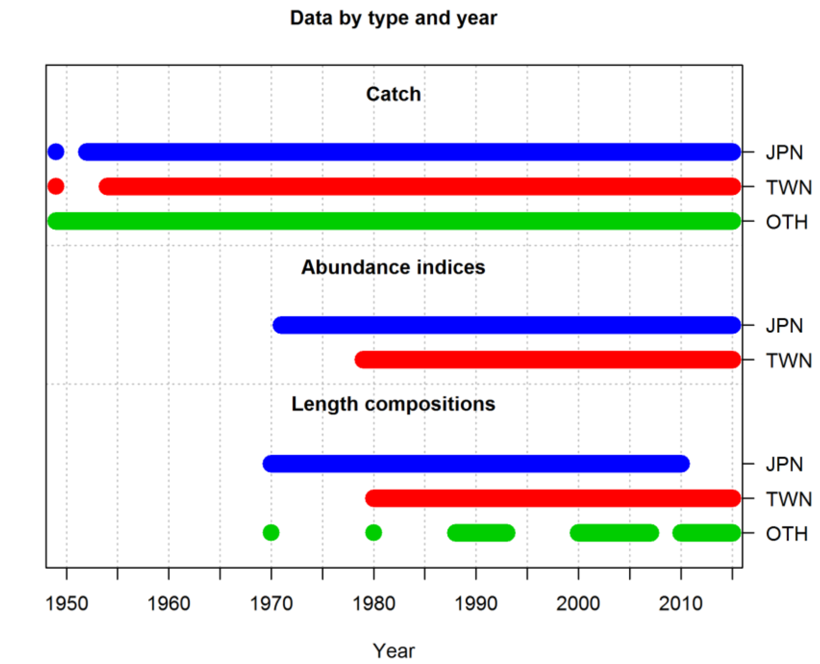


Fig. 2. Data presence by year for each fleet used in the stock assessment of blue marlin in the Indian Ocean.

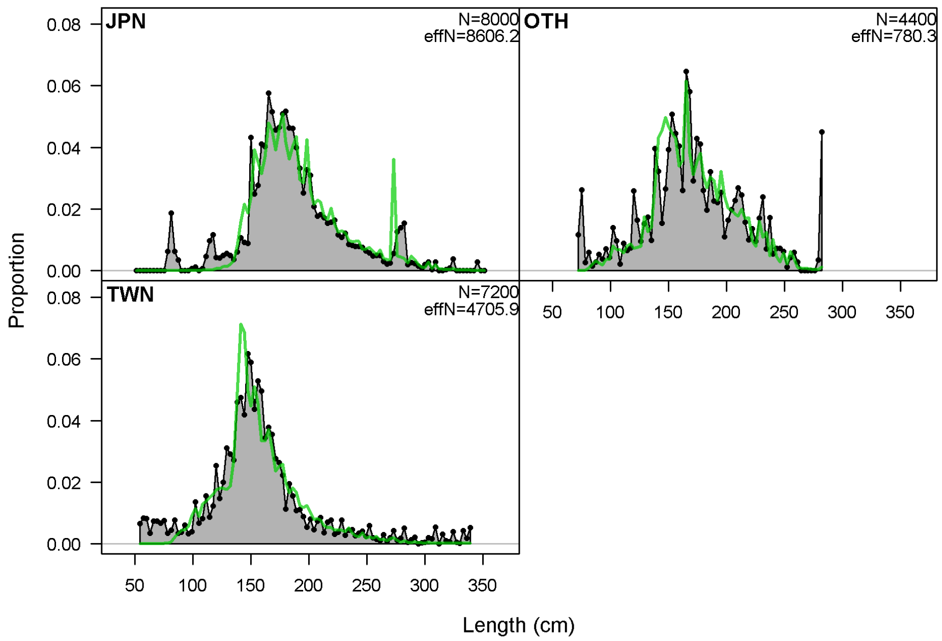
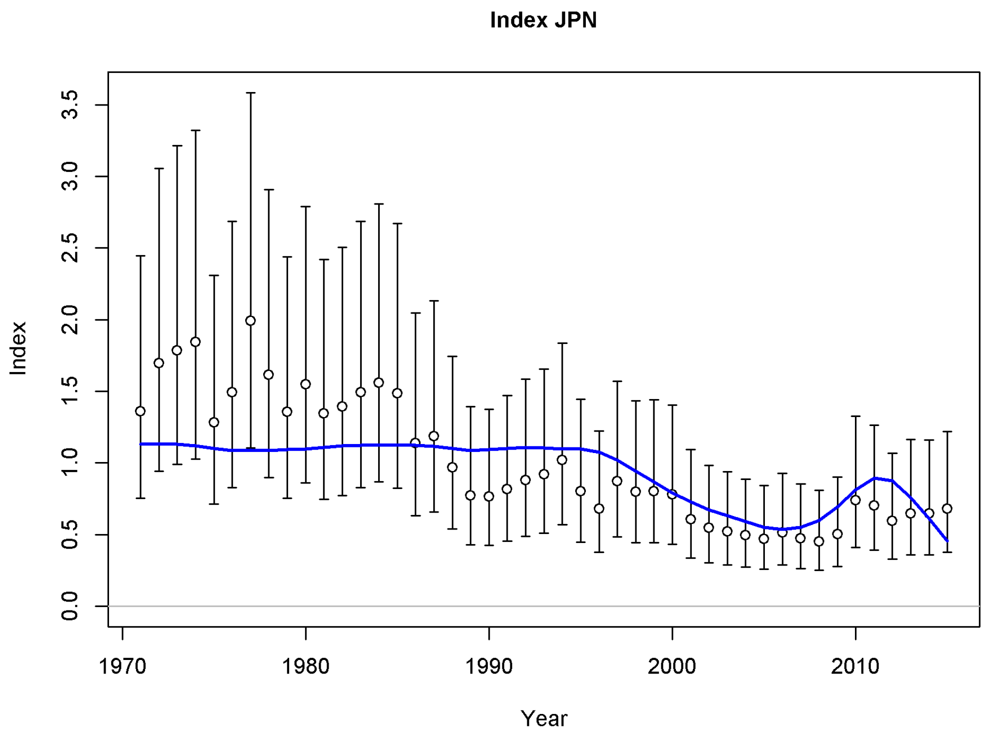


Fig. 3. Observed (shaded areas) and model-estimated (lines) length-frequencies of blue marlin in the Indian Ocean. The data were aggregated across time by fleets based on the base-case.



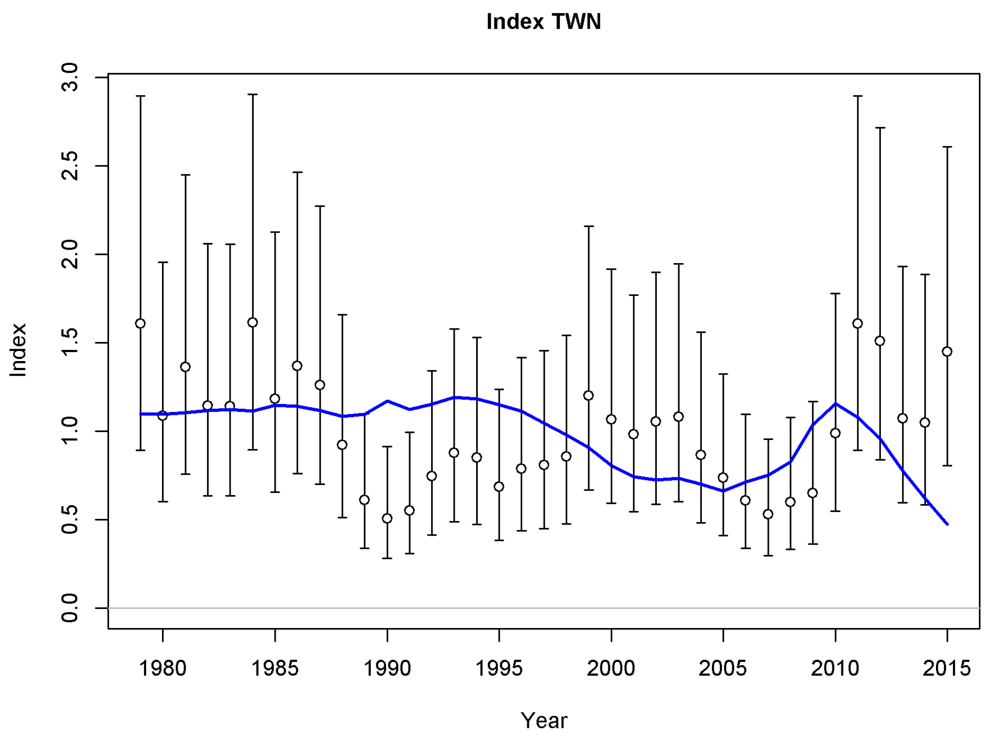


Fig. 4. Observed CPUE (dots) with 95% confidence intervals (vertical lines) and model-estimated CPUE (lines) of blue marlin in the Indian Ocean based on the base-case.

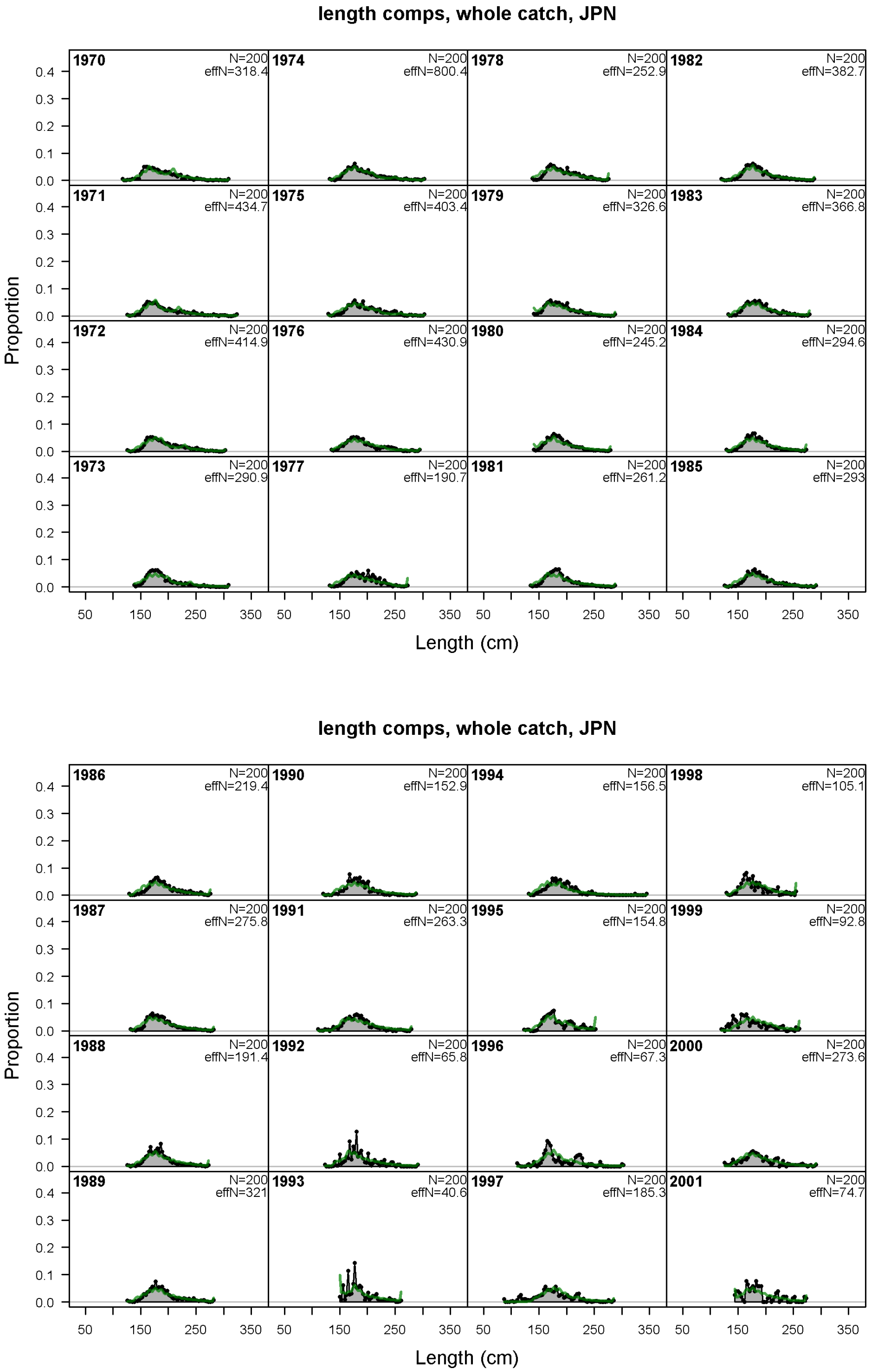
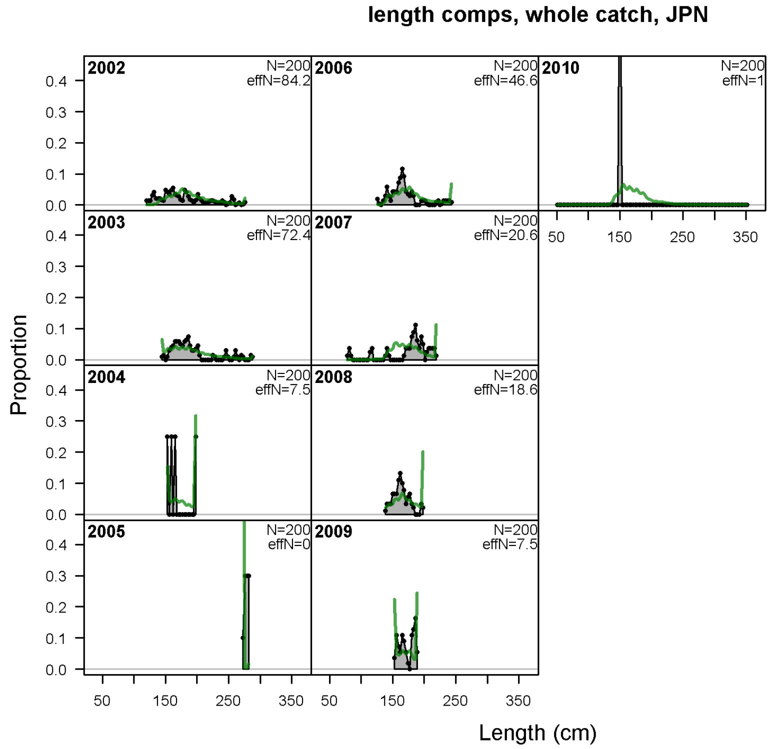


Fig. 5. Observed (shaded areas) and model-estimated (lines) length-frequencies of blue marlin in the Indian Ocean based on the base-case.



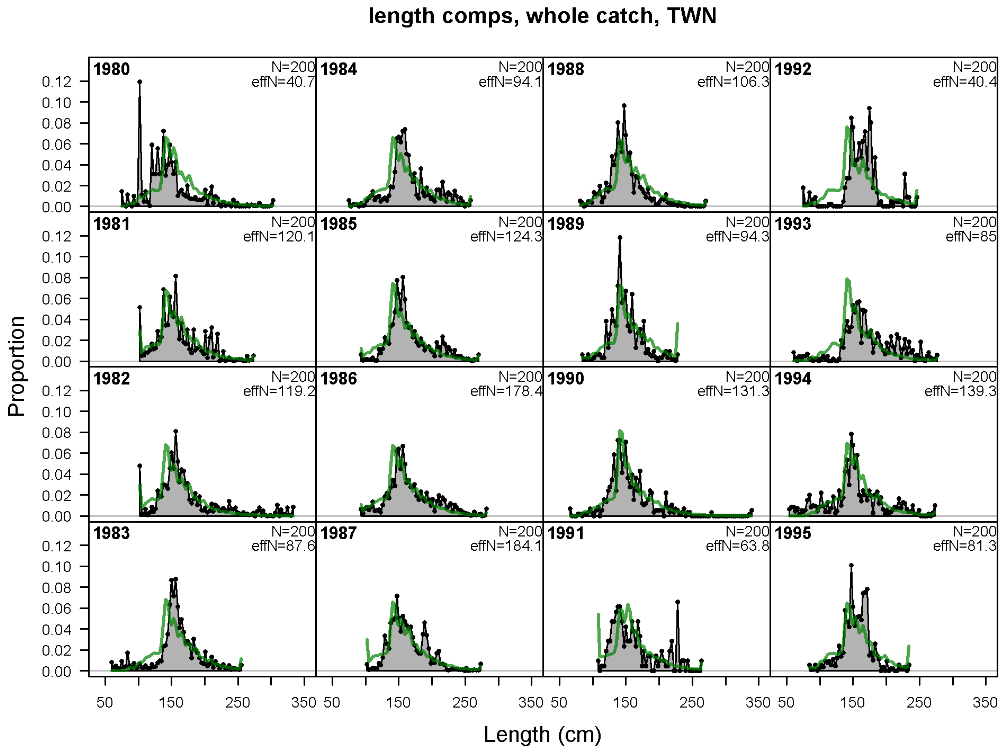
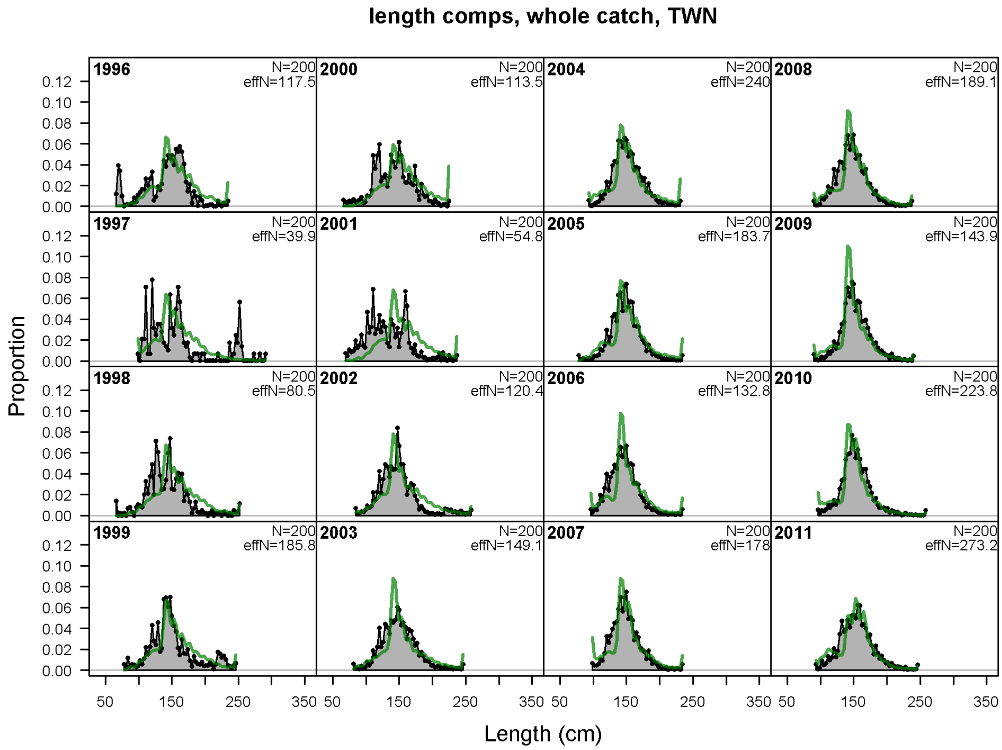
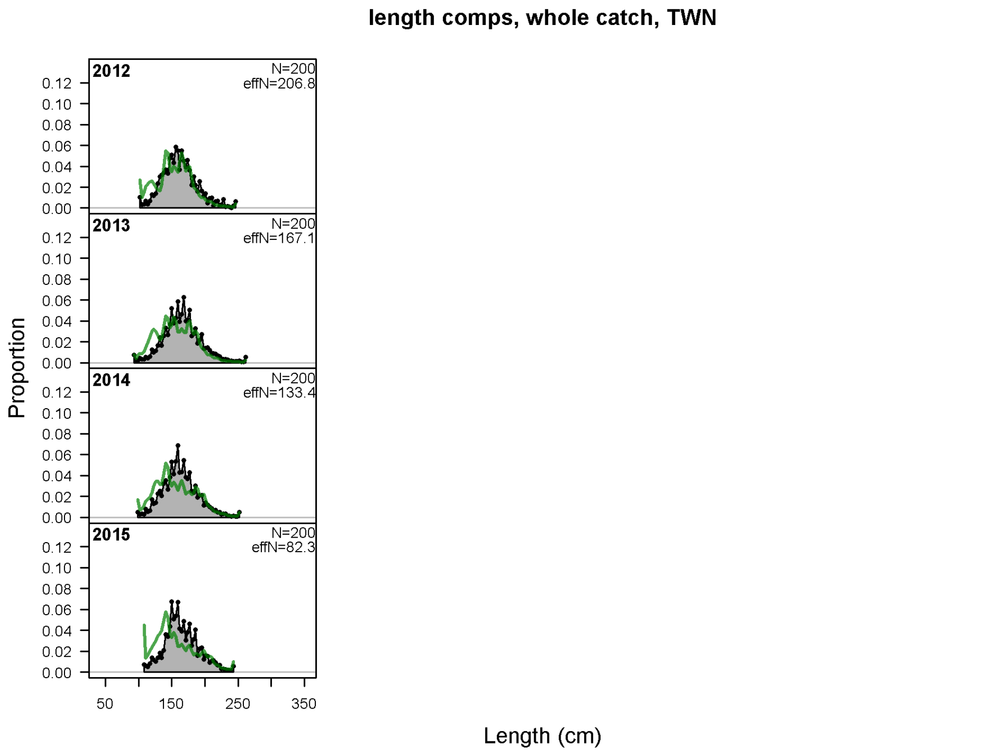


Fig. 5. (Continued).





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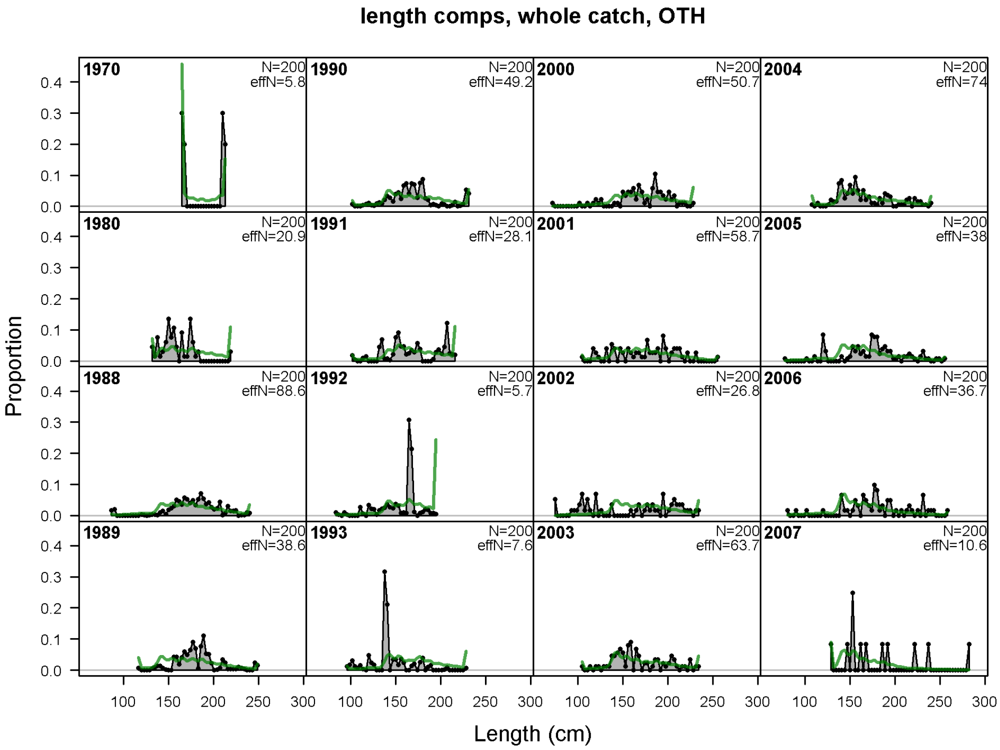

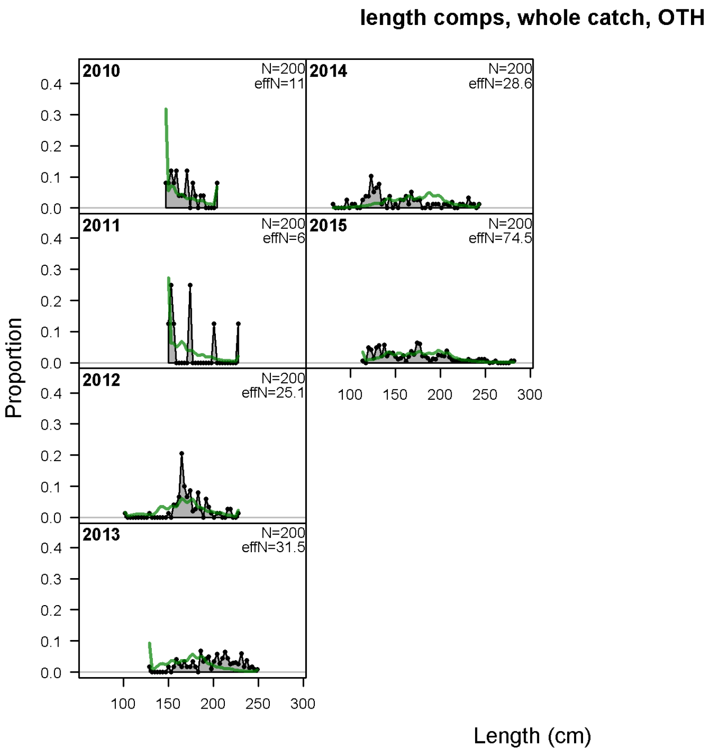

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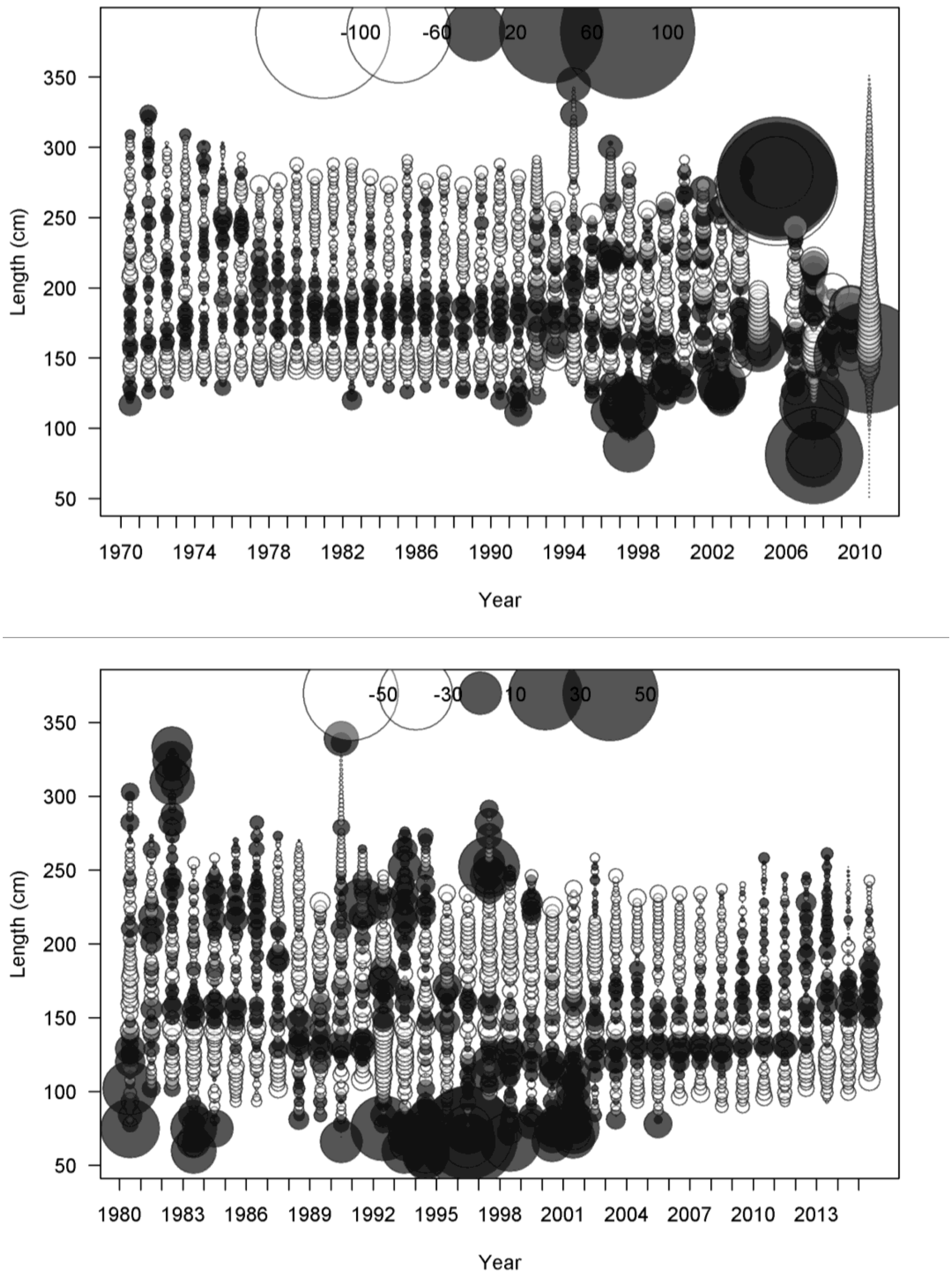

Fig. 6. Pearson residuals of the model fits to length-frequency data of blue marlin in the Indian Ocean based on the base-case. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected). Upper panel for JPN and lower panel for TWN.

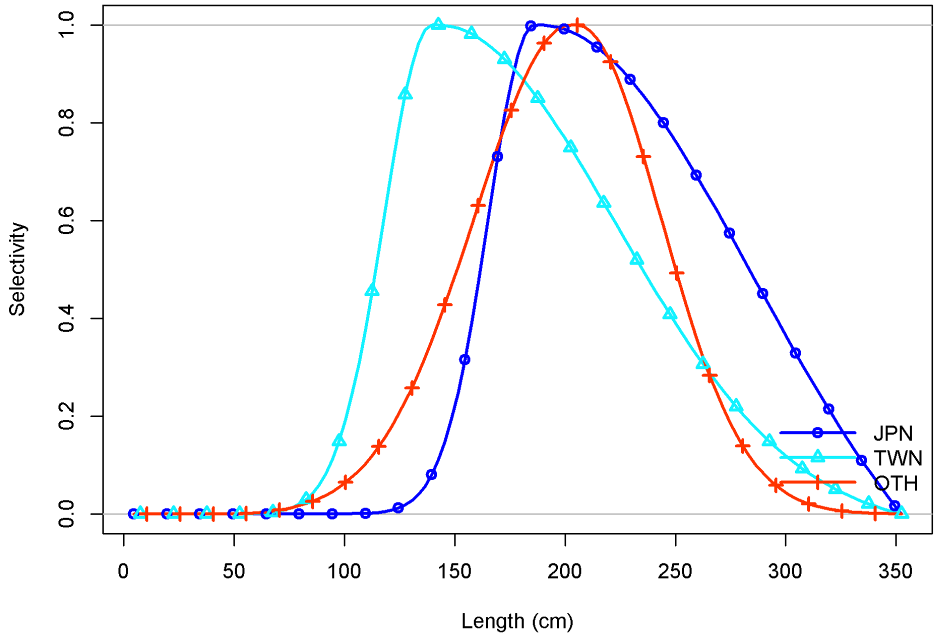

Fig. 7. Model estimated Selectivity at length for blue marlin in the Indian Ocean based on the base-case.

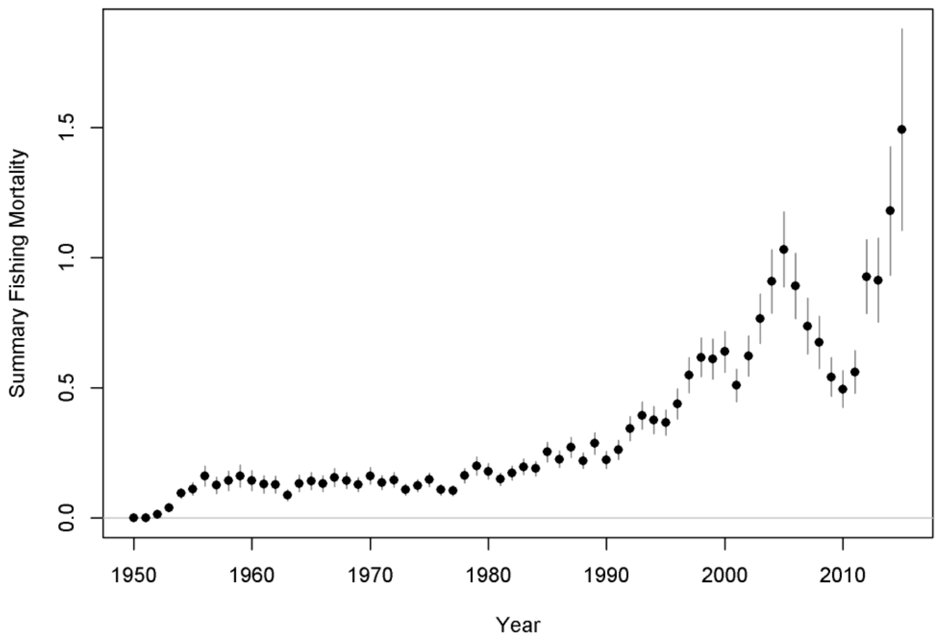

Fig. 8. Time trajectory of the maximum likelihood estimate (dots) of total fishing mortality with 95% confidence intervals (vertical lines) for blue marlin in the Indian Ocean based on the base-case.

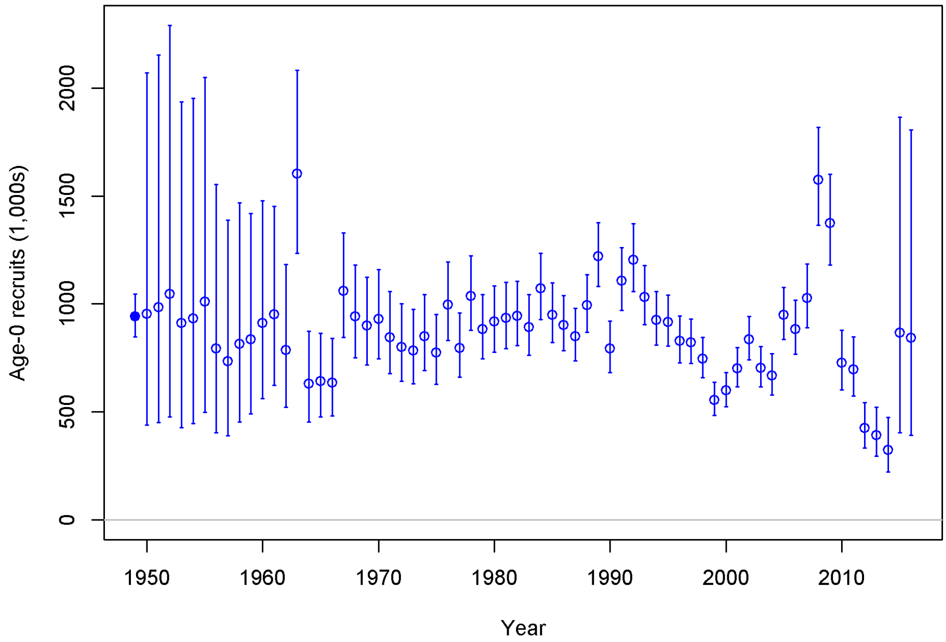

Fig. 9. Time trajectory of the maximum likelihood estimate (dots) of recruitment with 95% confidence intervals (dashed lines) for blue marlin in the Indian Ocean based on the base-case.

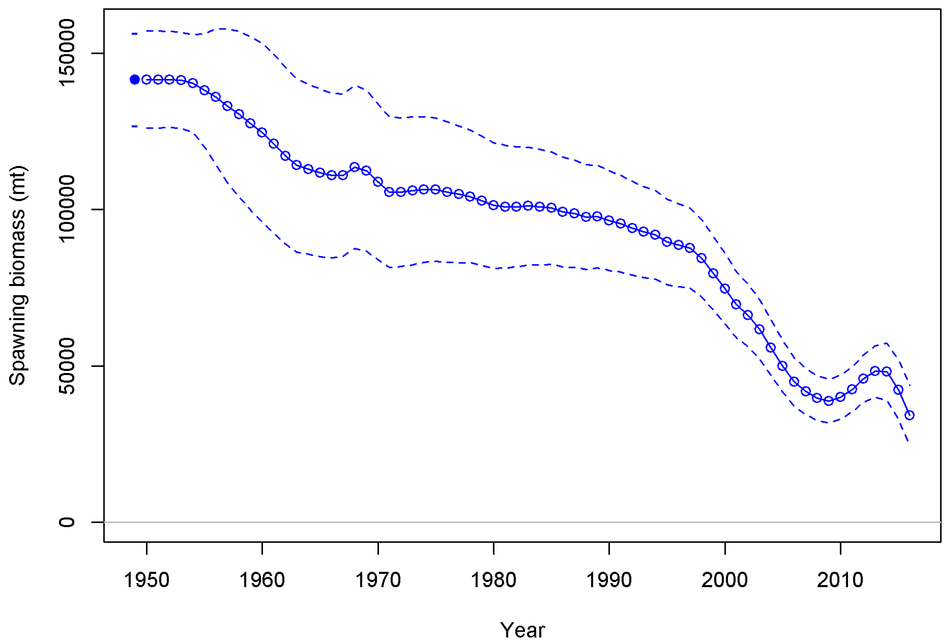

Fig. 10. Time trajectory of the maximum likelihood estimate (line with dots) of spawning biomass with 95% confidence intervals (dashed lines) for blue marlin in the Indian Ocean based on the base-case.

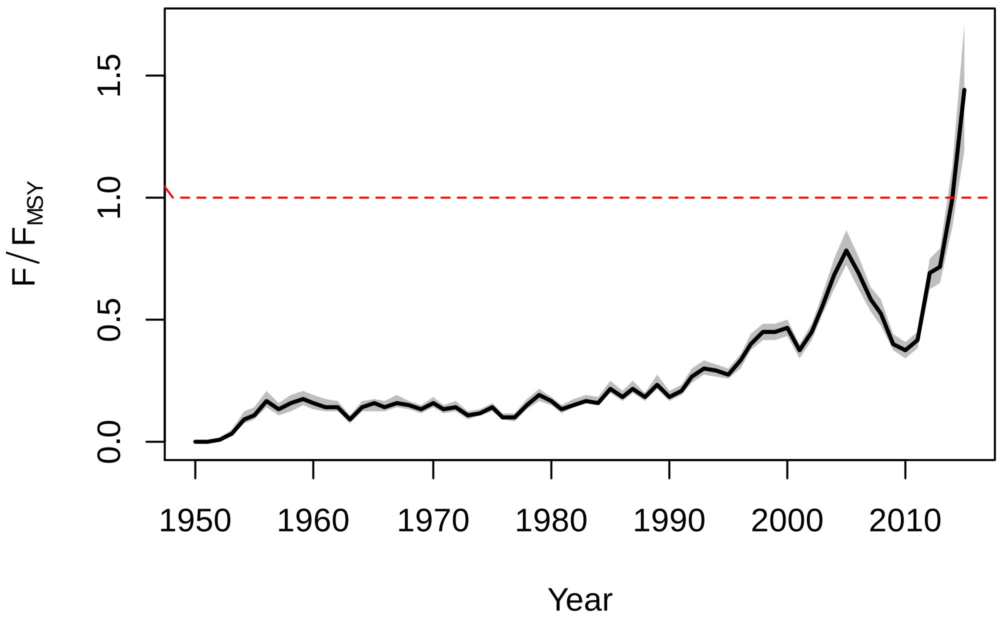

Fig. 11. Time trajectory of the maximum likelihood estimate (line) of the fishing mortality as a ratio of that at which MSY is achieved with 95% confidence intervals (shaded area) for blue marlin in the Indian Ocean based on the base-case.

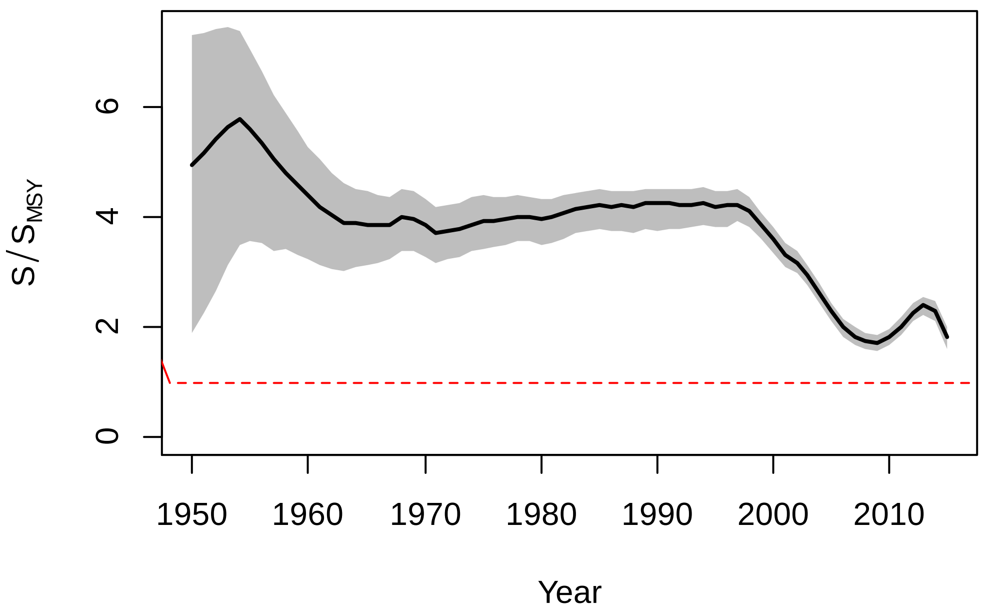

Fig. 12. Time trajectory of the maximum likelihood estimate (line) of the spawning biomass as a ratio of that at which MSY is achieved with 95% confidence intervals (shaded area) for blue marlin in the Indian Ocean based on the base-case.

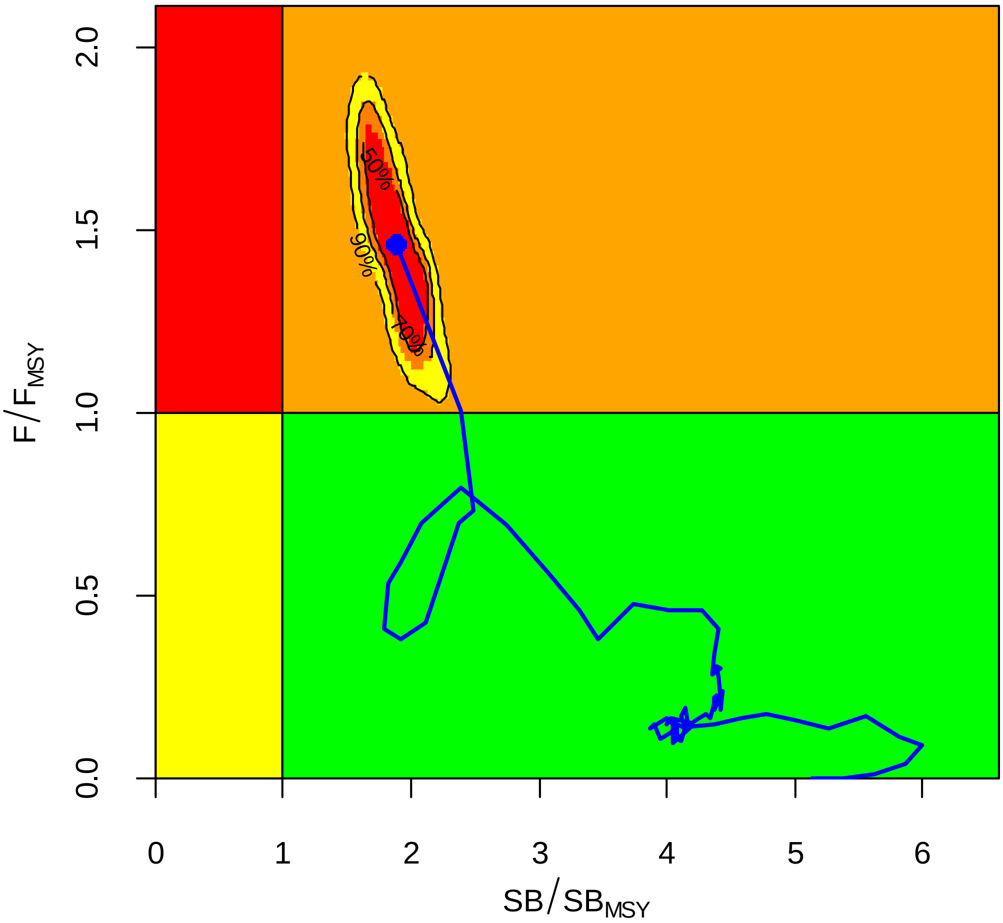

Fig. 13. Kobe plot for blue marlin in the Indian Ocean based on the base-case. The trajectory (blue line) was calculated based on the median of posterior distribution. Blue dot indicates the median estimate for 2015. Concentric ellipses represent 50%, 70% and 90% confidence surface of the estimates for 2015.

Table 1. Life-history parameters of blue marlin used in this study.

Parameter	Female	Male
Natural mortality (M, year^{-1})	0.22	0.37
Length at youngest age ($L1$, cm)	Estimated	Estimated
Length at oldest age ($L2$, cm)	Estimated	Estimated
Growth coefficient (K, year^{-1})	Estimated	Estimated
Length-Weight (a)	1.844E−5	1.37E−05
Length-Weight (b)	2.956	2.975
Length at 50% maturity (cm)	179.76	
Maturity slope	-0.25	
Spawner-recruit steepness (h)	0.87	0.87
Variation in recruitment (σ)	0.4	0.4

Table 3. Model assumptions of scenarios conducted for sensitivity analysis.

Case	M (year^{-1})*	h	Selectivity	$L1$ (cm)*	$L2$ (cm)*	K (year^{-1})*
Base-case	0.22, 0.37	0.87	Double normal	Estimated	Estimated	Estimated
hhigh	0.22, 0.37	0.99	Double normal	Estimated	Estimated	Estimated
hlow	0.22, 0.37	0.75	Double normal	Estimated	Estimated	Estimated
Mhigh	0.37, 0.37	0.87	Double normal	Estimated	Estimated	Estimated
Mlow	0.22, 0.22	0.87	Double normal	Estimated	Estimated	Estimated
Seldom	0.22, 0.37	0.87	Asymptotic	Estimated	Estimated	Estimated
FixG	0.22, 0.37	0.87	Double normal	144, 144	304.178, 226	0.107, 0.211

* Value for female and male, respectively.

Table 3. Key management quantities based on the base-case assessment of Stock Synthesis for blue marlin in the Indian Ocean.

Management Quantity	Aggregate Indian Ocean
2015 catch estimate	15,705
Mean catch from 2011–2015	14,847
MSY (1000 t) (80% CI)	11.206 (10.432–11.981)
Data period (catch)	1950–2015
F_{MSY} (80% CI)	0.263 (0.259–0.268)
SB_{MSY} (1,000 t) (80% CI)	23.133 (21.567–24.698)
F_{2015}/F_{MSY} (80% CI)	1.492 (1.239–1.746)
SB_{2015}/SB_{MSY} (80% CI)	1.829 (1.532–2.125).
SB_{2015}/SB_{1950} (80% CI)	0.299 (0.250–0.347)

Table 4. Kobe II Strategy Matrix based on the base-case assessment of Stock Synthesis for blue marlin in the Indian Ocean. Values represent probability (percentage) of violating the MSY-based reference points for nine constant catch projections (average catch level from 2013–15 (15,400 t), ± 10%, ± 20%, ± 30% and ± 40%) projected for 3 and 10 years.

Reference point and projection timeframe	**Alternative catch projections (relative to the average catch level from 2012–14) 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%**
$SB_{2018} < SB_{MSY}$	30.1	41.2	53.8	68.2	78.8	84.4	90.2	94.6	98
$F_{2018} > F_{MSY}$	32.2	57.4	82.2	98.4	100	100	100	100	100
$SB_{2025} < SB_{MSY}$	32.2	57.4	82.2	98.1	100	100	100	100	100
$F_{2025} > F_{MSY}$	5.8	52.8	80	100	100	100	100	100	100

Table 5. The estimates of the management quantities and values of negative log-likelihood for the CPUE, and the length–frequency data and total negative log-likelihood based on different cases.

	Case						
	Base	hhigh	hlow	Mhigh	Mlow	Seldome	FixG
Management quantity							
MSY (t)	11206		9590		9031	8205	14497
F_{MSY}	0.263		0.193		0.246	0.299	0.573
S_{MSY} (t)	23133		33501		9384	13179	20140
F_{2015}/F_{MSY}	1.492		2.061		2.155	1.777	1.079
S_{2015}/S_{MSY}	1.829		1.261		1.339	1.610	2.064
S_{2015}/S_{1950}	0.299		0.285		0.546	0.265	0.342
Value of negative log-likelihood							
Length-frequency	7762.7		7762.7		7926.3	7764.0	19227.6
CPUE	-46.9		-47.2		-41.3	-26.8	-47.2
Total	7675.4		7675.2		7849.4	7706.8	19142.0