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A Flexible Spatially-Disaggregated Production Model for Exploratory Assessment of Indian Ocean Swordfish

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Introduction

A number of surplus production models were fit to Indian Ocean broadbill swordfish catch and CPUE data as a first attempt at a formal model-based stock assessment at the 5th IOTC Working Party on Billfish (Anon. 2006). These models yielded plausible inferences about the impact of the swordfish fishery on the whole of the Indian Ocean population. In 2008, the WPB will attempt to update the assessment and explore methodological refinements in relation to data and insight acquired since 2006. This paper briefly describes some of the evidence available to consider whether spatial disaggregation is appropriate for the Indian Ocean swordfish assessment, and discusses some modeling options that might be feasible within the timeframe of the WPB in 2008. The deterministic Spatially-Disaggregated Pella-Tomlinson (SDPT) production model might prove useful for a preliminary assessment of the Indian Ocean swordfish population if there is distinct spatial structure. Whether or not the model proves useful will depend primarily on:

1) informative relative abundance indices (standardized CPUE) need to be generated for the individual spatial areas (as do catch series)
2) The populations need to conform to the dynamic assumptions of the deterministic production models (e.g. particularly recruitment should not show very high, or temporally correlated regime shift type dynamics).
3) Migration dynamics should not have a strong element of interannual variability (e.g. driven by IOO or ENSO events)

It is hoped that a set of models can be explored at the 2008 WPB meeting.

Spatial considerations for the assessment

In the South-West Pacific, a number of lines of evidence were examined in relation to the spatial boundaries and stock connectivity to be used in the assessment (Kolody and Davies 2008). A brief attempt was made to consider similar evidence in the Indian Ocean:

- Genetic studies – these studies are often conflicting, and the absence of evidence from a particular genetic analysis does not mean that the populations are homogenously mixed, but might simply mean that the sampling design and markers examined were not sensitive enough to detect differences). Lu et al

(2006) describe mitochondrial DNA evidence for three possible population delineations within the Indian Ocean (but recognize that increased sample sizes would be desirable). These populations are roughly indicated in Figure 1. J. Bourjea (pers. comm.) has indicated that a separate study with larger sample sizes has also found Indian Ocean population structure and noted that further collaborative work is being undertaken in this direction.

- Larval distributions (and adult spawning activity) – discrete areas of swordfish spawning and larvae might indicate preferable spawning regions. However, these studies do not indicate the degree of mixing between populations, either of foraging grounds or among spawning grounds. In the Indian Ocean, a large continuous larval distribution in the eastern Indian Ocean is described in Nishikawa et al (1985) (Figure 2), unfortunately, other regions of the Indian Ocean were not as heavily sampled.

- Catch demographics – fishery catch characteristics typically provide considerable insight into population dynamics. Size, sex and maturity distributions will probably provide some evidence about the importance of an area for spawning or foraging. Differences among areas in the interannual trends in size composition and catch rates (seasonally standardized) might help to demonstrate whether adjacent regions are highly mixed or not. CPUE and size trends that are consistent across broad areas might indicate that populations are well mixed, but it might also mean that the production dynamics and fishery trends are consistent across vast areas (e.g. fishers might pursue the Ideal Free Distribution, and decrease global abundance of separate stocks at a comparable rate). Nishida et al (2008) describe preliminary work in catch rate standardization.

- Tagging studies – These studies potentially provide the strongest and most direct evidence for movement rates among populations. Unfortunately, we are aware of a very few tag releases and recaptures in the Indian Ocean. It would be worth acquiring whatever tagging data are available for the Indian Ocean and producing a qualitative synthesis of movements.

The SDPT model can (or should be modifiable within the duration of the IOTC WPB to) represent any of the situations defined in Figure 3:

1) one or more discrete stocks (the simplest and typical application of production models)
2) two or more populations that are produced from a common spawning ground, but have foraging grounds site fidelity (i.e. while this is a single population genetically, depletion can differ in different regions at different rates)
3) two or more populations have distinct spawning grounds, but may be mixed on foraging grounds and caught in a common fishery. This latter version of the model has not been tested within the software at present, but should represent a straightforward extension.

The Fletcher-Pella-Tomlinson Surplus Production Model

Any stock assessment modeling exercise involves consideration of the optimal model complexity for the problem. A model that is too simple will tend to have statistical biases (e.g. resulting from the aggregation of non-homogenous components), while more realistic models will tend to have high statistical estimation variance, because there is not enough data to precisely estimate all of the required parameters. It is currently unclear whether there is enough size data in the Indian Ocean swordfish fisheries to justify the fitting of a fully age-structured model, and this should be reviewed at the 2008 WPB for future consideration. There are however sufficiently plausible catch data and standardized catch rate indices to suggest that fishing is having an impact on the stock, and it seems feasible to at least attempt to quantify this impact with simple production models. If there are effectively distinct sub-populations within the Indian ocean, (or relatively slow mixing rates within a genetically homogenous population), then an aggregated assessment will probably not adequately describe the fishery impact on the different regions (i.e. there could be localized populations that are over-fished relative to the average of the Indian Ocean).

Most dynamic stock assessment models are based on the very simple idea that we can describe dynamic changes in a fish population using simple arithmetic:

$$\begin{aligned} Number_{year=t+1} = {} & Number_t - Catch_t - NaturalDeaths_t + recruits_{t+1} \\ & - immigration_t + emigration_t \end{aligned}$$

This basic equations can rapidly get complicated when we try to keep track of different portions of the population that act differently (e.g. age-structure, sex composition, spatial structure, etc), impose theoretical constraints (e.g. stock recruitment curves), and statistical structure (e.g. describing stochastic relationships between reality and observations). The equations of the Spatially-disaggregated Pella-Tomlinson (SDPT) model are presented below. In this case, the equation above are simplified somewhat, because natural mortality, recruitment and growth processes are combined into a single density-dependent term (production).

A slightly modified version of the SDPT model as described below was applied to SW Pacific swordfish stocks in 2006. The general inferences and uncertainties from the modelling exercise were very similar to the results of fully integrated assessments (Multifan-CL and CASAL) conducted at the same time (Kolody et al 2006). The deterministic version of the Pella-Tomlinson model (Pella 1993, Fletcher 1978) is modified below to include three spatial regions (though it is flexible and can represent an arbitrary number of spatial units). Production models are generally based on biomass, but our initial exploratory version was based on numbers, the units most commonly recorded for swordfish longline fisheries catch and catch rate standardization. Production models are based on the simple ecological idea that the growth rate of a population is 0 when the population is equilibrated in an unfished state (without this carrying capacity concept, populations would grow exponentially forever), the production is also 0 when the population is 0 (you need parents to produce offspring). Somewhere between a population of zero and carrying capacity, production peaks, with the level of productivity and shape of the peak are determined by life history and fishery characteristics.

Production is essentially intended to account for increase in numbers due to recruitment, loss in numbers due to natural mortality (and growth in the case of a biomass model). Production (*P*) for a given year is determined by the current level of depletion of the stock, and the production curve parameters:

$$P_{t+1} = N_t^{total} + \gamma C_{\max} N_t^{total} - \gamma C_{\max}\left(\frac{(N_t^{total})^n}{K^{n-1}}\right),$$

where:

P_t = surplus production in year t

t = year index

N_t^{total} = number of swordfish in year t

K = population size before fishing (carrying capacity)

$C_{\max}$ = maximum sustainable catch (numbers) expressed as a proportion of K

n, γ = parameters controlling the shape of the production curve, such that

$$\gamma = \frac{n^{n/(n-1)}}{n-1}.$$

N_t is the aggregate population size over all areas. This assumes that all (or a constant proportion) of the total population is available to the spawning area each year. The productivity (hereafter often referred to, for simplicity, as new recruits) is distributed among the regions according to:

$$N_{t,r}^{BM} = N_{t-1,r}^{BM} + d_r P_{t,r},$$

where:

r = region (1-3),

$N_{t,r}^{BM}$ = number of swordfish in region r at time t, before migration and catch extraction

d_r = the proportion of recruitment occurring in region r.

Migration takes place after the recruitment process, and before the catch is removed. We adopted the implicit method of differentiation (as used in MultiFan-CL, Kleiber et al 2005) to approximate the instantaneous transfer between regions. The implicit method is very similar to the explicit method when transfer rates are small, but is much more numerically stable when transfers are large. Migration is described by:

$$N_t^{AM} = B^{-1} N_{t-1}^{BM}$$

where:

N_t^{AM} = the vector of numbers in each region r at time t, *After Migration*, but before catch extraction

B = the matrix of transfer co-efficients (for a 3 area model):

$$B = \begin{bmatrix} 1 + m^{12} + m^{13} & -m^{21} & -m^{31} \\ -m^{12} & 1 + m^{21} + m^{23} & -m^{32} \\ -m^{13} & -m^{23} & 1 + m^{31} + m^{32} \end{bmatrix},$$

m^{xy} = the transfer co-efficient describing the net annual migration from region *x* to region *y*.

B^{-1} = the inverse of *B*

Catch extraction occurs after migration:

$$N_{t,r}^{AC} = N_{t,r}^{AM} - C_{t,r} ,$$

where:

$N_{t,r}^{AC}$ = numbers in region *r* at time *t*, after catch extraction

$C_{t,r}$ = catch (numbers) in region *r* at time *t*.

The model is fit to a number of CPUE series, assuming that each is a relative abundance index,

$$CPUE_{t,r}^{\text{pred}} = q_r \tfrac{1}{2}(N_{t,r}^{AM} + N_{t,r}^{AC}) .$$

Where:

$CPUE_{t,r}^{\text{pred}}$ = predicted CPUE at time *t* in region *r*, and

q_r = relative abundance scaling co-efficient for region *r*.

σ_r = standard deviation of the observation errors, and

Observed CPUE is assumed to be related to predicted CPUE by the following:

$$CPUE_{t,r}^{\text{obs}} = CPUE^{pred} \exp(Normal(0, \sigma_r))$$

where:

$CPUE_{t,r}^{\text{obs}}$ = observed CPUE at time *t* in region *r*.

Parameter Estimation

The model is implemented with AD Model Builder software (http://otter-rsch.com/admodel.htm), which allows for efficient function minimization using automatic differentiation, and has a convenient facility for approximating Bayesian posteriors for parameter estimates using Markov Chain Monte Carlo Methods. Fitting consists of minimizing the likelihood-based objective function (finding the best agreement between predicted and observed CPUE):

$$\sum_{r}^{R} \sum_{t}^{T} (\log \sigma + \frac{1}{2\sigma_r^2} (\log(q_r \tfrac{1}{2} (B_{r,t}^{BeforeCatch} + B_{r,t}^{AfterCatch}) / CPUE_{r,t}^{\text{obs}}))^2),$$

In this case, we estimated the carrying capacity of the stock and the standard deviation of the CPUE observation errors as free parameters (*q* was estimated analytically). Previous applications for South-West Pacific swordfish suggested that estimation of the production curve parameters, *n* and *Cmax* indicated a tendency to move into a parameter space that seemed implausible on the basis of life history considerations. Instead, we used life history bounds to illustrate an envelope of plausible productivity characteristics as described in the following section. Uncertainty quantification consisted of generating confidence limits using the multi-variate normal approximation from the inverse Hessian matrix.

Bounding Pella-Tomlinson Productivity Parameters Based on Swordfish Life History Characteristics

The Pella-Tomlinson shape parameters allow one to represent a surplus production curve that can potentially represent the characteristics of a particular fishery better than the Schaefer and Fox models (which are each a unique case of the PT model). In the (spatially-aggregated) 2006 assessment, we defined production curves on the basis of the aggregate production characteristics of fully age-structured population models:

$$N_{t+1,a+1} = N_{t,a} \exp(-M_a - F_{t,a})$$
$$N_{a=0} = SR(SSB_t)$$

Where:

$N_{t,a}$ = Numbers at time *t*, of age-class *a*

M_a = natural mortality of age-class *a* (assumed constant over time)

$SR()$ = stock recruitment relationship where recruitment is a function of spawning biomass (SSB)

$F_{t,a}$ = fishing mortality of age-class *a* in time *t*, such that

$F_{t,a} = Effort_t \cdot S_a$,

S_a = fishery selectivity for age-class *a* (assumed constant over time)

$Effort_t$ = fishing effort at time *t*

$SSB_t^{mass} = \sum_a Maturity(a) AM(a) N_{t,a}^N$ =spawning biomass

$AM(a)$ = the mean mass for a fish of age *a*.

Catch is defined by:

$$C_{t,a}^N = \frac{F_{t,a}}{F_{t,a} + M_{t,a}} N_{t,a} (1 - \exp(-M_a - F_{t,a}))$$

$$C^{mass}_{total,t} = \sum_a AM(a) C^N_{t,a}$$

Where:

$C^N_{t,a}$ = Catch in numbers at time *t*, of age-class *a*.

This is a fairly typical age–structured population representation used as the core of many stock assessment models. If one iterates the model over time with a constant level of fishing effort, it will eventually equilibrate to a constant level of sustainable catch and biomass. Repeating this equilibration at different levels of fishing effort will result in equilibration to different levels of catch and biomass. Table 1 lists the life history parameters (stock recruitment curve functions and natural mortality) roughly corresponding to high and low productivity pelagic fish populations that might plausibly bound the Indian Ocean production models. Maturity and growth parameters were adopted from SW Pacific swordfish characteristics. However we note that there remains large uncertainty about the growth rates, maturity schedules and natural mortality for swordfish. The resulting production curves are illustrated in. Table A2 lists the actual production curve parameters used in the Indian Ocean assessment, and the corresponding curves are illustrated in Figure 4 and Figure 5.

Conclusions

This paper is presented as a basis for discussion, and we would caution that even if concrete defendable proposals for spatial structure can be identified in the WPB, there is no guarantee that a satisfactory assessment can be produced. Deterministic production models are very limited in terms of the dynamics that they can represent. Depending on the outcome of the WPB, it is worth considering more sophisticated modelling approaches in the future and discussion of the types of data that will be required to improve future assessments.

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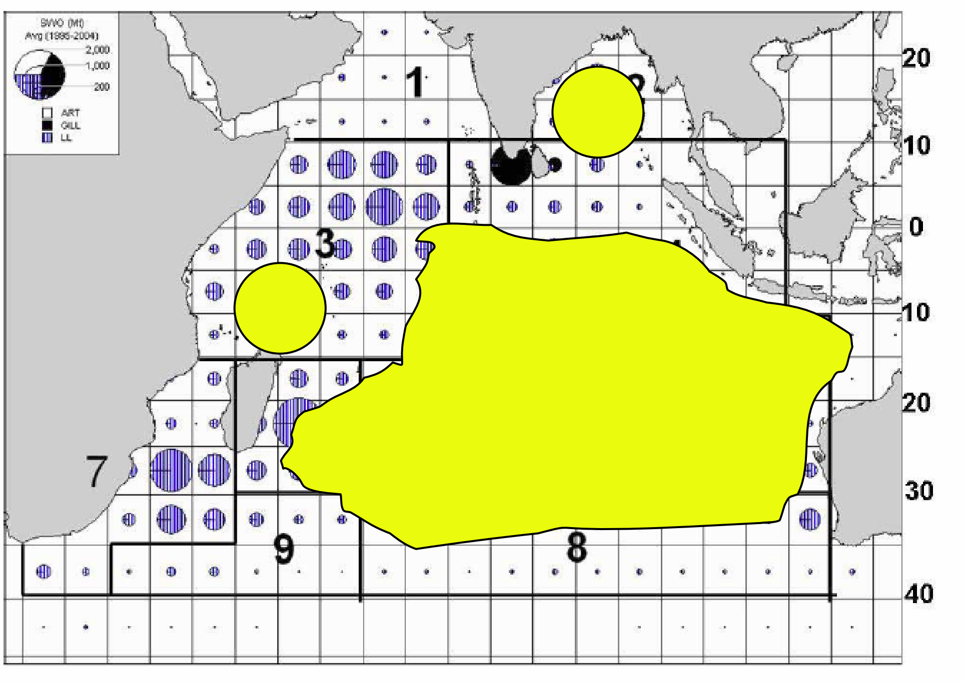

Figure 1. Lu et al 2006 suggest that two populations of Indian Ocean swordfish can be distinguished from the remainder.

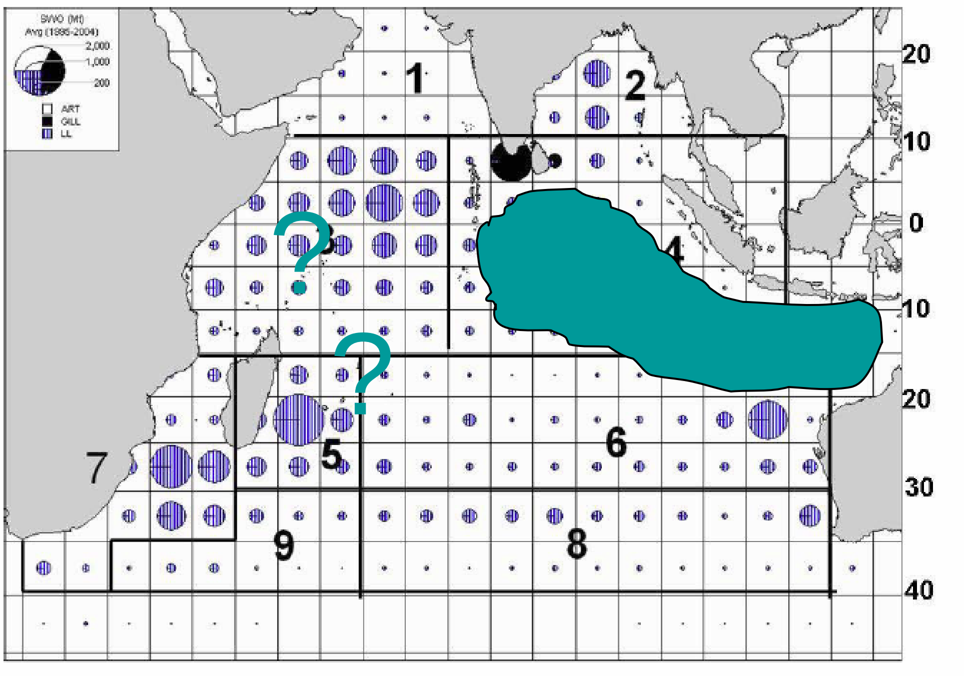

Figure 2. Swordfish larvae distributions found in the Indian Ocean (rough approximation of Nishikawa et at 1985).

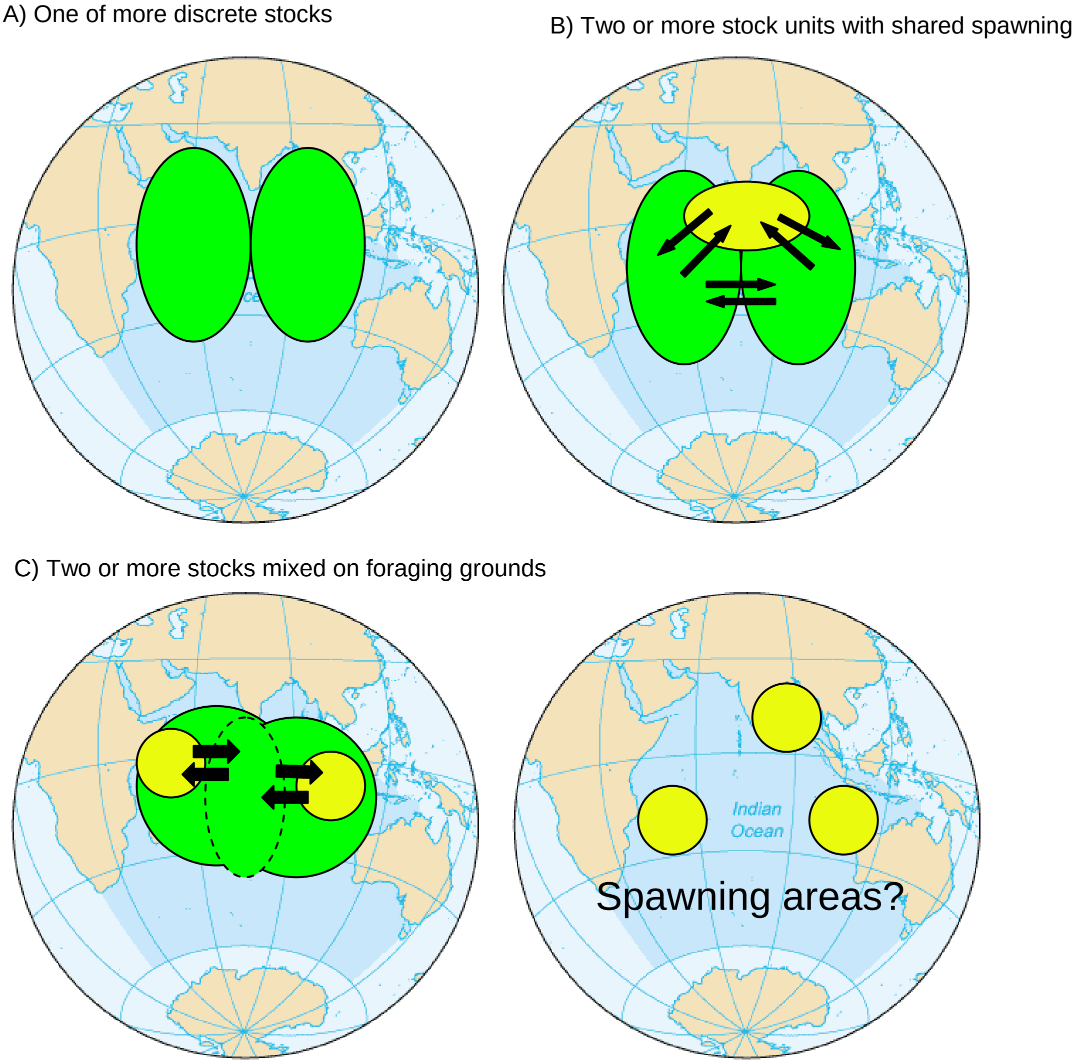

Figure 3. Conceptual illustration of spatial options worth considering for the Indian Ocean swordfish stock assessment. Specific foraging and spawning regions need to be investigated.

Table 1. Life history parameters used in defining the Pella-Tomlinson surplus production curve shape parameters. Lengths correspond to female SW Pacific swordfish. Mass is trunked. Uncertainty about these parameters is greater now than was assumed in 2006.

High Productivity Scenario (possibly resembling yellowfin)			**Low Productivity Scenario (possibly resembling Southern Bluefin)**		
Beverton-Holt Stock recruitment steepness			Beverton-Holt Stock recruitment steepness		
0.8			0.4		
Natural Mortality Rate			Natural Mortality Rate		
0.4			0.2		
Age-specific characteristics of both scenarios					
age	maturity	Selectivity	length (cm)	dressed mass (kg)	
0	0	0	76	6	
1	0	0	93	11	
2	0	0	108	17	
3	0	0.25	123	25	
4	0	0.5	136	33	
5	0	0.75	148	43	
6	0	1	160	53	
7	0	1	170	64	
8	0.25	1	180	75	
9	0.5	1	189	86	
10	0.75	1	197	98	
11	1	1	205	109	
12	1	1	212	120	
13	1	1	218	131	
14	1	1	224	142	
15	1	1	230	152	
16	1	1	235	162	
17	1	1	239	172	
18	1	1	244	181	
19	1	1	248	190	
20	1	1	252	198	
21	1	1	255	206	
22	1	1	258	214	
23	1	1	261	221	
24	1	1	264	227	
25	1	1	266	234	
26	1	1	268	239	
27	1	1	271	245	
28	1	1	273	250	
29+	1	1	274	255	

Table 2. Pella-Tomlinson surplus production curve shape parameters used in the Indian Ocean swordfish assessment in 2006. Note that the reasoning behind the use of these parameters relates to the life history considerations as defined in Table 1 and the curves illustrated in Figure 5.

	High Productivity	Low Productivity
$C_{\max}$	0.15	0.05
n	0.55	1.3

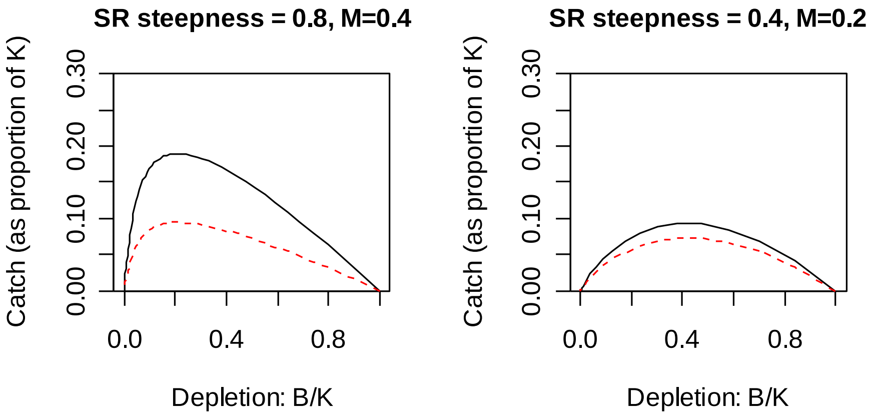

Figure 4. Surplus production curves corresponding to the high (left) and low (right) productivity scenarios for the age-structured population characteristics listed in Table A1. The solid lines represent surplus production as a percentage of exploitable biomass, broken lines represent production as a percentage of total biomass.

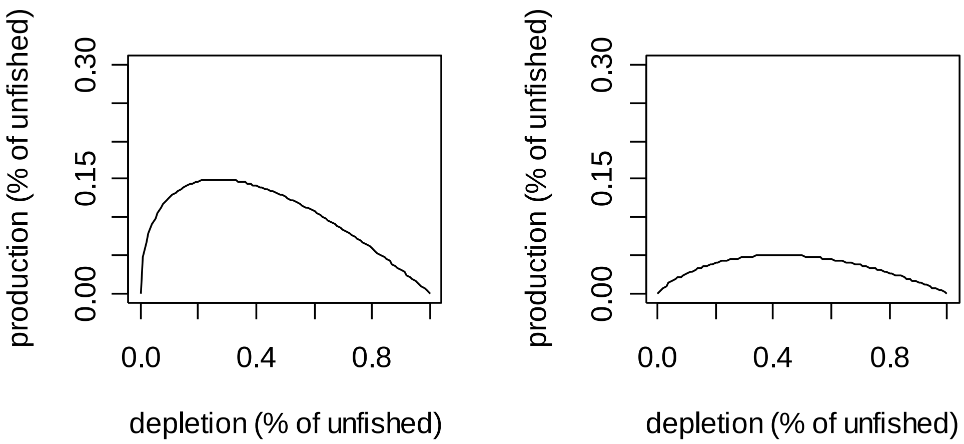

Figure 5. The Pella-Tomlinson surplus production curves used as plausible bounding scenarios in the Indian Ocean swordfish assessment.