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The application of an age-structured assessment model to swordfish (*Xiphias gladius*) in the Indian Ocean

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ABSTRACT

This study evaluated the stock status of swordfish in the Indian Ocean based on the age-structured integrated approach (ASIA). Since local depletion occurred for swordfish in the southwestern Indian Ocean in recent years, this study also attempted to evaluate the status for the stock only in the southwestern Indian Ocean. Based on the results of this study, the current stock status for the entire Indian Ocean might not be overfishing or overfished though various results resulted from different assumptions of pre-specified biological parameters. However, the results indicated that the status of the stock in the southwestern region is probably not in a health condition but the assessment results are very sensitive to the assumption of steepness. The stock status could shift from optimistic condition with a high reproductive assumption to pessimistic condition with a low reproductive assumption. The results of projection analysis indicated that there is a very probability of the spawning biomass dropping bellows < S_{MSY} and the probability of the fishing intensity exceeding above F_{MSY} even with a 40% increase in catch.

INTRODUCTION

Swordfish in the Indian Ocean (*Xiphias gladius*) was historically taken mainly by Japan and Taiwan, 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 and exploitation of semi-industrial longline and artisanal fisheries (Fig. 1 and Table 1). 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 25,000 tonnes. 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).

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 is the first attempt to fit an assessment model to all the fishery and biological data to estimate exploitation rates, recruitment, and biomass.

Swordfish in the Indian Ocean are known to be sexually dimorphic (Wang et al., 2010). Wang et al. (2005 and 2007) also showed using simulation and sensitivity analyses that ignoring sex-structure when conducting population model-based stock assessments can lead to biased results while the estimations of relative management quantities remains robust. Owing to the absence of sex-specific data of catch and length-frequency for swordfish in the Indian Ocean, however, we attempt to modify the age-structured assessment model conducted by Wang et al. (2005) and Wang et al. (2007) for applying to the swordfish in the Indian.

MATERIALS AND METHODS

Data used

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. 2). No catch of semi-industrial longline fleets of France-Reunion, France-Mayotte, Madagascar, Mauritius and the Seychelles occurred in the northeastern area (SE). The data used for assessment are the catches, length–frequencies, and CPUE-based indices of abundance (Table 1).

The historical catches in weight and length-frequency are available for all fisheries and these data were reported to Indian Ocean Tuna Commission (IOTC) by each fishery (Table 1). Generally, the time series of the length-frequency data for these 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 of Taiwanese (1995-2009), Japanese (1980-2009), Spanish (2001-2006) and Reunion (1994-2000) longline fisheries. The CPUEs were standardized using General Linear Model (GLM) (see Kolody et al. (2010), Nishida et al. (2011), Ramos-Cartelle et al. (2011) and Wang and Nishida (2011) for details).

For assessment of swordfish in the southwestern Indian Ocean, the data of fisheries in area SW are only used to fit to the model.

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 2.

Assessment model

The population dynamics model developed by Wang et al. (2005) and Wang et al. (2007) was used in this study. The model was modified by eliminating the sex-structured factors from the model. This model considers the lifespan of swordfish from age 0 to 10 (age 10 being treated as a ‘plus group’). 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 relationship between sex-ratio and length from Wang et al. (2010) was used to calculate female abundance for estimating spawning biomass (eq. (A.10) in Wang et al. (2007)). The recruitment deviations for the years prior to 1980 are all set to zero due to insufficient length frequency data which could inform year-class strength for these years whereas those for the years after 1980 are treated as parameters of the assessment model with a penalty based on the distributional assumption.

The logistic curve, which assumes that the vulnerability of a fish increases monotonically to an asymptote with increasing length, is commonly used in fisheries stock assessment models to represent selectivity for longline gear. For most fisheries, however, few swordfish with length larger than 200 cm were caught (Fig. 4) and the assumption that selectivity follows a logistic curve might be inadequate. In this study, therefore, the selectivities were assumed to be dome-shaped curve (represented by a normal distribution) for all fleets.

Parameter estimation

The parameters of the model can be divided into those for which auxiliary information is available (Table 2) and those which need to be estimated from the monitoring data (Table 3). 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 in the Indian Ocean, *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.

The objective function was minimized to find the estimates of the estimated parameters of the model. The objective function combines the likelihoods for the CPUE and length-frequency data, and the penalty for the annual recruitment deviates. The model is implemented using AD Model Builder (version 9.0.x).

Sensitivity analyses

Sensitivity is examined to the value assumed for natural mortality M (0.2 year^{-1} and 0.3 year^{-1}), that assumed for the steepness of the stock-recruitment relationship *h* (0.6, 0.8 and 0.95)..

For each scenario, *MSY*-based reference points are and fleet-aggregated fishing intensity (defined as the ratio of total catch to exploitable biomass, see Wang et al. (2005) for details) were examined for sensitivity analyses.

Projection

The objective of the forward projection and risk analysis is to examine the future status of the population for a variety of situations and potential future management actions. This study exams the risk related to the probability of the spawning biomass dropping below S_{MSY} and the probability of the fishing intensity exceeding above F_{MSY} for five constant catch levels, i.e. current catch level (2009; i.e. 0% change), catches 20% and 40% less than current and catches 20% and 40% above current catch, reported for 3 year and 10 years in the future.

The analyses are based on 1000 simulations, each of which involves randomly selecting a parameter vector from the posterior distribution to account for uncertainty about model parameters, and generating future deviations about the stock-recruitment relationship to allow for uncertainty in future recruitment. The posterior distributions are constructed based on samples generated by conducting 1,100,000 cycles of the Markov Chain Monte Carlo (MCMC) algorithm, ignoring the first 100,000 cycles as the "burn in" period, and selecting every 1000th parameter vector thereafter.

RESULTS AND DISCUSSION

Assessment for entire Indian Ocean

Fig. 3 shows the fits of the model to the observed CPUE data. Based on the results of base-case, the model cannot fitted to Japanese CPUEs in the west areas very well because these CPUEs changed sharply since the mid of 1990s, while catchabilities were assumed to be constant over time for each fleet.

The observed and the model estimated length frequencies aggregated across years are shown in Fig. 4. In substance, the model estimated length-frequencies mimics the observed length frequency data well for all fleets. The model estimated selectivites are shown in Fig. 5. The gillnet, trolling, artisanal fleets, EU fleets in the northern areas and semi-industrial longline fleet in the northern west area tend to select smaller fishes than other fleets.

Fig. 6 shows the time trajectories of MPD estimates for S_{current}/S_0, $S_{\text{current}}/S_{MSY}$ and $F_{\text{current}}/F_{MSY}$ for base-case analysis. 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. In recent three years, the estimates of fleet-aggregated fishing intensity has decreased to about 60-80% of F_{MSY} and the spawning biomass maintained at about 140% of S_{MSY}, while the depletion of spawning biomass (S_{current}/S_0) was still under a relatively low level of about 30% of S_0.

The results of sensitivity analyses are listed in Table 4. Based on the different assumptions related to M and h, the results indicated that current fishing intensity was about 60-80% of F_{MSY} and the spawning biomass maintained at the level above S_{MSY}. The results are sensitive to the value of h. The most pessimistic stock status occurred when assuming a relative low value of h (low reproductive assumption), while the most optimistic status occurred when assuming a relative high value of h (high reproductive assumption). Based on the Kobe plot, however, the results of this study indicated that the status of swordfish in the Indian Ocean might not be under an overexploitation condition (Fig. 7). The estimates of quantities of management interest based on the base-case are summarized in Table 6.

Assessment for southwestern Indian Ocean

Similar to the result of the assessment for entire Indian Ocean, the model generally fits to the length frequency and CPUE data well, except for Japanese CPUE before the mid 1990's (Figs. 8 and 9). Based on the estimates of selectivity, Japanese longline fleet tented to catch larger fishes (Figs. 9 and 10).

The time trajectories of MPD estimates for S_{current} / S_0, $S_{\text{current}}/S_{MSY}$ and $F_{\text{current}}/F_{MSY}$ for base-case analysis indicated that substantial increasing catch since the early 1990's led to the increasing of fishing intensity and decreasing of spawning biomass (Fig. 11). Recently, fishing intensity might have exceeded the F_{MSY} level and spawning biomass might have decreased to the level under S_{MSY}.

Similarity, the assessment results are very sensitive to the assumed value of *h*. Although the results of most cases reveal pessimistic stock status, assuming a high value of *h* (high reproductive assumption) could obtain an optimistic result (Fig. 12 and Table 5). The estimates of quantities of management interest are summarized based on the base-case in Table 6.

Projection

In this study, the projection analysis only performed based on the base-case. The results indicated that the probability of the spawning biomass dropping below S_{MSY} and the probability of the fishing intensity exceeding above F_{MSY} for could be ignored over next 10 years under current catch level or under the catch with 20% and 40% decreases. Even with a 40% increase in catch, the probability the spawning biomass dropping below S_{MSY} and the probability of the fishing intensity exceeding above F_{MSY} are only about 5.6% and 7.4%, respectively (Table 7).

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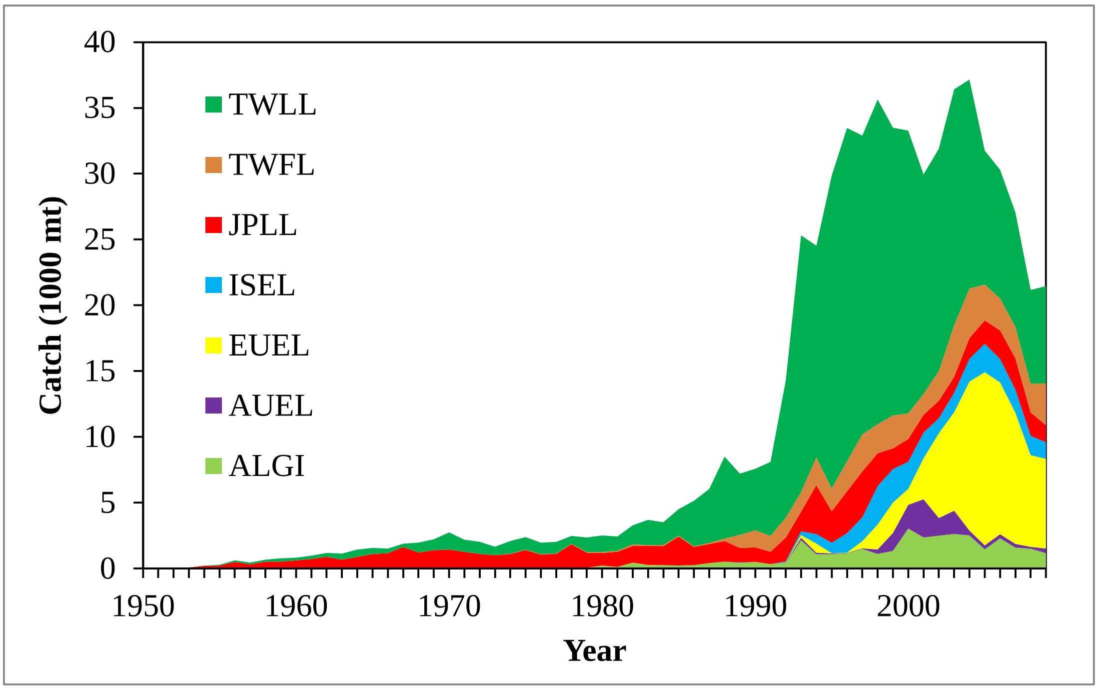

Fig. 1. Annual nominal catches (NC) of swordfish in the Indian Ocean from 1950 to 2008.

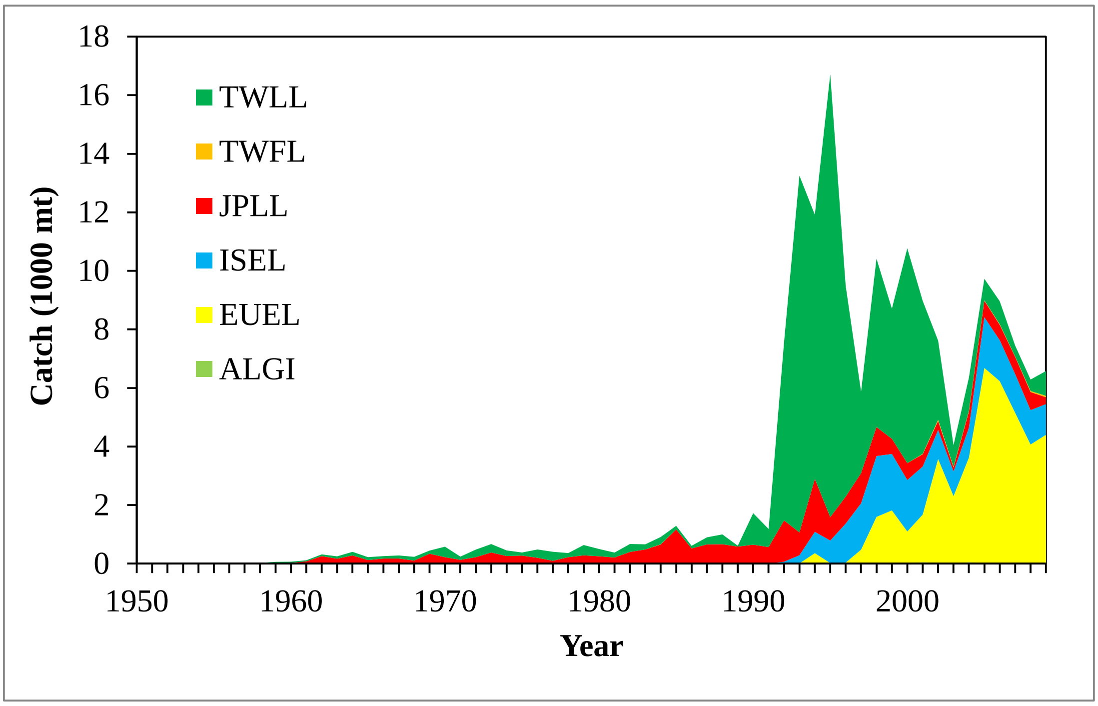

Fig. 2. Annual nominal catches (NC) of swordfish in the southwestern Indian Ocean from 1950 to 2008.

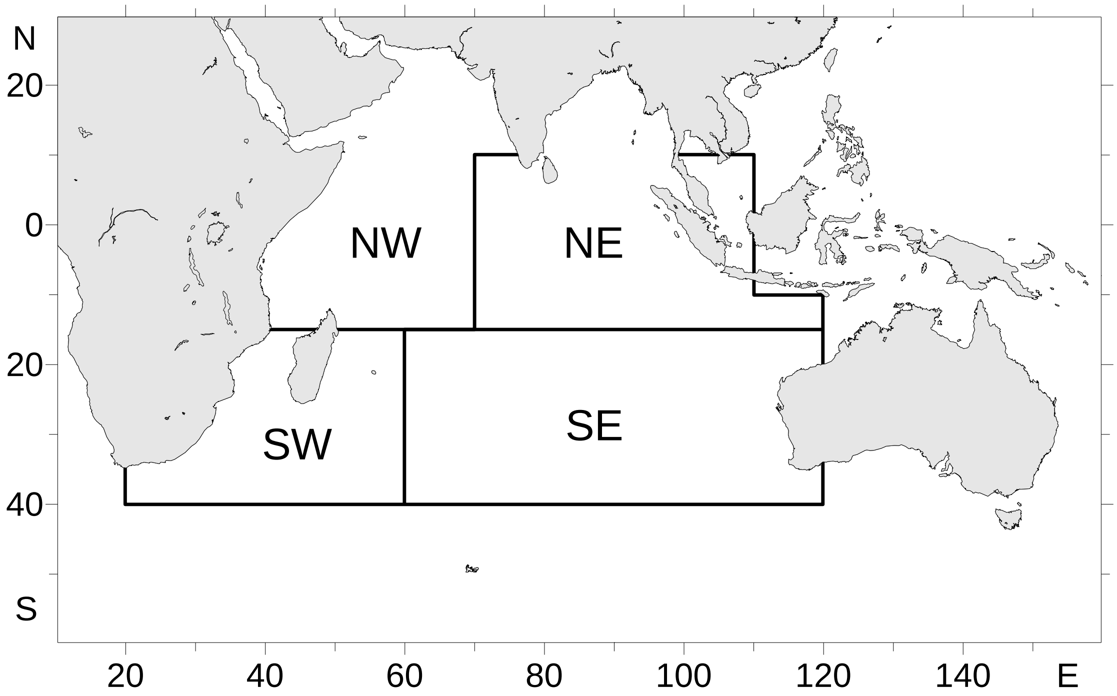

Fig. 2. The definition of areas used in the analyses for swordfish in the Indian Ocean.

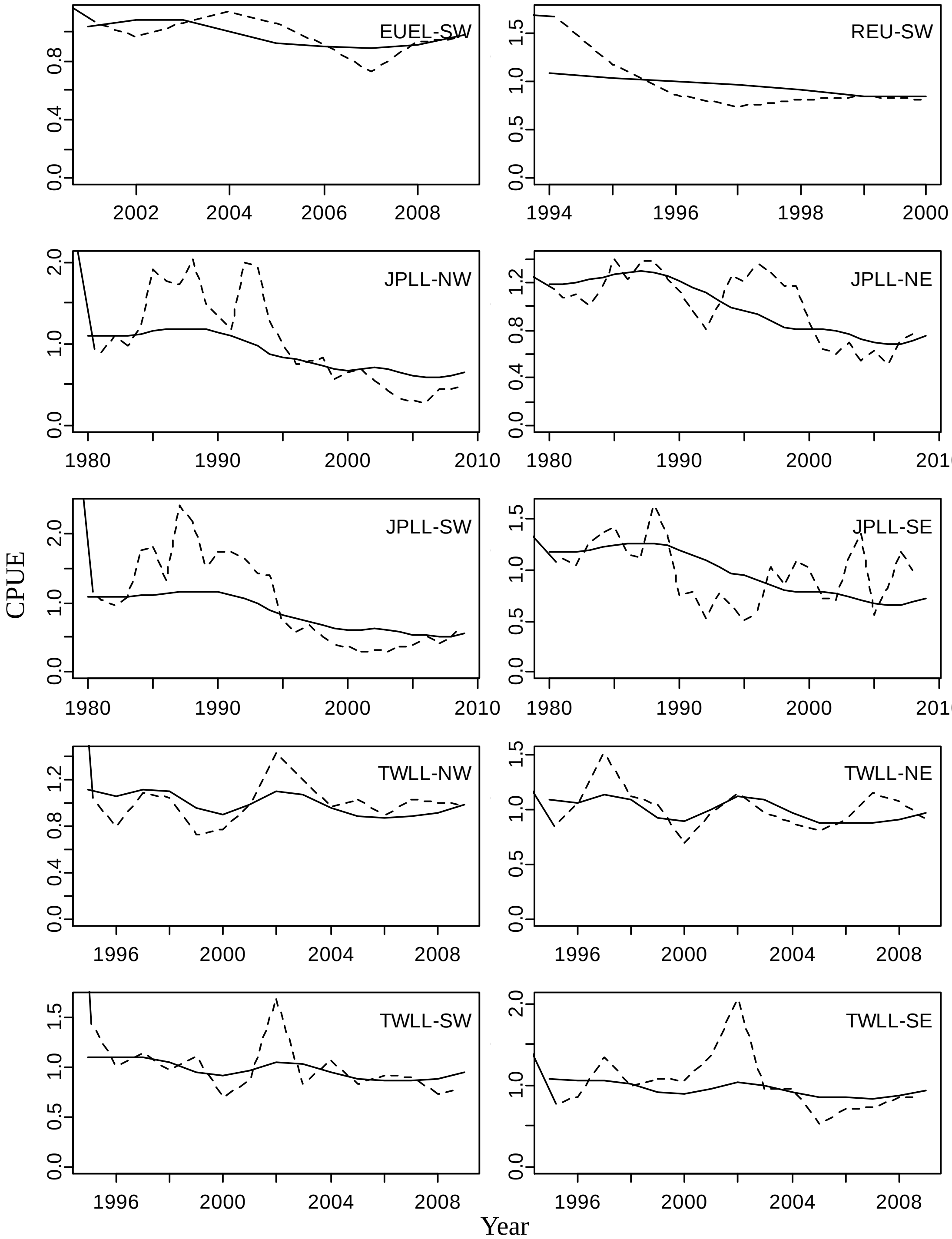

Fig. 3. Standardized observed CPUE (dot lines) and model-estimated CPUE of swordfish in the Indian Ocean based on the base-case analysis (solid lines).

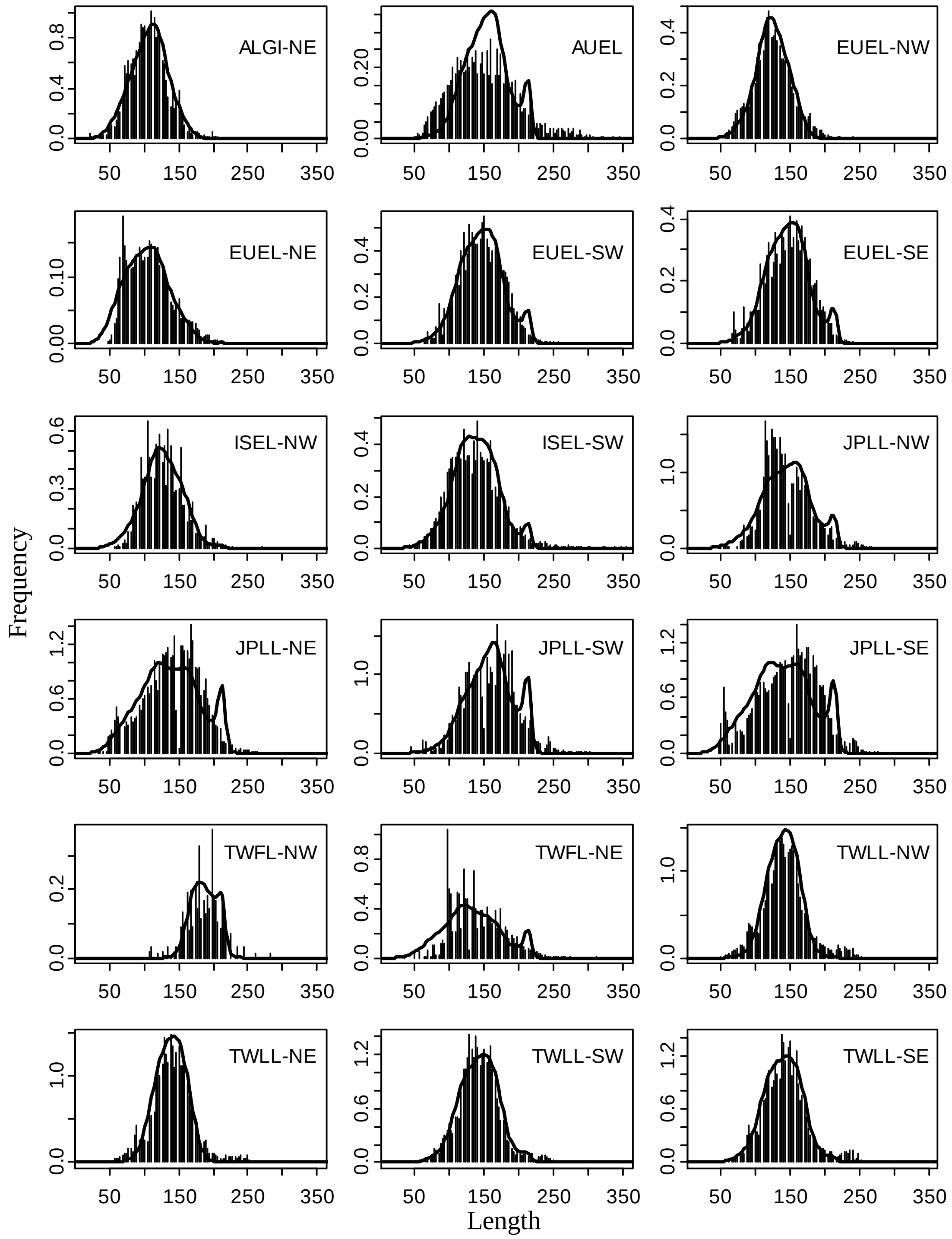

Fig. 4. Observed (histograms) and model-estimated (lines) length-frequencies of swordfish in the Indian Ocean based on the base-case analyses.

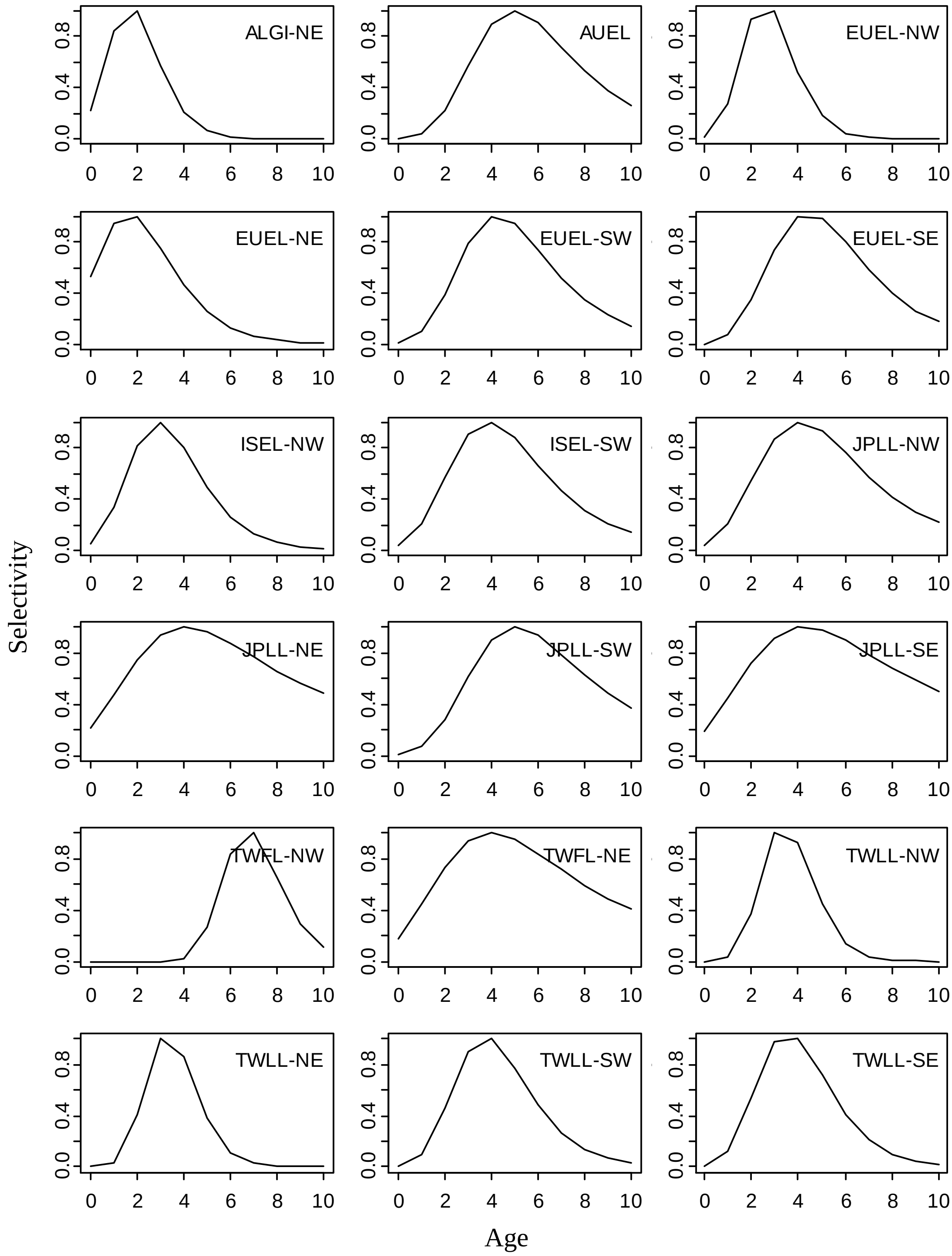

Fig. 5. Model-estimated selectivity curves for swordfish in the Indian Ocean based on the base-case analysis.

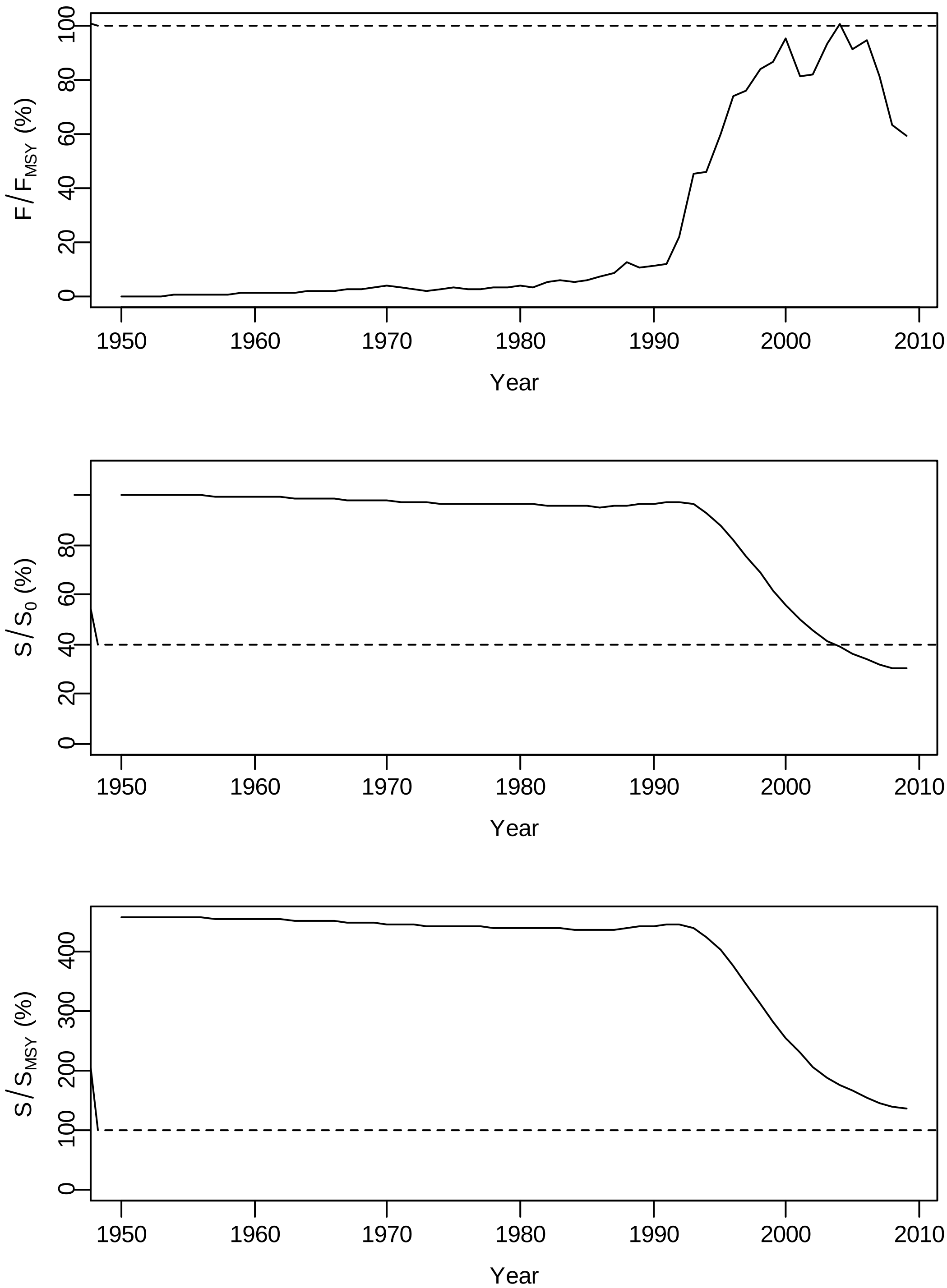

Fig. 6. Time trajectories of MPD estimates for the spawning biomass as a ratio of the unexploited spawning biomass (S_{2008} /S_0), the spawning biomass as a ratio of S_{MSY} (S_{2008}/S_{MSY}) and the fleet-aggregated fishing intensity as a ratio of that at which *MSY* is achieved (F_{2008}/F_{MSY}) for swordfish in the Indian Ocean based on the base-case analysis.

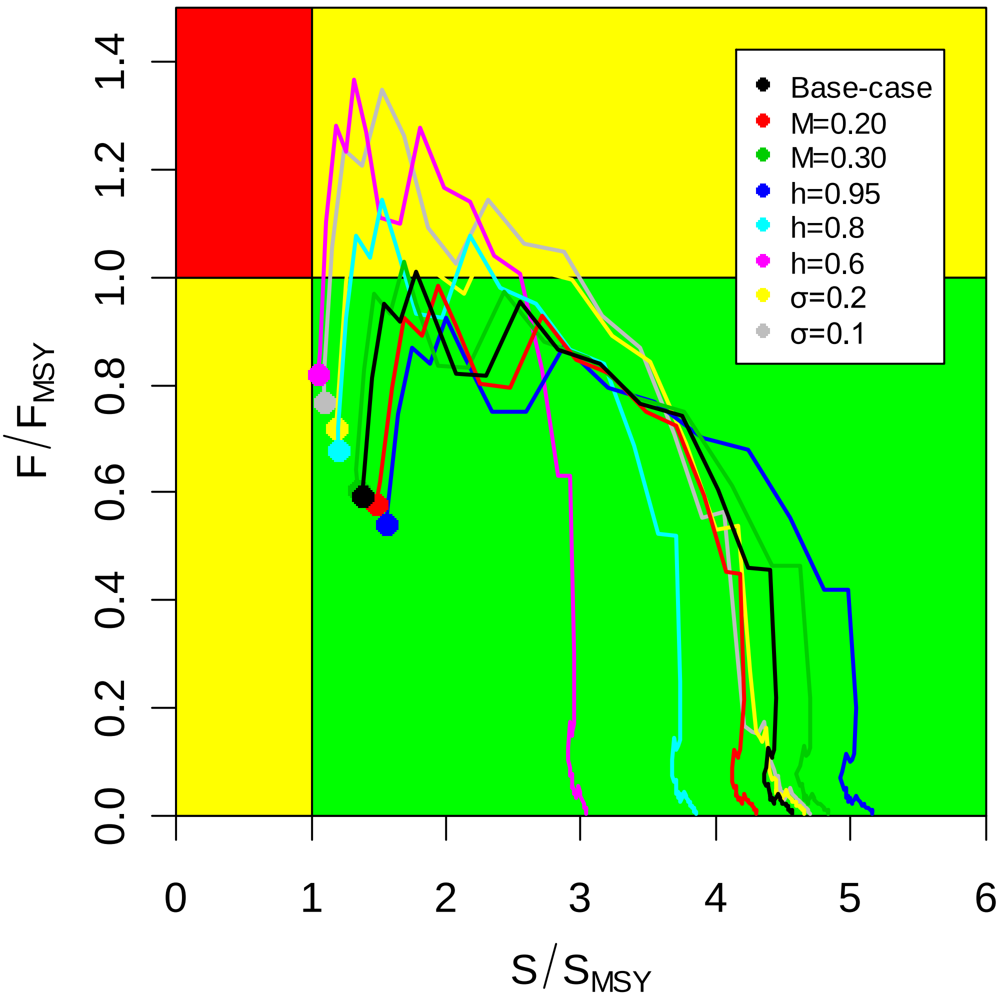

Fig. 7. Kobe plot for swordfish in the Indian Ocean based on different assumptions of natural mortality and stepness of the stock-recruitment relatonship.

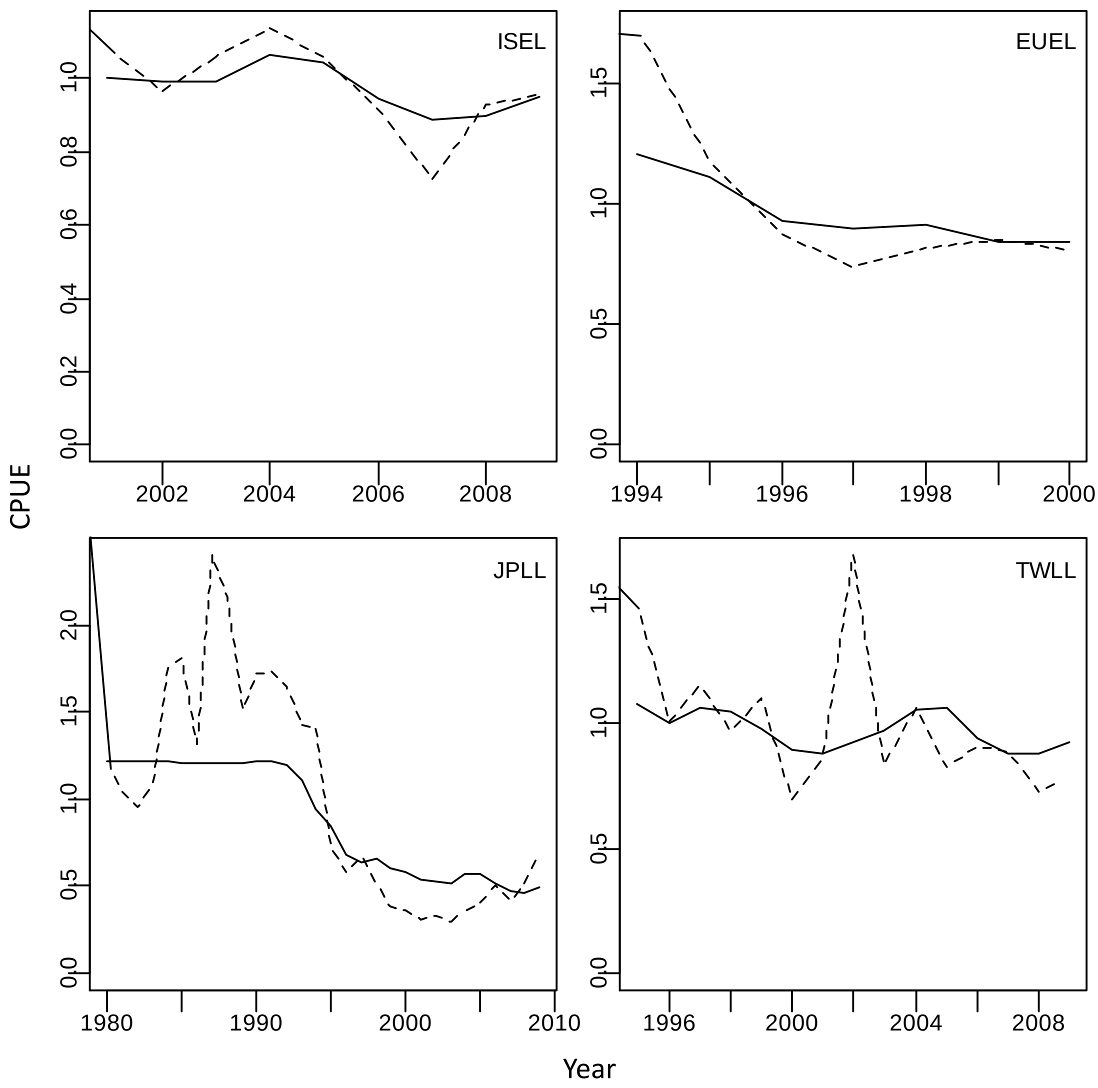

Fig. 8. Standardized observed CPUE (dot lines) and model-estimated CPUE of swordfish in the southwestern Indian Ocean based on the base-case analysis (solid lines).

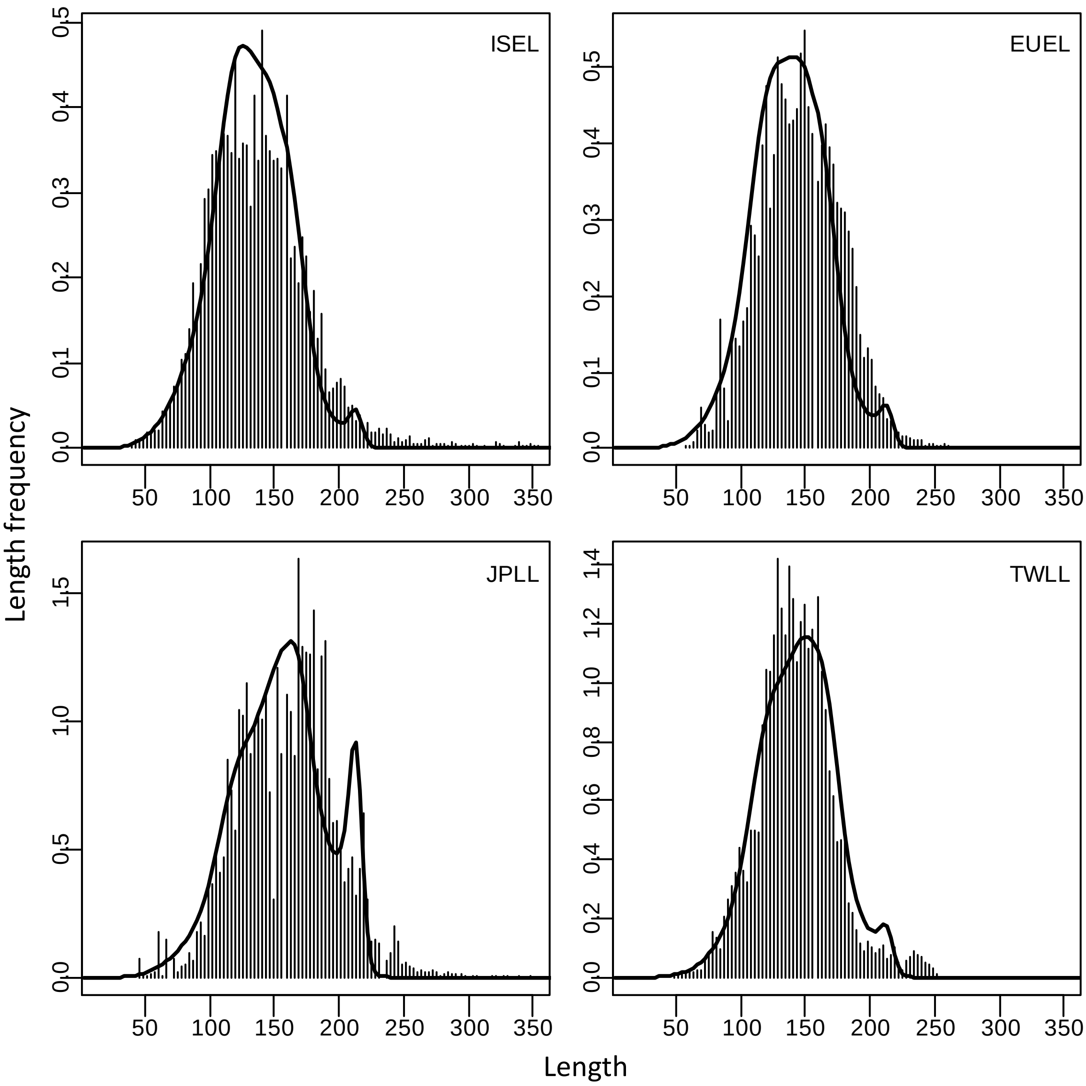

Fig. 9. Observed (histograms) and model-estimated (lines) length-frequencies of swordfish in the southwestern Indian Ocean based on the base-case analyses.

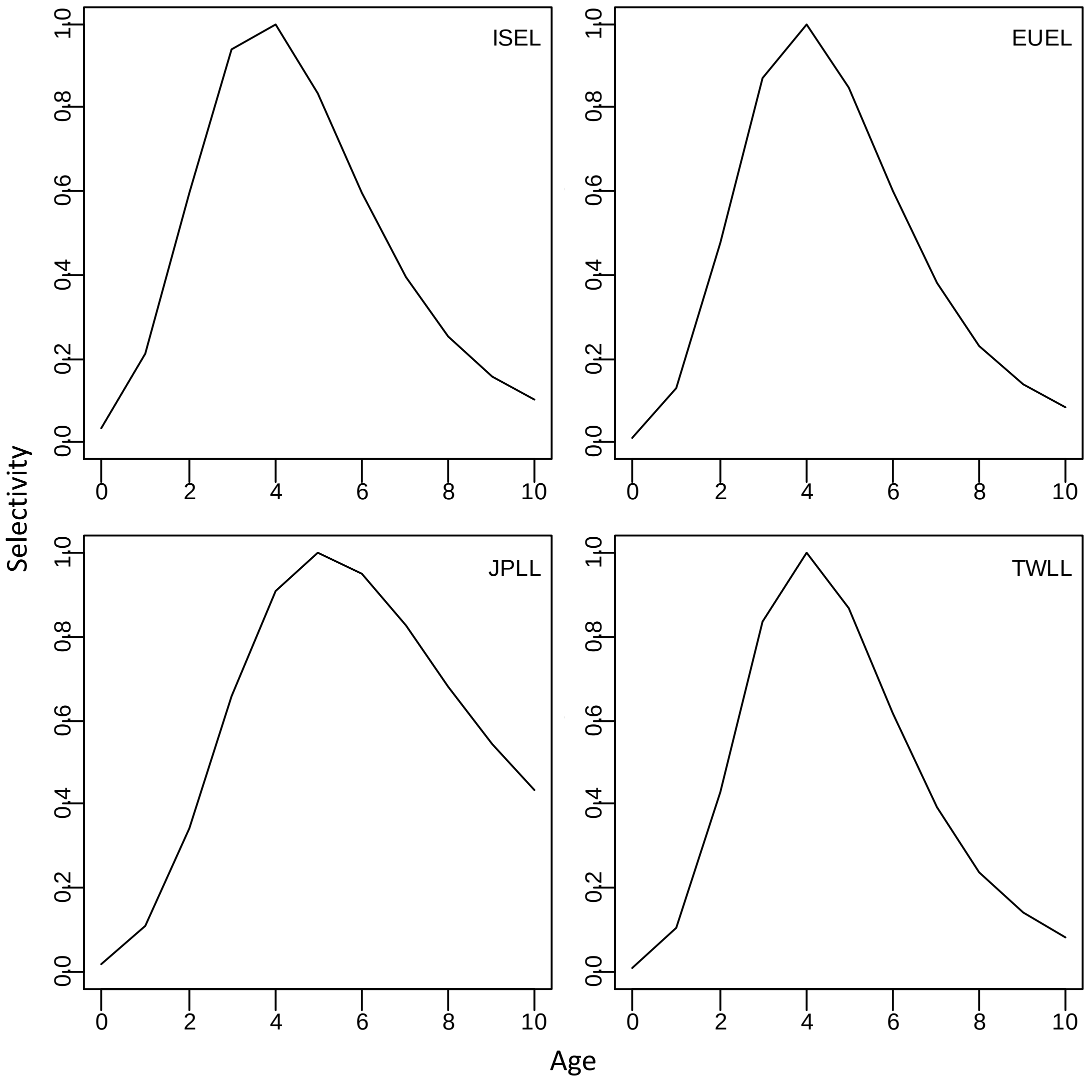

Fig. 10. Model-estimated selectivity curves for swordfish in the southwestern Indian Ocean based on the base-case analysis.

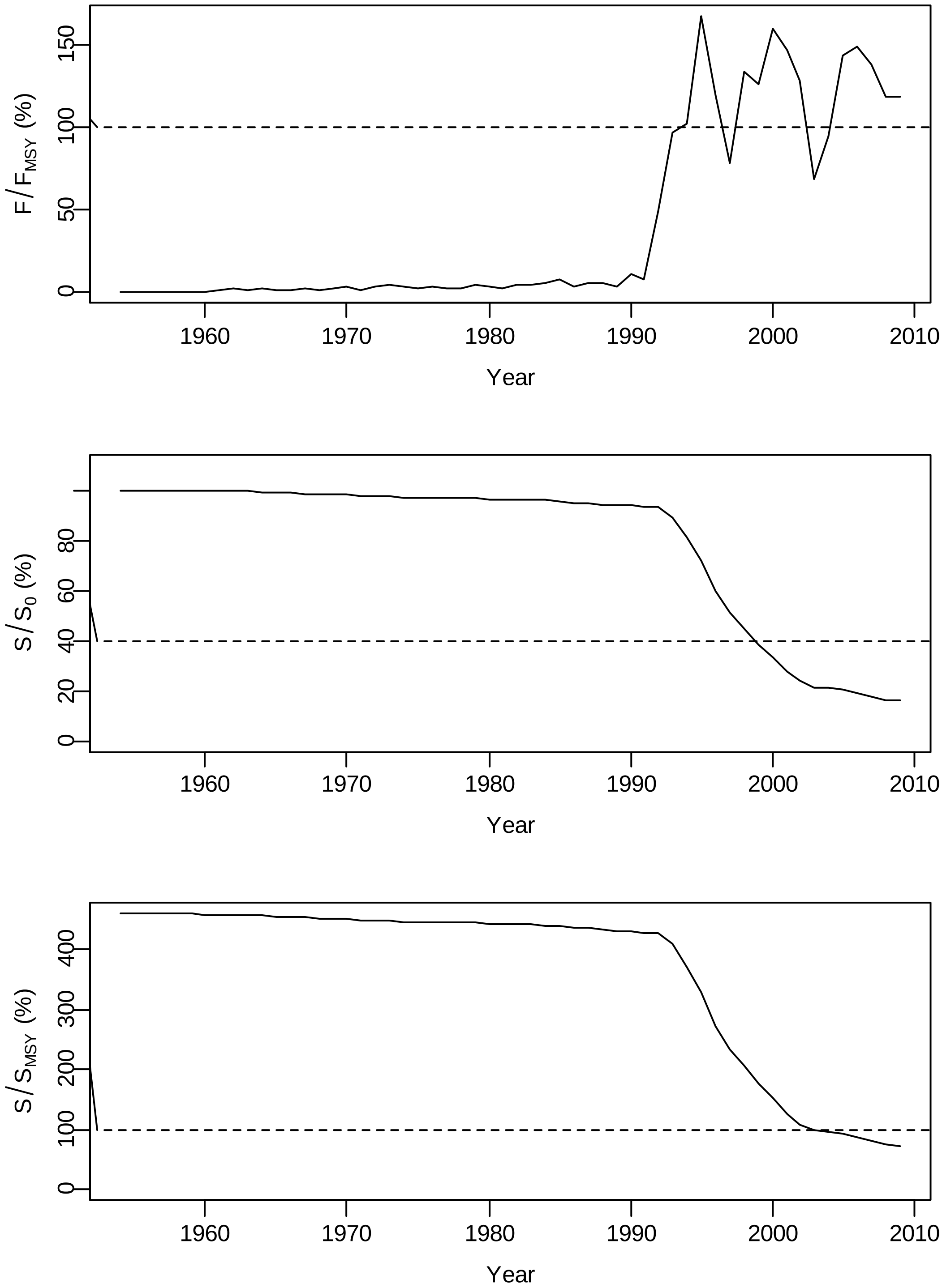

Fig. 11. Time trajectories of MPD estimates for the spawning biomass as a ratio of the unexploited spawning biomass (S_{2008} /S_0), the spawning biomass as a ratio of S_{MSY} (S_{2008}/S_{MSY}) and the fleet-aggregated fishing intensity as a ratio of that at which *MSY* is achieved (F_{2008}/F_{MSY}) for swordfish in the southwestern Indian Ocean based on the base-case analysis.

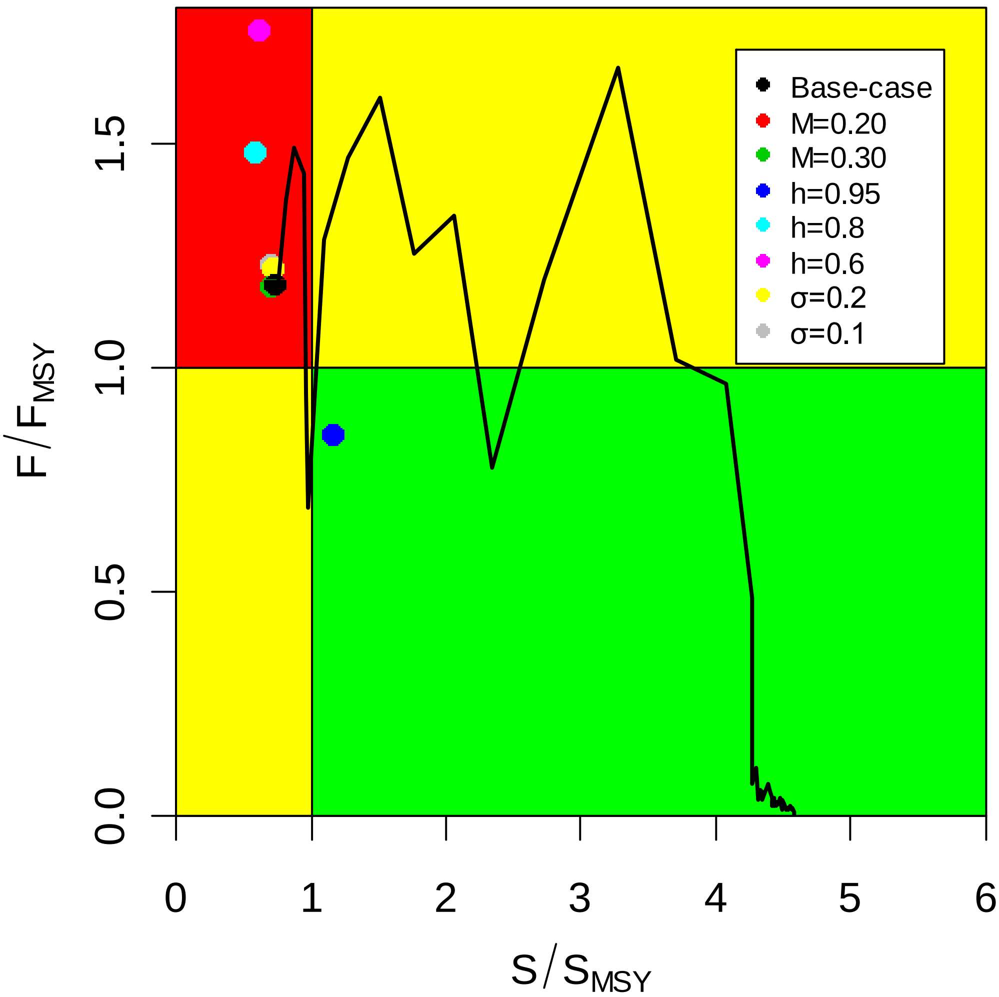

Fig. 12. Kobe plot for swordfish in the southwestern Indian Ocean based on different assumptions of natural mortality and stepness of the stock-recruitment relatonship.

Table 1. Definition of the fleets operating in the Indian Ocean and the data availability for each fleet in the period of 1950-2009.

Fleet	Fleet Code	Area	Catch data	Length data	CPUE
Gillnet, trolling and other minor artisanal fleets	ALGI	NW	✓	-	-
		NE	✓	✓	-
		SW	✓	-	-
		SE	✓	-	-
Longline fishery of Australia	AUEL	SE	✓	✓	-
Longline fleets of EU (from Spain, Portugal and the UK)	EUEL	NW	✓	✓	-
		NE	✓	✓	-
		SW	✓	✓	✓
		SE	✓	✓	-
Semi-industrial longline fleets of France-Reunion, France-Mayotte, Madagascar, Mauritius and the Seychelles	ISEL	NW	✓	✓	-
		SW	✓	✓	✓
		SE	✓	-	-
Longline fleets of Japan	JPLL	NW	✓	✓	✓
		NE	✓	✓	✓
		SW	✓	✓	✓
		SE	✓	✓	✓
Fresh-tuna longline fleets of Taiwan and Indonesia, and sport and hand line fleets	TWFL	NW	✓	✓	-
		NE	✓	✓	-
		SW	✓	-	-
		SE	✓	-	-
Longline fleet of Taiwan	TWLL	NW	✓	✓	✓
		NE	✓	✓	✓
		SW	✓	✓	✓
		SE	✓	✓	✓

Table 2. 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)	10	10

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

Table 3. The parameters of the population dynamics model not known from auxiliary Information.

Parameter	No. of parameters
Estimated	
Unfished recruitment, R_0	1
Process errors, v_t	1 per year from 1980 to 2009
Selectivity	
Dome-shaped	
Length-at-mean-selectivity, L^f_{mu}	1 per fleet, expect for the AUEL, JPLL and TWFL
Standard deviation of selectivity, L^f_{sd}	1 per fleet, expect for the AUEL, JPLL and TWFL
Logistic curve	
Length-at-50%-selectivity, L^f_{50}	1 per fleet for the AUEL, JPLL and TWFL
Length-at-95%-selectivity, L^f_{95}	1 per fleet for the AUEL, JPLL and TWFL
Pre-specified	
Natural mortality, M	1
Steepness, h	1
Variation in recruitment, σ_v	1

Table 4. The value of the MPD estimates of the quantities of management interest for swordfish in the Indian Ocean based on the base-case analysis and sensitivity analyses.

	MSY	$S_{current}/S_0$	$S_{current}/S_{MSY}$	$F_{current}/F_{MSY}$
Base-case	34203	0.301	1.376	0.595
M = 0.20	34628	0.343	1.474	0.580
M = 0.30	33838	0.278	1.346	0.605
h = 0.95	35685	0.300	1.552	0.543
h = 0.8	31899	0.309	1.191	0.678
h = 0.6	28121	0.346	1.053	0.820
σ = 0.2	28487	0.253	1.178	0.722
σ = 0.1	26934	0.233	1.092	0.769

Table 5. The value of the MPD estimates of the quantities of management interest for swordfish in southwestern the Indian Ocean based on the base-case analysis and sensitivity analyses.

	MSY	S_{current}/S_0	$S_{\text{current}}/S_{MSY}$	$F_{\text{current}}/F_{MSY}$
Base-case	7058	0.159	0.727	1.187
M = 0.20	7018	0.198	0.856	1.146
M = 0.30	7124	0.144	0.694	1.180
h = 0.95	7805	0.226	1.147	0.851
h = 0.8	6645	0.149	0.577	1.483
h = 0.6	5966	0.197	0.599	1.751
σ = 0.2	6404	0.153	0.703	1.221
σ = 0.1	6249	0.151	0.696	1.228

Table 6. Aggregate Indian Ocean Stock status summary table (based on the base-case).

Management Quantity	Aggregate Indian Ocean	SW Region Only
Most recent catch estimate (t)	25255	7787
Mean catch over last 5 years (t)	31002	9176
MSY (t)	34203	7058
Current Data Period	1950-2009	1954-2009
F(Current)/F(MSY)	0.595	1.187
B(Current)/B(MSY)	1.177	0.823
SB(Current)/SB(MSY)	1.376	0.727
B(Current)/B(0)	0.420	0.299
SB(Current)/SB(0)	0.301	0.159
B(Current)/B(Current, F=0)	-	-
SB(Current)/SB(Current, F=0)	-	-

Table 7. Kobe 2 Strategy Matrix for Aggregate Indian Ocean (based on the base-case).

	Constant Catch Level (relative to 2009)				
Probability	**60%**	**80%**	**100%**	**120%**	**140%**
B(2012) <B(MSY)	0.008	0.012	0.021	0.026	0.037
F(2012) >F(MSY)	0.000	0.000	0.001	0.017	0.062
B(2019) <B(MSY)	0.000	0.000	0.003	0.016	0.056
F(2019) >F(MSY)	0.000	0.000	0.002	0.029	0.074