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Stock assessment of swordfish (*Xiphias gladius*) in the Indian Ocean using age-structured integrated analysis

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ABSTRACT

This study evaluated the stock status of swordfish in the Indian Ocean based on the sex-specific age-structured integrated approach (ASIA). Nine scenarios were conducted based on the different assumptions related to incorporation of CPUE data and pre-specific biological parameters. For all scenarios, the model generally fits to the observed length frequency data well for all fleets, while the model cannot fit to CPUEs very well for some of fleets in years before early-1990s, especially for JPLL-SW and TWLL-SW because these CPUEs changed sharply since the mid of 1990s but catchabilities were assumed to be constant over time for each fleet. For whole Indian Ocean, the results of most scenarios indicated that the current fishing intensity was lower than MSY level and the current spawning biomass was higher than MSY level, while the current fishing intensity may slightly higher than MSY level when lower reproductivity was assumed for swordfish. For southwest Indian Ocean, the results of all scenarios indicated that the current fishing intensity was lower than MSY level and the current spawning biomass was higher than MSY level. Base on the results of this study, the status of swordfish in the Indian Ocean and in the southwestern Indian Ocean might not be overfishing or overfished.

1. INTRODUCTION

Swordfish in the Indian Ocean (*Xiphias gladius*) was historically taken mainly by Japan (JPLL) and Taiwan (TWLL), but the catch was low. Since the early 1990s, the catch of swordfish in the Indian Ocean increased substantially owing to the seasonal targeting of the Taiwanese fishery, the targeting of EU longline fisheries from Spain, Portugal and the UK (EULL) and exploitation of semi-industrial longline (ISEL), Australian longlie (AUEL), artisanal fisheries (ALGI) and fresh tuna longline (TWFL). The catch of swordfish in the Indian Ocean increased from less than 10,000 mt before early 1990’s to around 35,000 mt in the late 1990’s and early 2000’s. The current catch of swordfish is around 26,000 mt. The increase in catch since the early 1990‘s is attributed to a change in target species from tunas to swordfish by part of the Taiwanese fleet, the development of longline fisheries in Australia, La Reunion, Seychelles and Mauritius targeting swordfish, and the arrival of longline fleets from the Atlantic Ocean (Portugal, Spain and other fleets operating under various flags) also targeting swordfish (IOTC, 2010).

For southwestern Indian Ocean, the catch of swordfish was also very low before 1990. The catch of swordfish substantially increased due to the exploitation of Taiwanese longline. Since early-2000s, the catch Taiwanese longline sharply decreased and the catch of EU longline substantially increased. The current catch of swordfish in the southwestern Indian Ocean is around 71,000 mt and is about 27% of the catch in the entire Indian Ocean.

Since biological parameters (e.g. Poisson et al., 2009; Wang et al. 2010) and historical length-frequency data are available for swordfish in the Indian Ocean, the length-based assessment methods (e.g. Fournier et al., 1998; Methot, 2005; Wang et al., 2005; Wang et al., 2007) can be applied to assess the population status. Therefore, this study attempt to evaluate the stock status of swordfish in the Indian Ocean using the sex-specific age-structured integrated analysis developed by Wang et al. (2005, 2007).

2. MATERIALS AND METHODS

2.1 Data used

The data used for assessment are the catches, length–frequencies, and CPUE-based indices of abundance. The historical catches in weight and length-frequency data from 1950 to 2013 for all fisheries were provided by Indian Ocean Tuna Commission (IOTC) (Figs. 1 and 2). Generally, the time series of the length-frequency data for most fisheries were shorter than the catch data. All of the length-frequency data were aggregated into 3 cm (lower jaw fork length) interval length-compositions for each fishery.

The relative abundance indices used in this study were based on the standardized CPUE from fleets of Taiwan (1980-2012), Japan (1971-2013), Spain (2001-2012) and Portugal (2000-2013) longline fisheries (Fernández-Costa et al., 2014; Nishida and Wang, 2014; Santos et al., 2014a,b; Wang and Nishida, 2014).

The definition of fisheries used in this study is listed in Table 1. Except for longline fishery of Australia, all fisheries were divided into four fleets based on four subareas (NW. SE, SW and SE) of the Indian Ocean which have been used for the swordfish assessment since 2009 (IOTC, 2008; Fig. 3). Because catches and sample sizes of length-frequency data of some fleets were very low, some fleets were aggregated into the same groups and 16 fleets were defined in the study (Table 1).

For assessment of swordfish in the southwestern Indian Ocean, the data of fisheries in area SW are only used to fit to the model and were grouped into four fleets (Table 2).

2.2 Biological information

The biological and demographic parameters, including the length-weight relationship, growth and maturity are available for swordfish in the Indian Ocean. The parameters of length-weight relationship and von Bertalanffy growth curve and the Standard deviation of length-at-age were based on the results of age and growth study for swordfish in the Indian Ocean (Wang et al., 2010). Poisson et al. (2009) provided the parameters of logistic maturity curve and also the relationship between sex-ratio and length for swordfish caught by the Reunio-based pelagic longline fishery. The biological parameters used in this study are listed in Table 3.

2.3 Assessment model

The sex-specific age–structured integrated analysis used in this study was based on the population dynamics model developed by Wang et al. (2005, 2007). This model considers swordfish from age 0 to 25 (age 25 being treated as a 'plus group') because the instantaneous growth rates were close to zero and the body lengths tended to an asymptotic length at about 25 years of age for both sexes. The model assumes that recruitment is related to spawning stock biomass according to a Beverton–Holt stock-recruitment relationship and that the deviations about this relationship are log-normally distributed. The recruitment deviations for the years prior to 1980 are set to zero due to lack of information in the length–frequency data about the year-class strength for these years. The recruitment deviations for the years after 1980 are treated as parameters of the assessment model, with a penalty based on the distributional assumption.

The parameters of the model can be divided into those for which auxiliary information is available and are estimated outside the assessment model (Table 3) and those that needed to be estimated by fitting the stock assessment model to the data (Table 4). The values for the parameters related to natural mortality (M), the steepness of the stock-recruitment relationship (h), and the extent of variation in recruitment (σ_v) cannot be determined from auxiliary information, nor can they be estimated reliably by fitting the model to the data (results not shown) and must therefore be pre-specified. In this study, the base-case value for M is taken to be 0.25 year^{-1} as previous assessment for swordfish, h is assumed to be 0.9 (Punt et al., 2001; Wang et al., 2005; Wang et al., 2007), and σ_v is assumed to be 0.4 (Punt et al., 2001). Constraints are imposed on the extent to which the number of 0-year-olds can deviate from the underlying stock-recruitment relationship.

Swordfish is exploited as a bycatch species by most fleets in the Indian Ocean. Fleets operating in different regions target different species, especially the Japanese and Taiwanese longline fleets, which are widely distributed in the Indian Ocean. We therefore assumed that selectivity is different for fleets operating in each region even though swordfish is considered as a single stock in the Indian Ocean. The logistic curve is commonly used in fisheries stock assessment models to represent selectivity for longline gears. However, few swordfish with lengths greater than 200 cm were caught by the fleets other than EU and Japanese longline fleets (Figs. 4 and 5). Therefore, the assumption that selectivity follows a logistic curve might be inadequate for these fleets. Therefore, selectivity patterns were assumed to be logistic curves for EU and Japanese longline fleets (EUEL and JPLL), and to be dome-shaped curves (represented by a double normal ogive (Bull et al., 2012)) for the other fleets. Catchability was assumed to be constant over time for all fleets.

The objective function, which was minimized, combines the negative log-likelihoods for the CPUE and length-frequency data, and a penalty for the annual recruitment deviates. The model is implemented using AD Model Builder (Fournier et al., 2012).

2.4 Sensitivity analysis

Because the catch and length-frequency data of EU countries were combined into one category as EU, the CPUEs from Spain and Portugal were aggregated by their average values for base-case analysis.

Based on the recommendations of working party, eight additional scenarios were conducted for comparing the results of stock assessments based on various assumptions related to usage of CPUE data and biological parameters (Table 5).

3. RESULTS AND DISCUSSION

3.1 Stock assessment for entire Indian Ocean

The observed and the model estimated length frequencies aggregated across years for base-case are shown in Fig. 4. In substance, the model estimated length-frequencies mimics the observed length frequency data well for all fleets. For other scenarios, the model can also fit to the length frequency data well (results not shown). The model estimated selectivites for females and males are shown in Fig. 5. The gillnet, trolling and artisanal fleets (ALGI) tended to select smaller fishes than other fleets, Taiwanese longline fleets (TWLL) targeted fishes with ages 4 to 7, while Australian longline fleet (AUEL), Semi-industrial longline fleets (ISEL) and Fresh-tuna longline fleets (TWEL) tend to select more large fish.. Due to the assumption of logistic selectivity, Japanese longline fleet selected more fishes when their ages reached 5 years. The patterns of estimated selectivities did not significantly changed when the model performed based on different assumptions (results not shown).

Fig. 6 shows the fits of the model to the observed CPUE data. Based on the results of base-case, the model cannot fitted to CPUE data very well for some of fleets, especially for JPLL-SW and TWLL-SW because these CPUE data changed sharply since the mid of 1990s but catchabilities were assumed to be constant over time for each fleet. The model fits to CPUE data did not obviously change when different assumptions related to biological parameters or CPUE data were adopted even only Japanese or Taiwanese CPUE was only used (Fig. 6).

Fig. 7 shows the time trajectories of Maximum Posterior Density (MPD) estimates of recruitment and spawning biomass for various scenarios. The estimates of recruitment and spawning biomass were obviously higher than other cases when higher natural mortality (M=0.4) and alternative growth parameters were used. Fig. 8 shows the time trajectories of MPD estimates of S_{current}/S_0, $S_{\mathrm{current}}/S_{MSY}$ and $F_{\mathrm{current}}/F_{MSY}$ for various scenarios. The fleet-aggregated fishing intensity substantially increased to more than 50% of F_{MSY} since the early1990s due to the increasing of catch (Fig. 1) and this leaded to the obvious decreasing of spawning biomass. The fleet-aggregated fishing intensity exceeded the MSY level during the mid-1990s to the mid-2000s and in recent years when the assumption of low reproductivity (h=0.6) was adopted. However, the estimates of the spawning biomass were obviously higher than S_{MSY}, and the depletion of spawning biomass (S_{current}/S_0) was still under a relatively high level (higher than about 50% of S_0)

Based on the Kobe plot, the results of most scenarios indicated that the status of swordfish in the Indian Ocean might not be under an overexploitation condition (Figs. 9 and 10). Generally, the stock status may be slightly pessimistic when the population was assumed to be low reproductive (h=0.6), while assuming higher natural mortality (M=0.4) may lead to relatively optimistic assessment results (Fig. 9). The estimates of key management quantities for swordfish in the Indian Ocean based on various assumptions were summarized in Table 6. In addition, the estimates with 80% confidential intervals of key management quantities based on the base-case assessment are summarized in Table 8.

3.2 Stock assessment for southwestern Indian Ocean

The stock assessment for swordfish in the southwestern Indian Ocean was also conducted based on various scenarios listed in Table 5. It should be noted that the estimations were obviously unreasonable when assuming a higher natural mortality (M=0.4), and the results based on this assumption should be ignored.

Similar to the result of the assessment for entire Indian Ocean, the model generally fits to the length frequency well, but cannot fit very well to Taiwanese and Japanese CPUE before the mid 1990's (Figs. 11 and 12). The estimates of selectivities for these four fleets are shown in Fig. 13. Due to the assumption of selectivity curves for fleets, Taiwanese fleet tended to select more small fishes, while more large fishes were selected by other fleets.

Fig. 14 shows the time trajectories of MPD estimates of recruitment and spawning biomass for various scenarios. The estimates of recruitment and spawning biomass were obviously higher than other cases when alternative growth parameters and only Taiwanese CPUE data were used. The time trajectories of MPD estimates for S_{current}/S_0, $S_{\text{current}}/S_{MSY}$ and $F_{\text{current}}/F_{MSY}$ indicated that substantial increasing catch since the early 1990's led to the increase in fishing intensity and decrease in spawning biomass (Figs. 3 and 15). The fishing intensity once exceeded the F_{MSY} level in the mid-1990s when the reproductivity was assumed to be lower (h=0.6). Recently, fishing intensity did not exceed the F_{MSY} and spawning biomass was higher than S_{MSY} although spawning biomass continuously decreased since the early 1990s.

Based on the Kobe plot, the results of all scenarios indicated that the status of swordfish in the southwestern Indian Ocean might not be under an overexploitation condition (Figs. 16 and 17). Similarly, the stock status may be relatively pessimistic when the population was assumed to be low reproductive (h=0.6). Since the results were not reasonable when assuming a higher natural mortality (M=0.4), most optimistic assessment results were obtained when only Taiwanese CPUE data were used (Fig. 17). The estimates of key management quantities for swordfish in the southwestern Indian Ocean based on various assumptions were summarized in Table 7. Also, the estimates with 80% confidential intervals of key management quantities based on the base-case assessment are summarized in Table 8.

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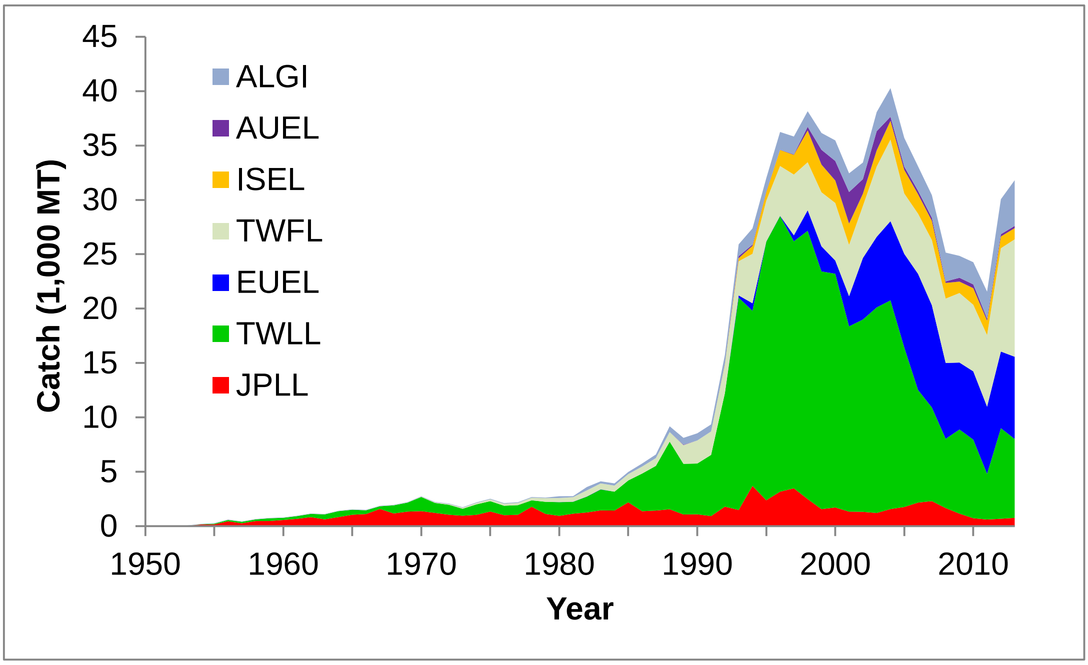


Fig. 1. Annual nominal catches (NC) of swordfish in the Indian Ocean from 1950 to 2008.

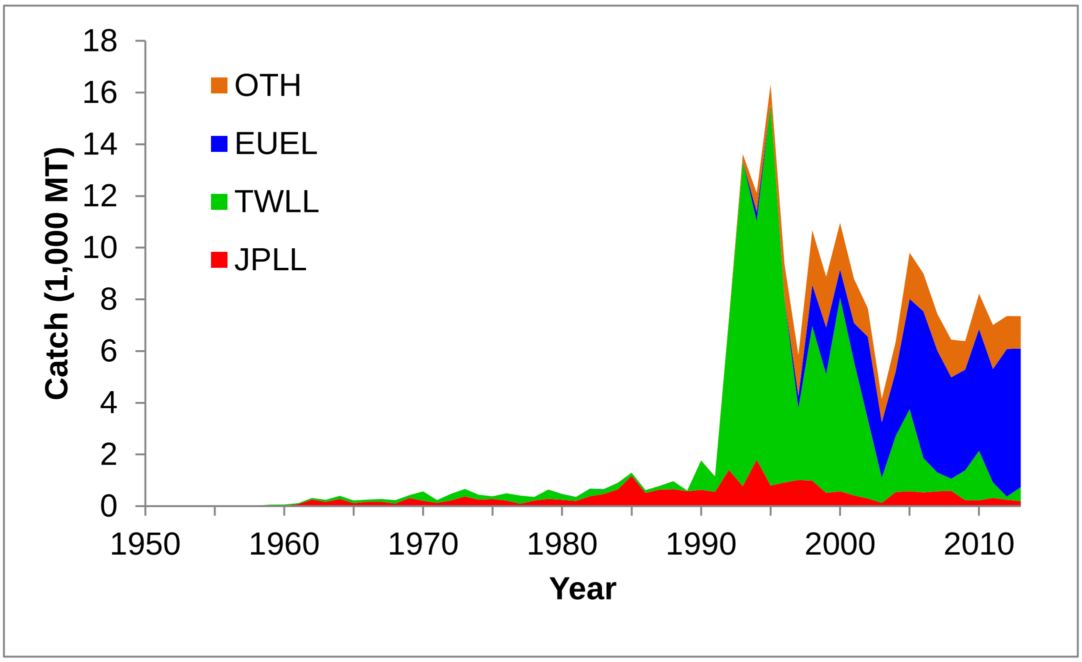


Fig. 2. Annual nominal catches (NC) of swordfish in the southwestern Indian Ocean from 1950 to 2008.

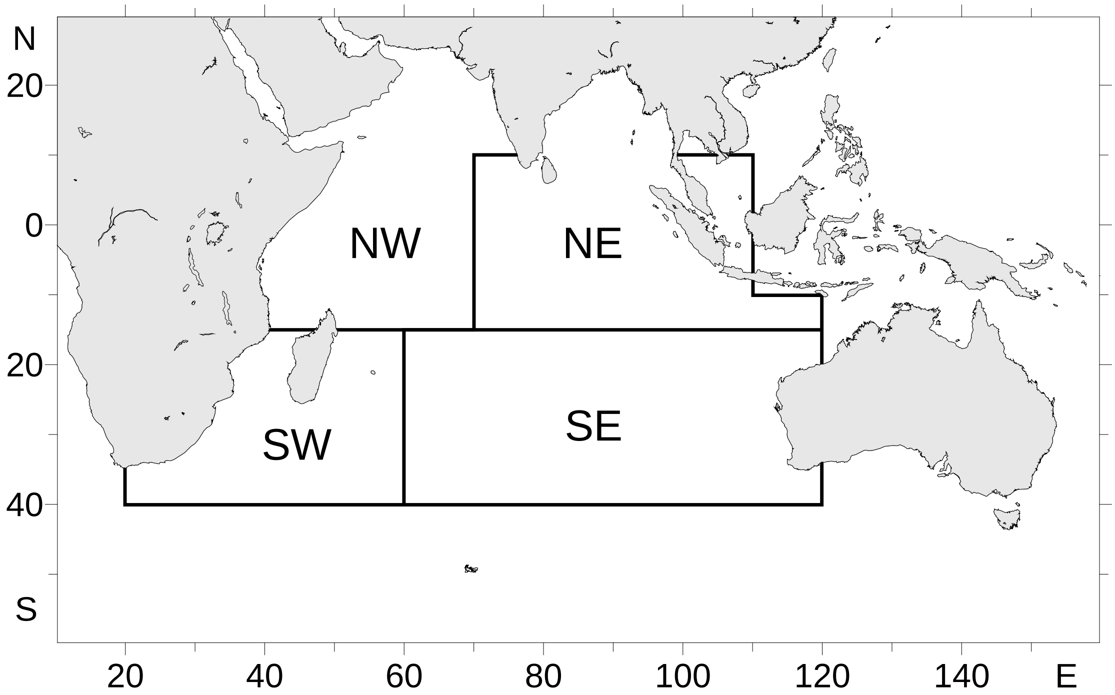


Fig. 3. The definition of areas used in the analyses for swordfish in the Indian Ocean.

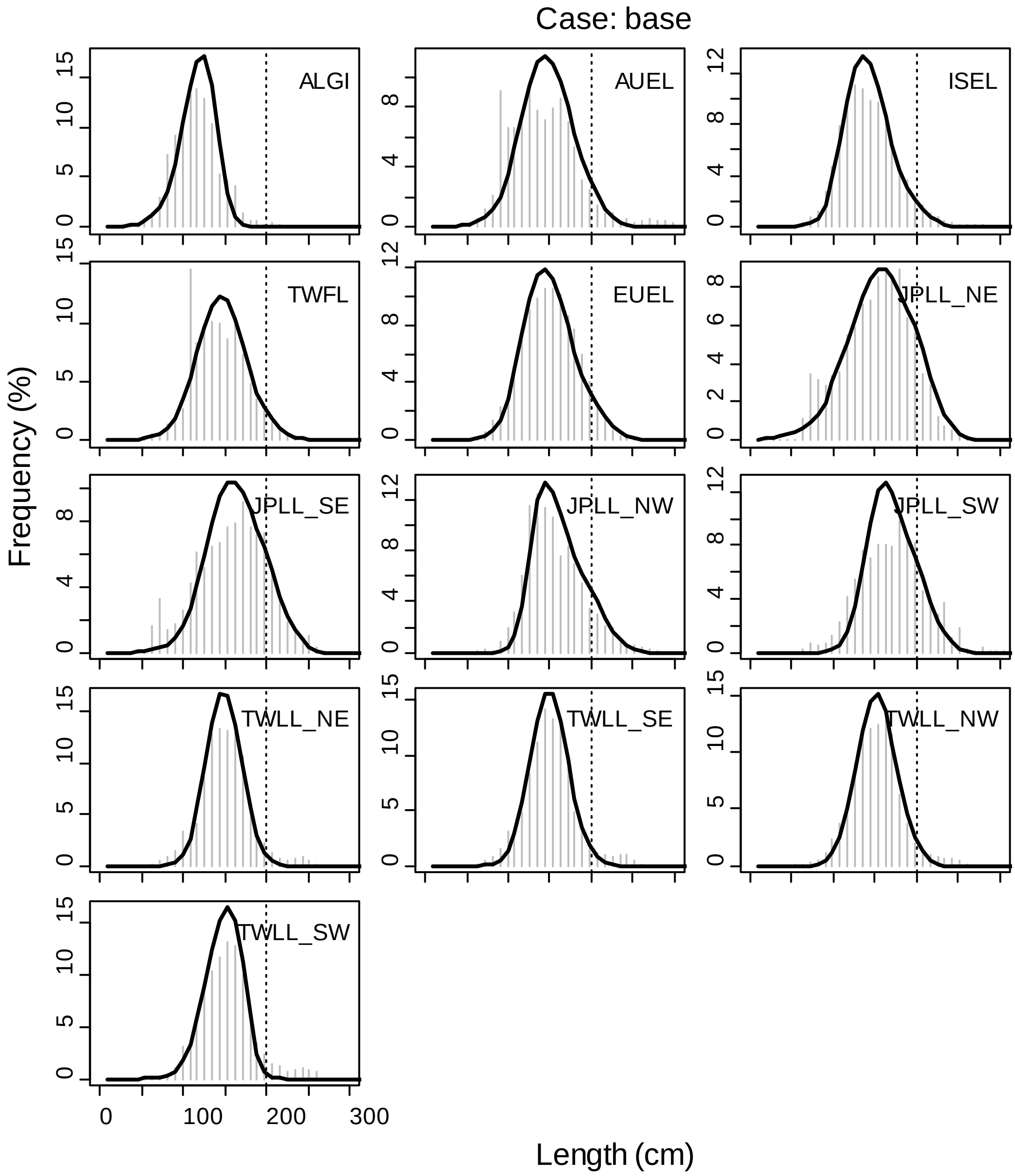


Fig. 4. Observed (histograms) and model-estimated (lines) length-frequencies of swordfish in the Indian Ocean based on the base-case assessment. Dotted lines indicate the body length of 200 cm.

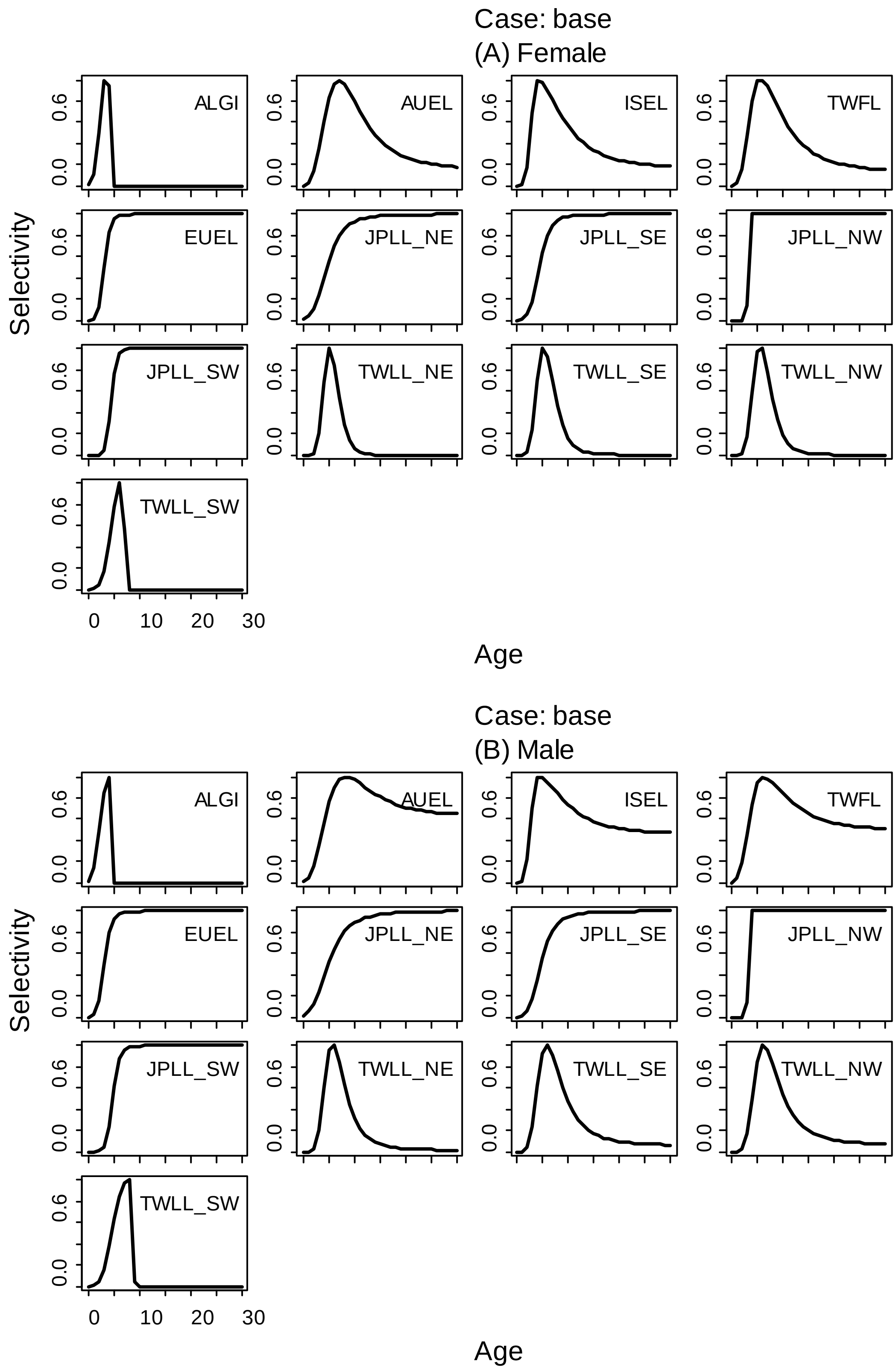


Fig. 5. Model-estimated selectivity curves for swordfish in the Indian Ocean based on the base-case assessment.

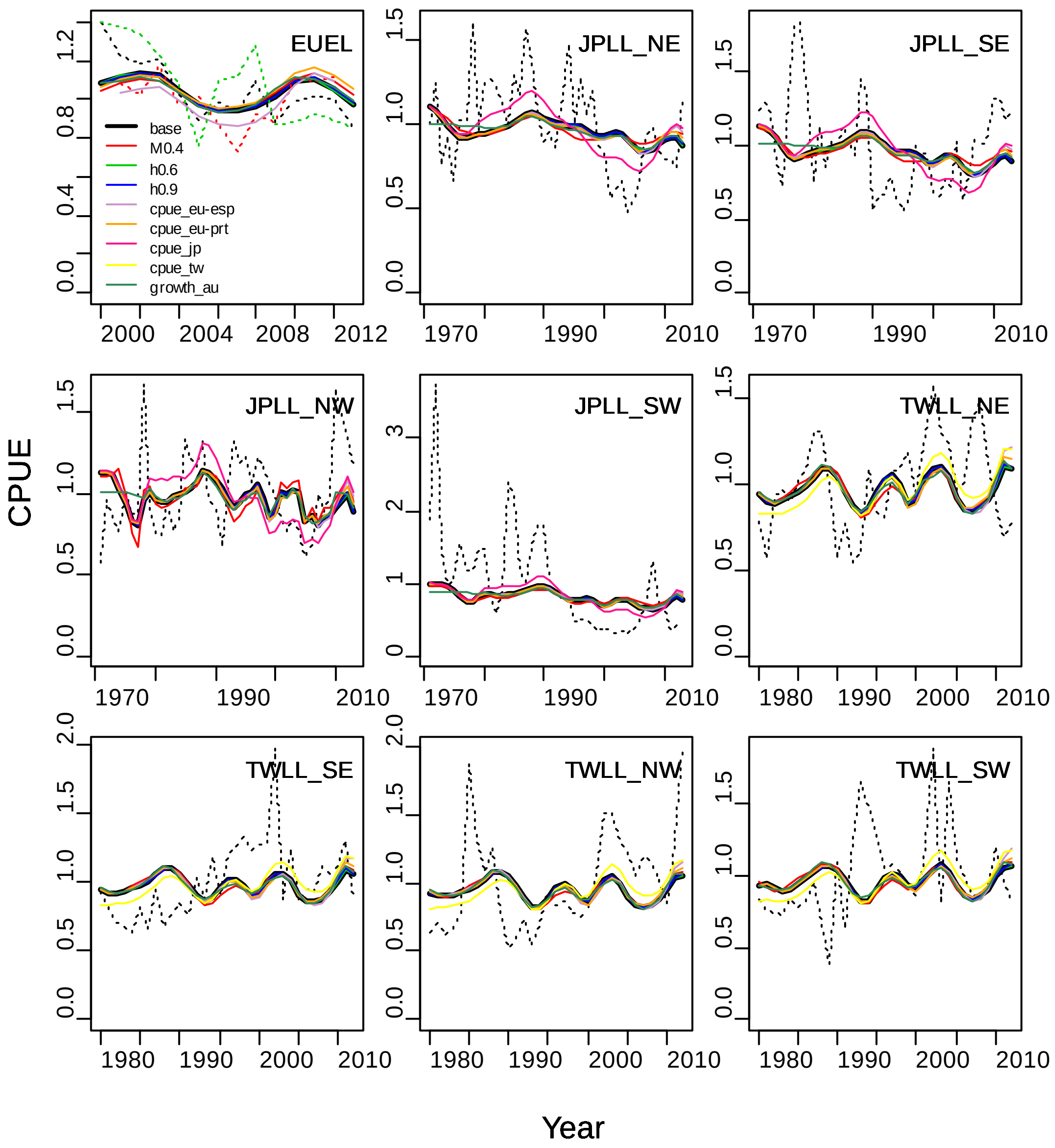
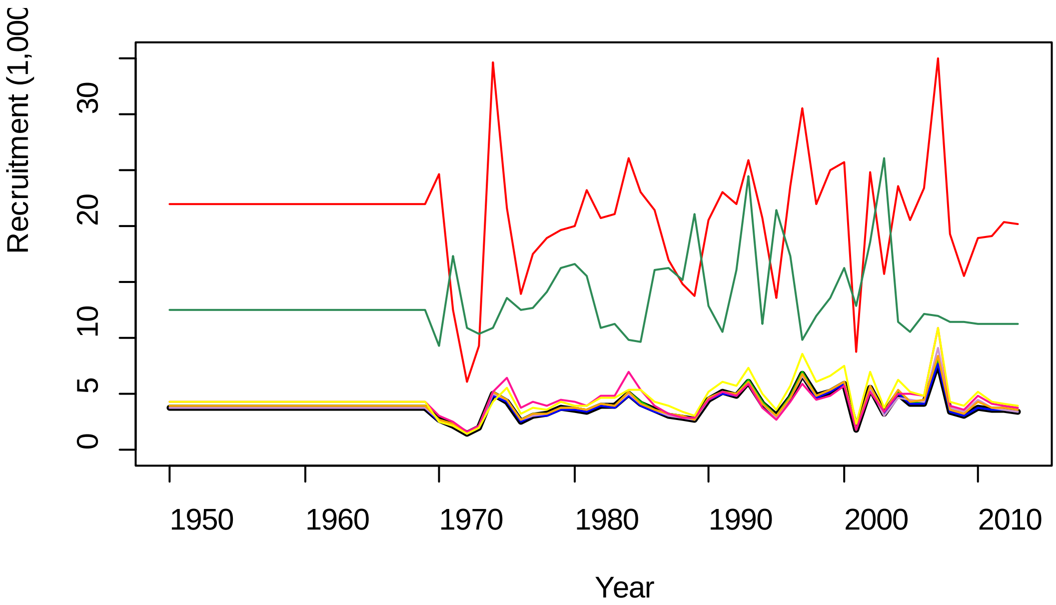


Fig. 6. Standardized observed CPUE (dotted lines) and model-estimated CPUE (solid lines) of swordfish in the Indian Ocean. Red and green dotted lines are Spanish and Portuguese observed CPUEs, respectively.



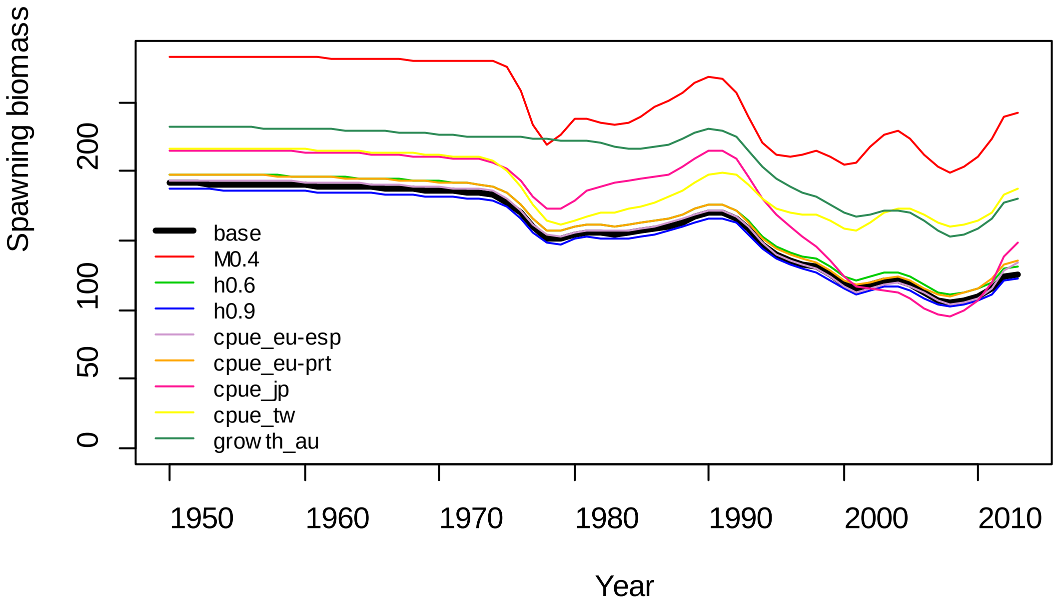


Fig. 7. Time trajectories of MPD estimates for recruitment the spawning biomass of swordfish in the Indian Ocean.

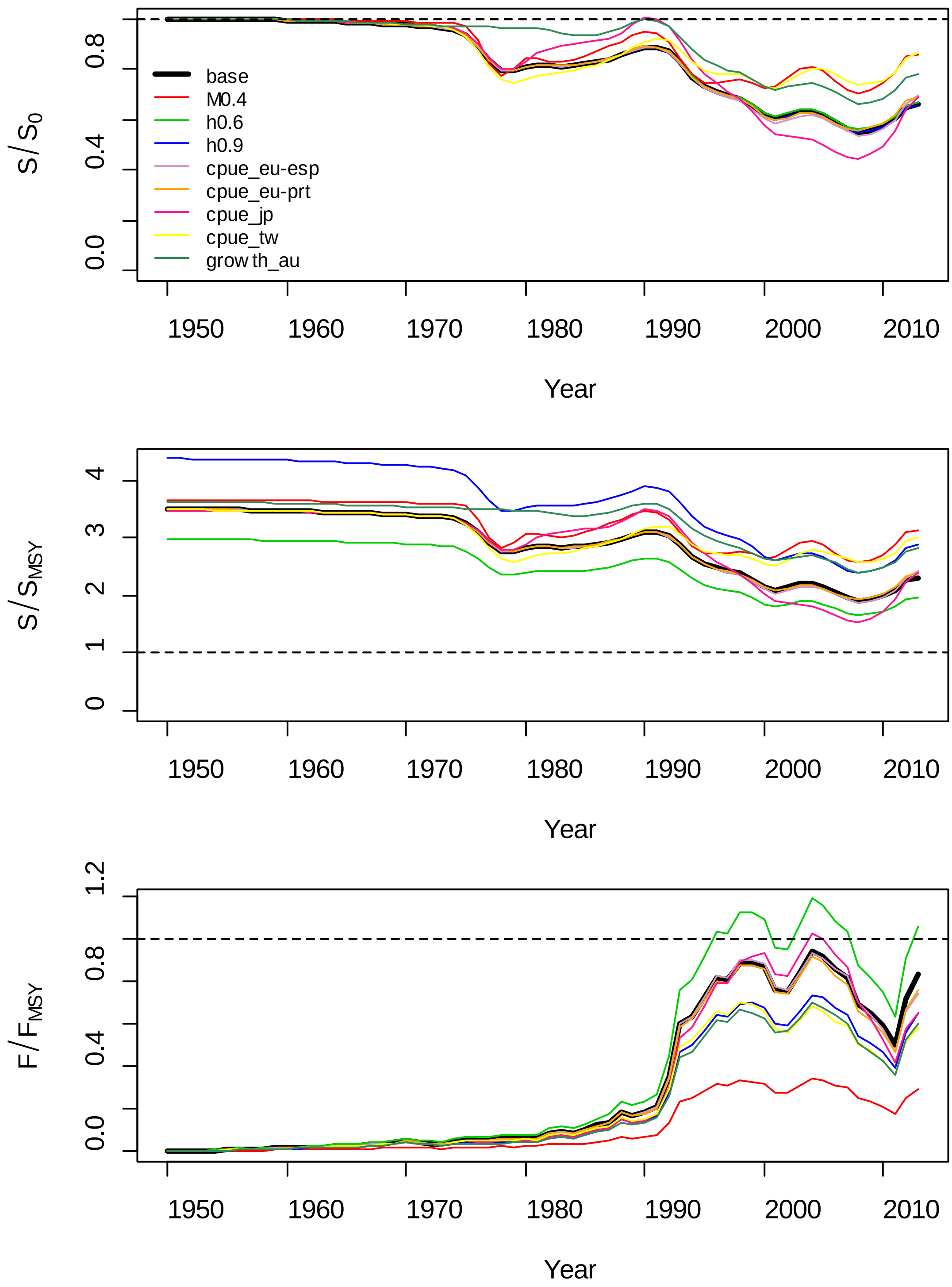


Fig. 8. Time trajectories of MPD estimates for the spawning biomass as a ratio of the unexploited spawning biomass (S /S_0), the spawning biomass as a ratio of S_{MSY} (S/S_{MSY}) and the fleet-aggregated fishing intensity as a ratio of that at which *MSY* is achieved (F/F_{MSY}) for swordfish in the Indian Ocean.

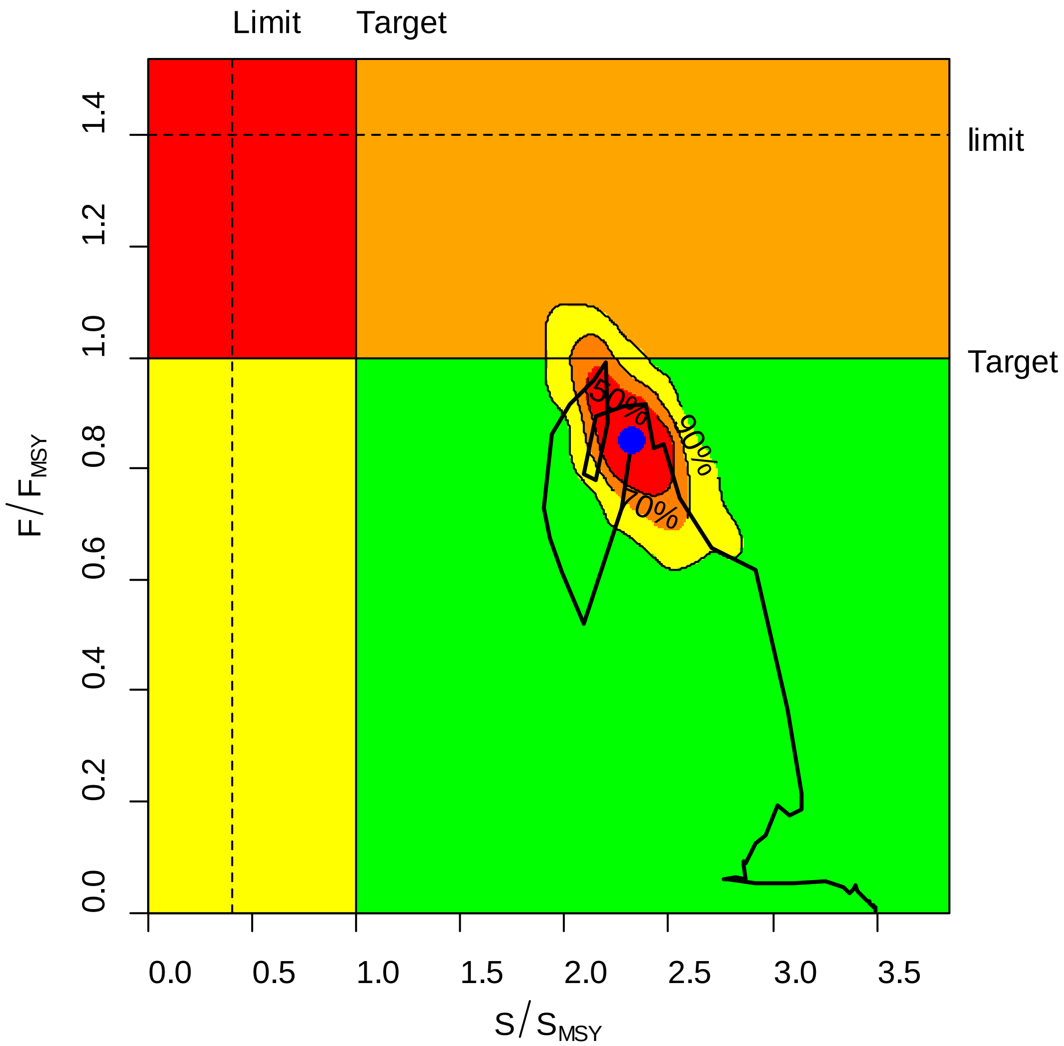


Fig. 9. Kobe plot for swordfish in the Indian Ocean based on base-case assessment. The trajectories were calculated based on the median of 1000 re-samplings of Bayesian posterior distribution. Blue circles indicate the estimates in 2013.

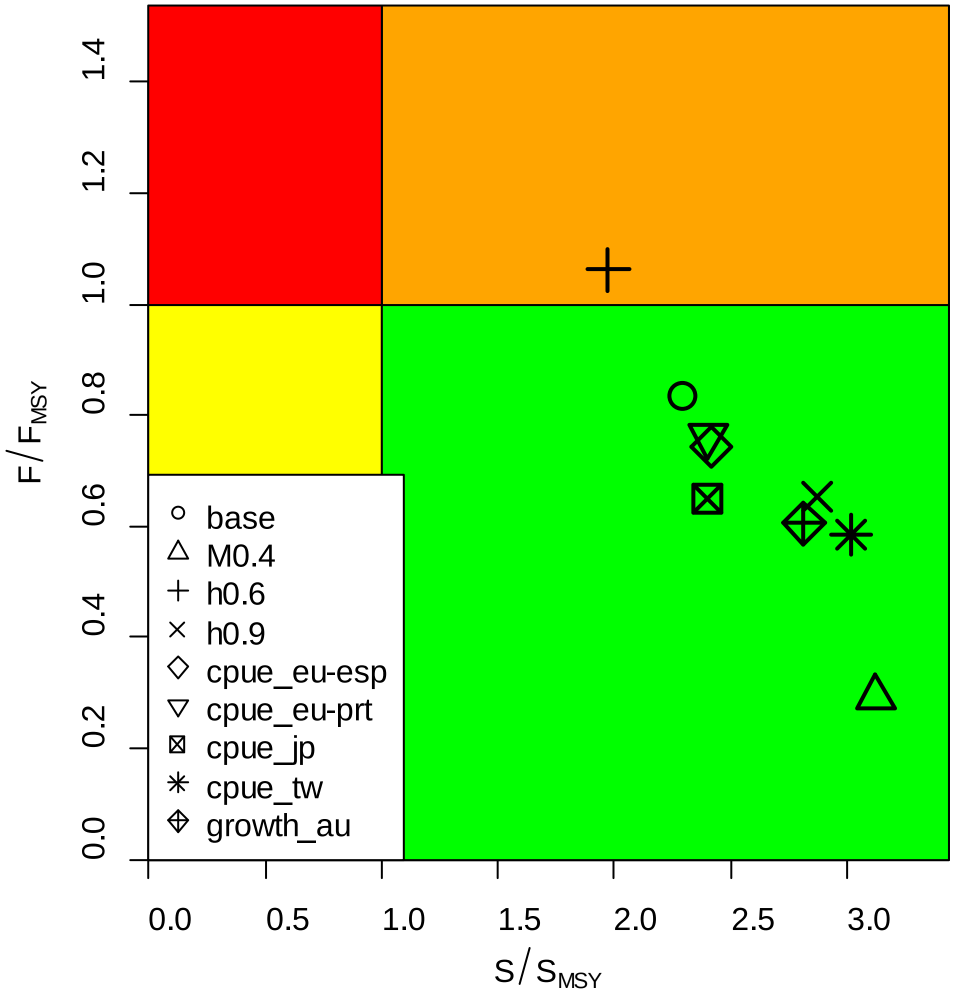


Fig. 10. Kobe plot for swordfish in the Indian Ocean based on the MPD estmates in current year for all scenarios.

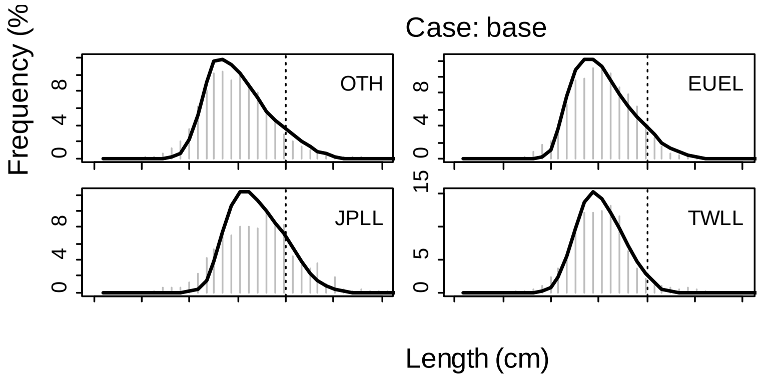


Fig. 11. Observed (histograms) and model-estimated (lines) length-frequencies of swordfish in the Indian Ocean based on the base-case assessment. Dotted lines indicate the body length of 200 cm.

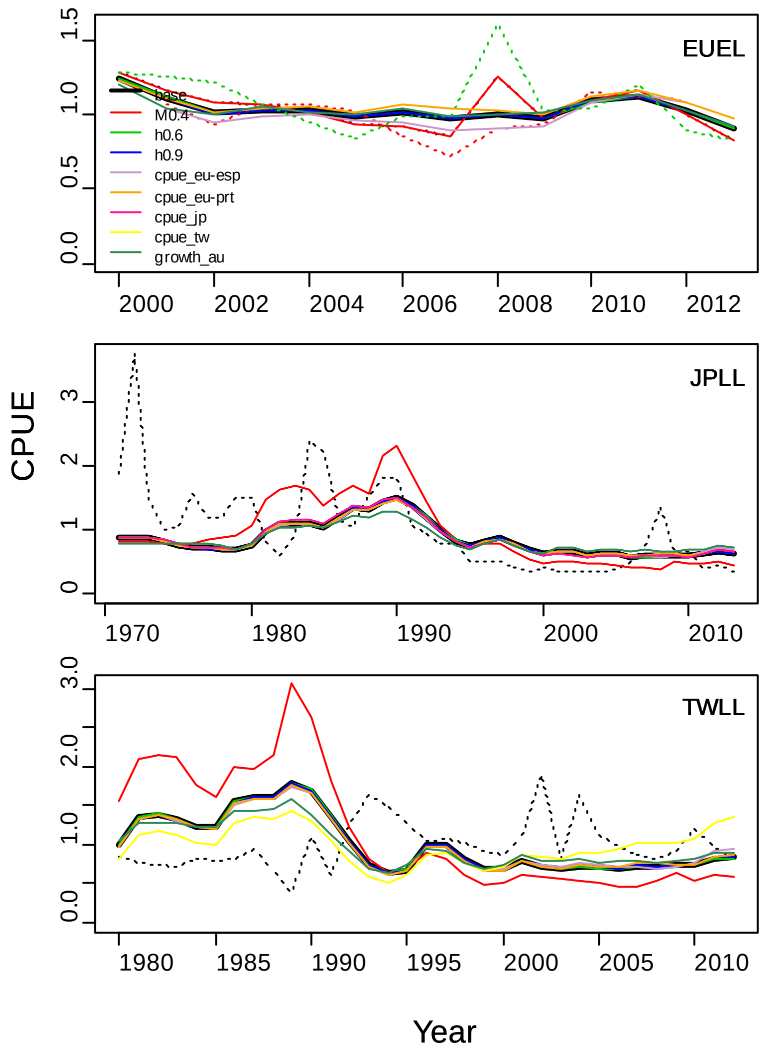


Fig. 12 Standardized observed CPUE (dotted lines) and model-estimated CPUE (solid lines) of swordfish in the southwestern Indian Ocean. Red and green dotted lines are Spanish and Portuguese observed CPUEs, respectively.

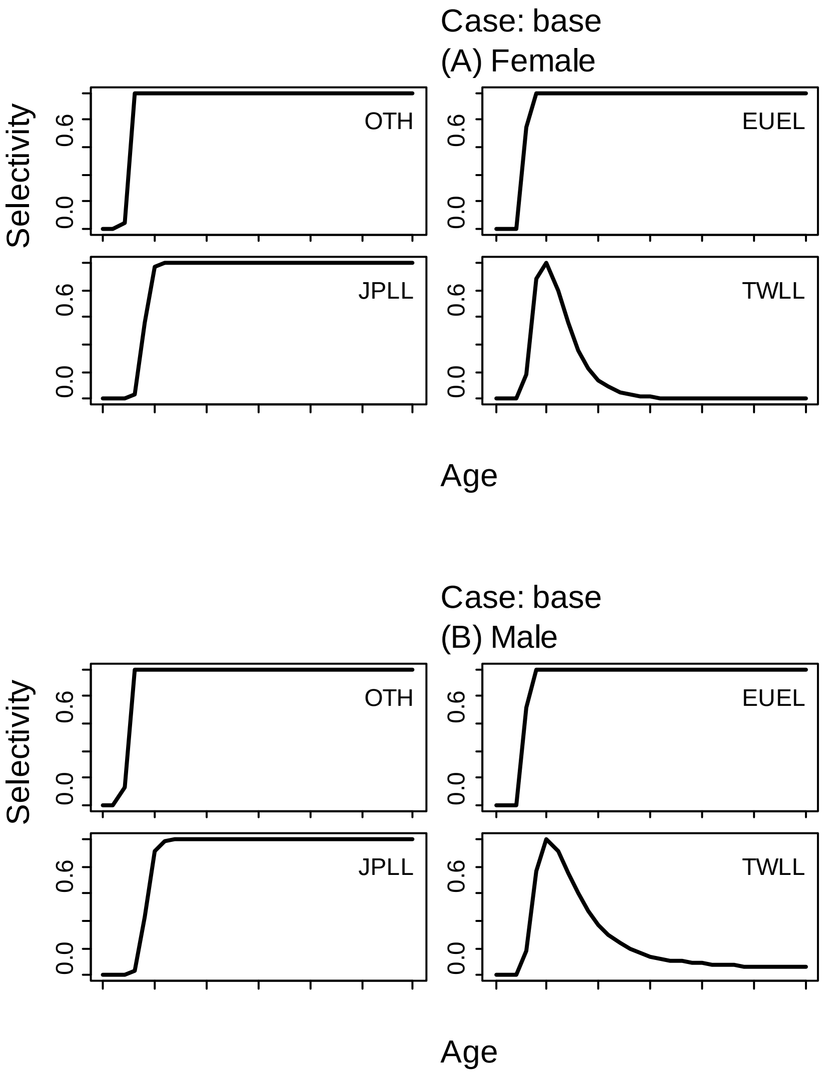


Fig. 13. Model-estimated selectivity curves for swordfish in the southwestern Indian Ocean based on the base-case assessment.

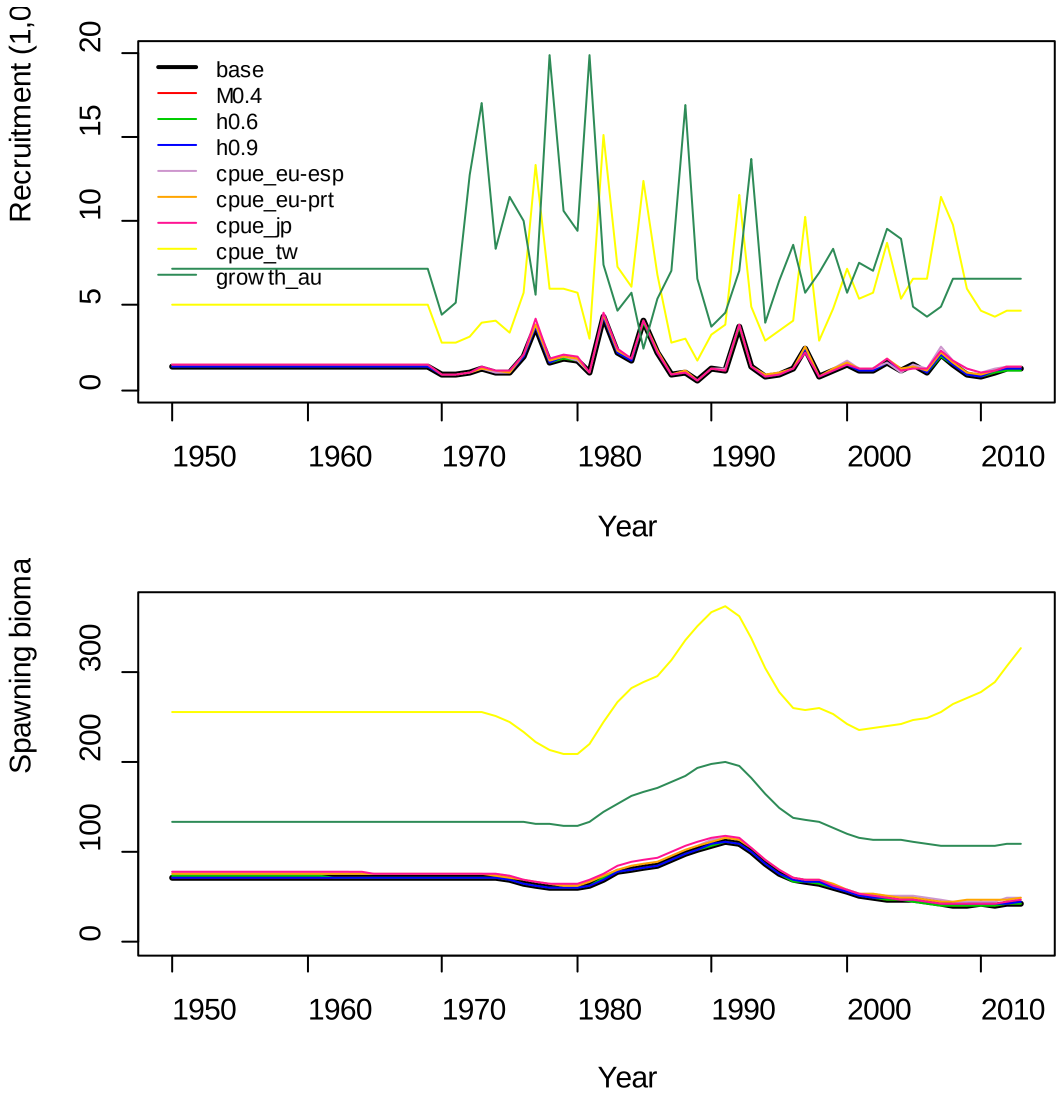


Fig. 14. Time trajectories of MPD estimates for recruitment the spawning biomass of swordfish in the southwestern Indian Ocean.

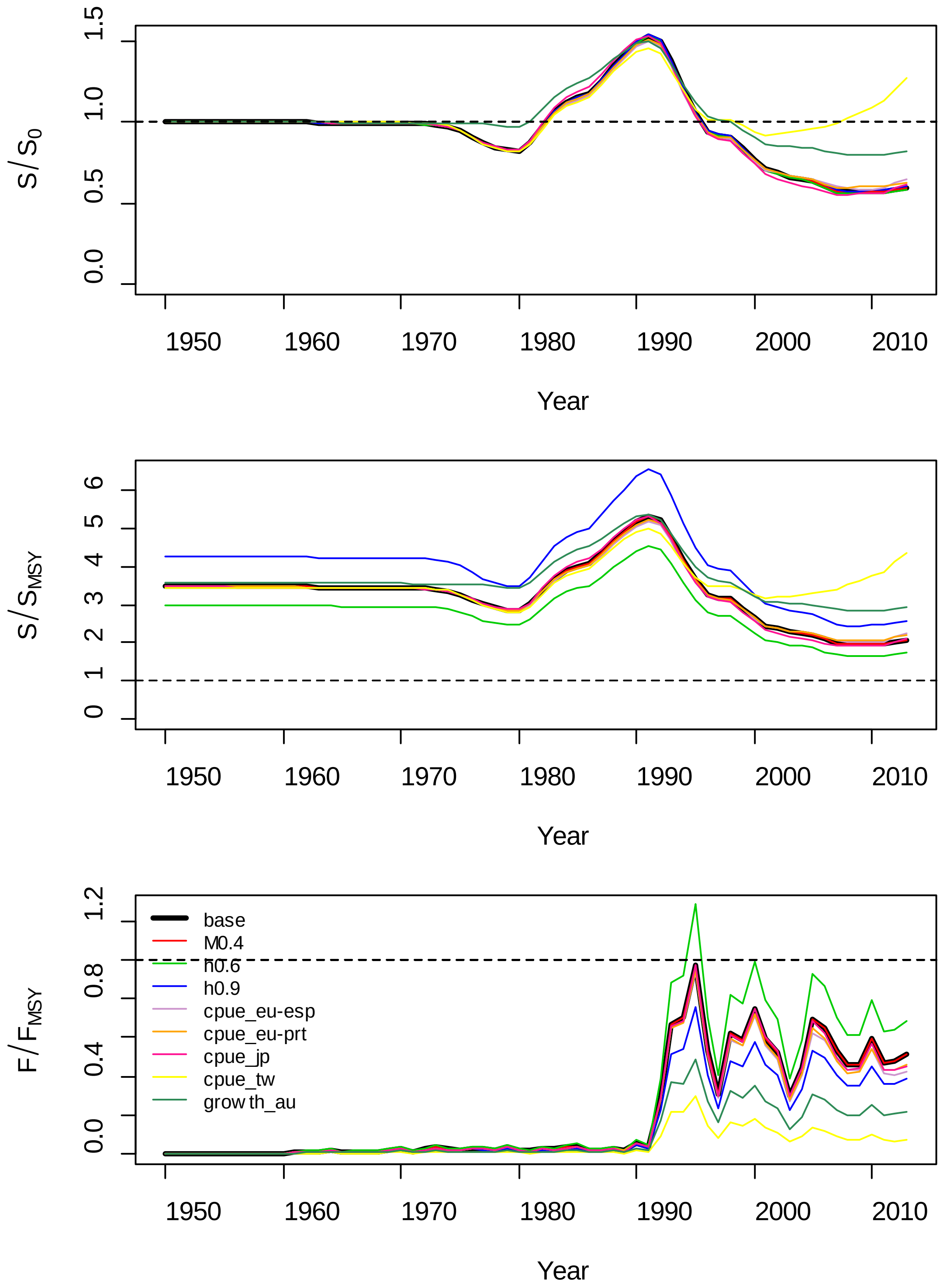


Fig. 15. Time trajectories of MPD estimates for the spawning biomass as a ratio of the unexploited spawning biomass (S/S_0), the spawning biomass as a ratio of S_{MSY} (S/S_{MSY}) and the fleet-aggregated fishing intensity as a ratio of that at which MSY is achieved (F/F_{MSY}) for swordfish in the southwestern Indian Ocean.

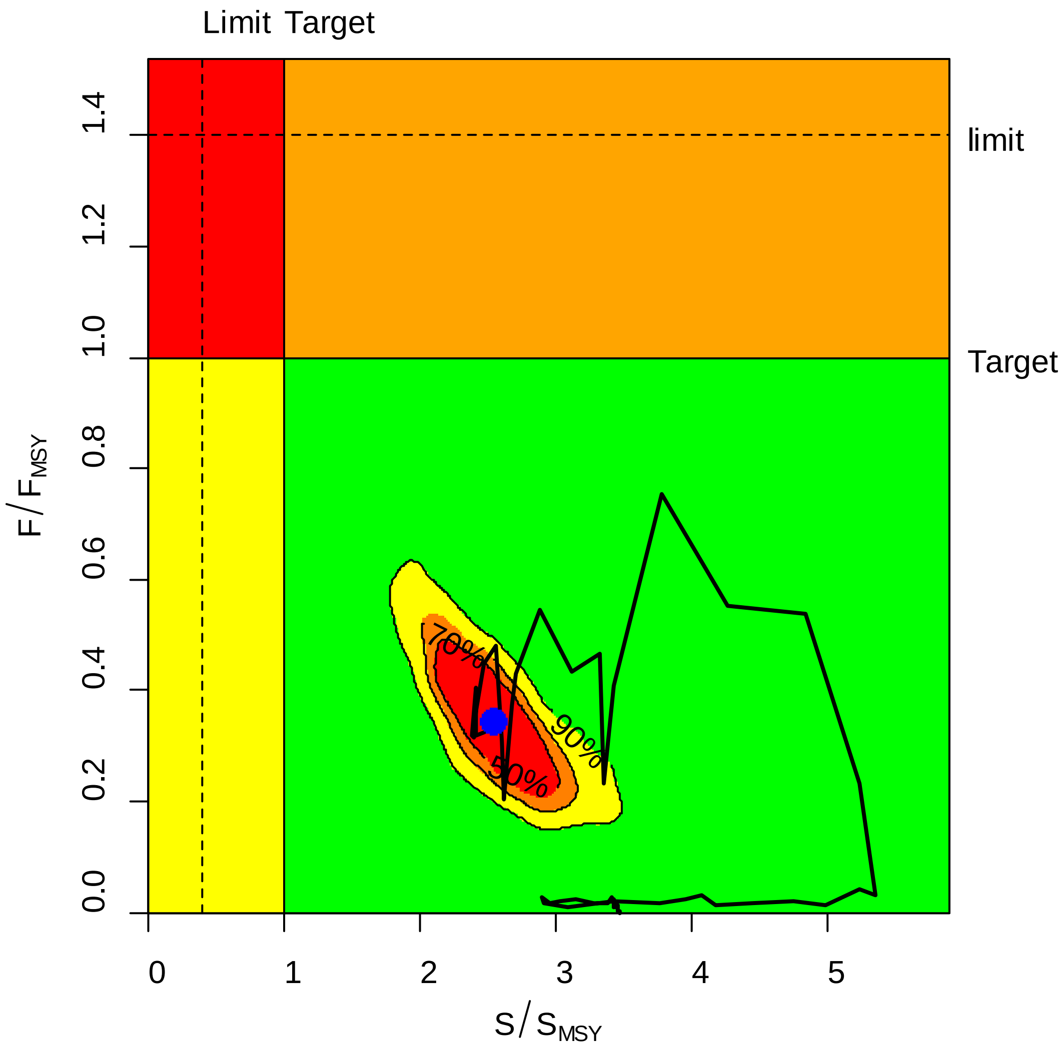


Fig. 16. Kobe plot for swordfish in the southwestern Indian Ocean based on base-case assessment. The trajectories were calculated based on the median of 1000 re-samplings of Bayesian posterior distribution. Blue circles indicate the estimates in 2013.

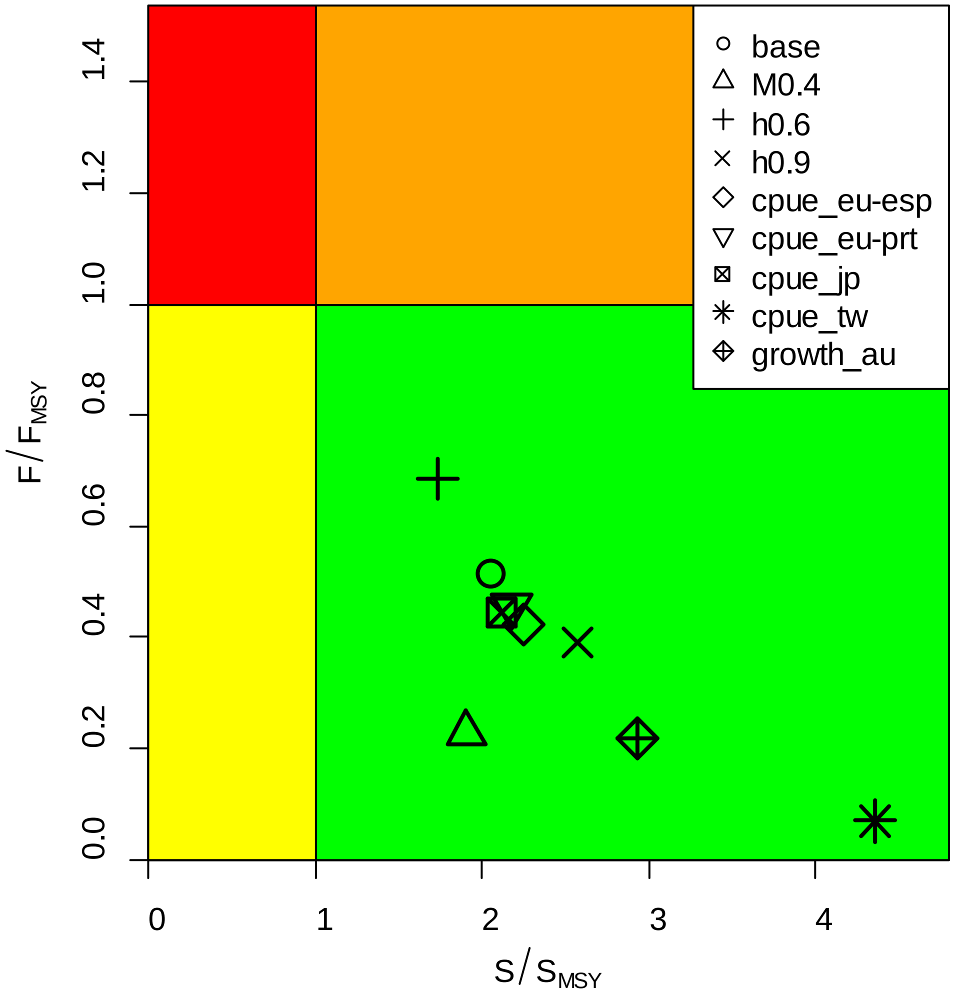


Fig. 17. Kobe plot for swordfish in the southwestern Indian Ocean based on the MPD estmates in current year for all scenarios.

Table 1. Definition of the fleets operating in the Indian Ocean and the data availability for each fleet in the period of 1950-2013.

			Data availability		
Fleet	Area	Fleet code	Catch	Length-frequency	CPUE
Gillnet, trolling and other minor artisanal fleets	All	ALGI	✓	✓	-
Longline fishery of Australia	All	AUEL	✓	✓	-
Semi-industrial longline fleets of France-Reunion, France-Mayotte, Madagascar, Mauritius and the Seychelles	All	ISEL	✓	✓	-
Fresh-tuna longline fleets of Taiwan and Indonesia, plus other fresh-tuna longline fleets assimilated to those and all sport fisheries and fleets operating hand lines	All	TWFL	✓	✓	-
Longline fleets of EU (from Spain, Portugal and the UK), plus other longliners assimilated to EU longliners	All	EUEL	✓	✓	✓
Longline fishery of Japan plus other fleets assimilated to the Japanese fleet (e.g. South Korea, Thailand, Oman)	NE	JPLL_NE	✓	✓	✓
	SE	JPLL_SE	✓	✓	✓
	NW	JPLL_NW	✓	✓	✓
	SW	JPLL_SW	✓	✓	✓
Large scale tuna longline fleet of Taiwan,China, plus other longline fleets assimilated to the Taiwanese fleet	NE	TWLL_NE	✓	✓	✓
	SE	TWLL_SE	✓	✓	✓
	NW	TWLL_NW	✓	✓	✓
	SW	TWLL_SW	✓	✓	✓

Table 2. Definition of the fleets operating in the southwestern Indian Ocean and the data availability for each fleet in the period of 1950-2013.

Fleet	Area	Fleet Code	Data availability		
			Catch	Length-frequency	CPUE
All fleets in southwestern Indian Ocean other than Japanese, Taiwanese and EU longline fleets	SW	OTH	✓	✓	-
Longline fleets of EU (from Spain, Portugal and the UK)	SW	EUEL	✓	✓	✓
Longline fleets of Japan	SW	JPLL	✓	✓	✓
Longline fleet of Taiwan	SW	TWLL	✓	✓	✓

Table 3. The biological parameters of length-weight relationships, von Bertalanffy growth curve, and maturity and age for swordfish in the Indian Ocean.

Parameter	Females	Males
Asymptotic size, L_∞ (cm)	274.86	234.00
Growth parameter, K (year^{-1})	0.1377	0.1694
Age-at-zero-length, t_0 (year)	-1.9975	-2.1809
Length-weight, A	9.133x10^{-6}	9.133x10^{-6}
Length-weight, B	3.012	3.012
Maturity slope, r_m	0.0953	-
Length-at-50%-maturity, L_m (cm)	170.4	-
Maximum age, λ (year)	25	25

Source: Poisson and Fauvel (2009) and Wang et al. (2010).

Table 4. The parameters of the population dynamics model not known from auxiliary Information.

Parameter	No. of parameters
Unfished recruitment, R_0	1
Process errors, v_t	1 per year from 1980 to 2012
Selectivity	
Dome-shaped	
Length-at-100%-selectivity, a_1	1 per fleet with dome-shaped selectivity
Shape parameter for left limb, s_L	1 per fleet with dome-shaped selectivity
Shape parameter for right limb, s_R	1 per fleet with dome-shaped selectivity
Logistic curve	
Length-at-50%-selectivity, L_{50}^f	1 per fleet with logistic selectivity
Length-at-95%-selectivity, L_{95}^f	1 per fleet with logistic selectivity

Table 5. Scenarios conducted for sensitivity analysis.

Scenario	Code	Description
Base-case	base	M=0.25, h=0.75, and all CPUE used
1	M0.4	M=0.4
2	h0.6	h=0.6
3	h0.9	h=0.9
4	cpue_eu-esp	ESP CPUE treated as EU CPUE
5	cpue_eu-prt	PRT CPUE treated as EU CPUE
6	cpue_jp	Ony JPN CPUE used
7	cpue_tw	Ony TWN CPUE used
8	growth_au	Growth patterns from AU

Table 6. The estimates of key management quantities for aggregated Indian Ocean based on various scenarios.

Scenario	code	R_0	MSY	S_{MSY}	F_{MSY}	S_{2013}/S_0	S_{2013}/S_{MSY}	F_{2013}/F_{MSY}
Base-case	base	3,744	23,399	54,693	0.23	0.66	2.30	0.83
1	M0.4	21,906	60,442	77,446	0.30	0.85	3.12	0.29
2	h0.6	3,877	19,657	66,527	0.17	0.66	1.97	1.06
3	h0.9	3,660	27,055	42,675	0.30	0.66	2.87	0.65
4	cpue_eu-esp	3,794	23,712	55,415	0.23	0.69	2.42	0.74
5	cpue_eu-prt	3,870	24,185	56,571	0.23	0.69	2.40	0.76
6	cpue_jp	4,218	26,352	61,778	0.23	0.69	2.40	0.65
7	cpue_tw	4,251	26,522	62,212	0.23	0.87	3.02	0.59
8	growth_au	12,481	28,215	64,014	0.21	0.78	2.82	0.60

Table 7. The estimates of key management quantities for southwest Indian Ocean for various scenarios.

Scenario	code	R_0	MSY	S_{MSY}	F_{MSY}	S_{2013}/S_0	S_{2013}/S_{MSY}	F_{2013}/F_{MSY}
Base-case	base	1,418	8,856	20,869	0.20	0.59	2.06	0.51
1	M0.4	10,343	28,654	37,459	0.24	0.53	1.90	0.23
2	h0.6	1,422	7,211	24,393	0.15	0.58	1.73	0.69
3	h0.9	1,419	10,446	17,031	0.26	0.60	2.57	0.39
4	cpue_eu-esp	1,514	9,451	22,309	0.20	0.65	2.25	0.42
5	cpue_eu-prt	1,497	9,344	22,062	0.20	0.63	2.18	0.46
6	cpue_jp	1,515	9,441	22,351	0.20	0.61	2.12	0.45
7	cpue_tw	5,034	31,227	74,833	0.21	1.27	4.36	0.07
8	growth_au	7,227	16,212	37,585	0.19	0.82	2.93	0.22

Table 8. The estimates of key management quantities for aggregated Indian Ocean and southwest Indian Ocean based on the base-case assessment.

Management Quantity	Aggregate Indian Ocean	Southwest Indian Ocean
2013 catch estimate	31,804	7,349
Mean catch from 2009–2013	26,510	7,265
MSY (1000 t) (80% CI)	23.40 (20.0–26.80)	8.86 (7.27–10.44)
F_{MSY} (80% CI)	0.23 (0.19–0.26)	0.20 (0.19–0.21)
SB_{MSY} (1000 t) (80% CI)	54.69 (46.59–62.80)	20.87 (17.09–24.65)
F_{2013}/F_{MSY} (80% CI)	0.83 (0.68–1.00)	0.51 (0.36–0.65)
SB_{2013}/SB_{MSY} (80% CI)	2.30 (2.04–2.56)	2.06 (1.71–2.41)
SB_{2013}/SB_{1950}(80% CI)	0.66 (0.58–0.73)	0.59 (0.49–0.70)