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A Methodological Description of the Pella-Tomlinson Production Model Used for Exploratory Indian Ocean Swordfish Assessment at the 5th IOTC WPB

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Introduction

At the 5th IOTC Working Party on Billfish (2006), a number of surplus production models were fit to Indian Ocean broadbill swordfish catch and CPUE data as a first attempt at a formal stock assessment. The ASPIC software package was initially used for model fitting (IOTC-WPB-2006-06 + Revisions + Addendum), however, due to numerical problems, only a limited number of the WPB recommended model scenarios could be fit during the meeting (Fox and Schaefer models, using the short Japanese CPUE series 1990-2004). This paper briefly describes application of an independently coded Pella-Tomlinson model, with which we were able to explore a number of alternative scenarios, including high and low productivity life history strategies, and the extended CPUE time series 1975-2004. This paper is intended only as brief documentation for the methods. Results of the model are summarized in the main text of the WPB report.

The Fletcher-Pella-Tomlinson Surplus Production Model

This model is based on the deterministic version of the Pella-Tomlinson model (Pella 1993, Fletcher 1978). The dynamics are iterated with the difference equations:

$$B_t^{AfterCatch} = B_t^{BeforeCatch} - C_t$$

$$B_{t+1}^{BeforeCatch} = B_t^{AfterCatch} + P_{t+1}$$

where:

B_t^X = Biomass in the stock in year t, where X indicates before or after catch extraction,

C_t = Catch (mass) at time t, and

P_t = Production at time t.

Production accounts for increase in biomass due to growth and recruitment and losses due to natural mortality. Production for a given year is determined by the current level of depletion of the stock, and the production curve parameters:

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

where:

$K =$ biomass before fishing (carrying capacity)

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

$n, \gamma =$ parameters controlling the shape of the production curve, such that

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

The model is fit to the CPUE series, assuming that it is a relative abundance index (directly proportional to B), with lognormal errors:

$$CPUE_t^{\text{obs}} = q \ \tfrac{1}{2}(B_t^{BeforeCatch} + B_t^{AfterCatch}) \exp(Normal(0,\sigma)) .$$

Where:

$CPUE_t^{\text{obs}} =$ observed CPUE at time t.

q = catchability (relative abundance scaling co-efficient).

$\sigma =$ standard deviation of the observation errors, and

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):

$$\sum_t (\log\sigma + \frac{1}{2\sigma^2}(\log(q \ \tfrac{1}{2}(B_t^{BeforeCatch} + B_t^{AfterCatch}) / CPUE_t^{\text{obs}}))^2) ,$$

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). Initial attempts to estimate the shape 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). 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:

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

$$C_{total,t}^{mass} = \sum_a AM(a) C_{t,a}^N$$

Where:

$C_{t,a}^N$ = 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 A1 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. The resulting production curves are illustrated in Fig. A1. Table A2 lists the actual production curve parameters used in the Indian Ocean assessment, and the corresponding curves are illustrated in Fig. A2. Fig. A3 compares the two model fits to the CPUE series, illustrating clearly that there is not much of a signal in the data to distinguish between the two models.

Concluding Remarks

This implementation of the Pella-Tomlinson model seemed to provide a numerically stable estimator for the Indian Ocean swordfish assessment. The parameter space bounded by the upper and lower productivity scenarios presumably provides a more realistic representation of uncertainty than the Fox and Schaefer results. Results are summarized in the main body of the WPB report.

We note that the exact shape of the production curve might be updated to more closely represent Indian Ocean swordfish dynamics. In this initial analysis, our goal was primarily to look at some fairly extreme bounds of the plausible parameter space, and we used characteristics from SW Pacific swordfish characteristics for expedience, since they were immediately available from other analyses (e.g. Kolody et al 2005). For future reference, we note the following points:

- The shape of the production curves are particularly sensitive to the stock recruitment relationships, which are usually difficult to estimate reliably.
- Natural mortality and fishery selectivity had a lesser effect on the production curve, and alternative scenarios were not exhaustively explored (dome-shaped selectivity could have a strong influence).
- We note that the low productivity scenario used in the model was probably too extreme (unproductive; compare production curves in Fig. A2 – A3).
- The length-at-age, weight-at-length and maturity-at-age schedules were based on SW Pacific swordfish females (age of 50% maturity ~9). Biological studies from the Indian Ocean and other regions suggest a much younger age at maturity, and it is unclear whether this is due to biological or methodological differences.

Finally, we note that these production models do not consider the transient age structure effects that will be important in a rapidly developing fishery such as the Indian Ocean swordfish. These models also ignore information on catch size and sex composition. A fully age- and possibly sex-structured model is needed to explicitly account for this extra detail. Whether or not an age-structured assessment results in improved inferences over the production models will largely depend on the quality of the data and validity of structural assumptions.

The results achieved in the 2006 WPB are not considered definitive by any means, but prior to engaging in further refinement to the population dynamics modeling, it would be worth revisiting some of the input data. e.g. Catch rate standardization of the shot by shot data of the Japanese longline fleets might lead to improved relative abundance indices, and it needs to be clarified whether or not there is catch data missing from a portion of the Taiwanese fleet.

References

Fletcher, R. 1978. On the restructuring of the Pella-Tomlinson system. Fish. Bull. 76:515-521.

Kolody, D., R. Campbell, P. Jumppanen and N. Davies. 2005. South-West Pacific Swordfish Assessment: 2005-6 Objectives and Preliminary Results. Western and Central Pacific Fisheries Commission Scientific Committee Meeting 1 – Stock Assessment Working Paper 7.

Pella, J. 1993. Utility of structural time series models and the Kalman filter for predicting consequences of fishery actions. Proceedings of the International Symposium on Management Strategies forExploited Fish Populations, Alaska Sea Grant College Program, AK-SG-93-02, 1993.

Table A1. Life history parameters used in defining the Pella-Tomlinson surplus production curve shape parameters. Lengths correspond to female SW Pacific swordfish. Mass is trunked.

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 A2. Pella-Tomlinson surplus production curve shape parameters used in the Indian Ocean swordfish assessment. Note that the reasoning behind the use of these parameters relates to the life history considerations as defined in Table A1 and the curves illustrated in Fig. A1, but the exact parameters adopted are only an approximation to the results of Table A1 as illustrated in Fig. A2.

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

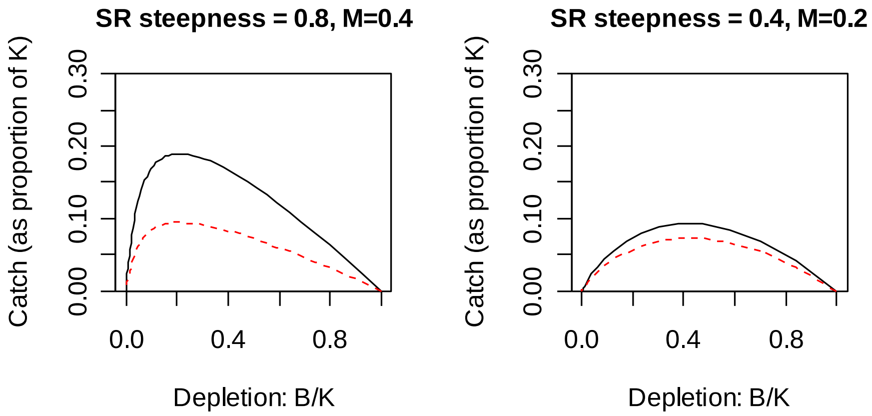

Fig. A1. Surplus production curves corresponding to the high (left) and low (right) productivity scenarios for the age-structured population characteristics listed in Table A1. The solid lines represent surplus production as a percentage of exploitable biomass, broken lines represent production as a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

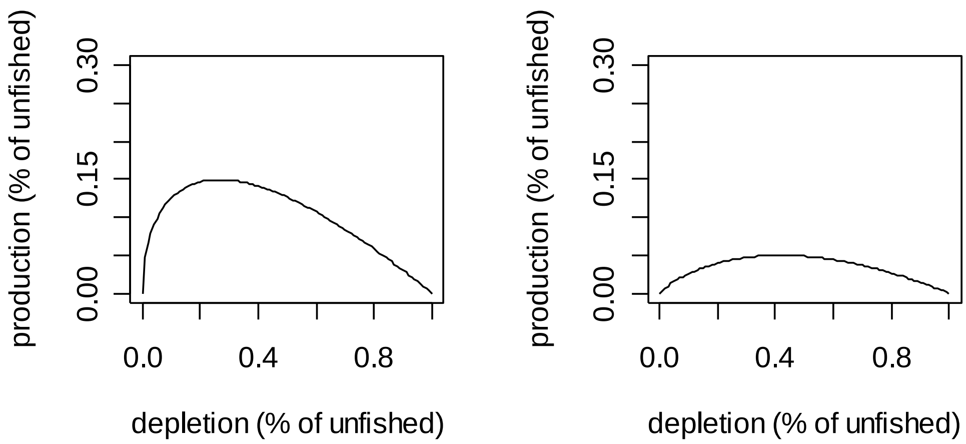

Fig. A2. The Pella-Tomlinson surplus production curves used as plausible bounding scenarios in the Indian Ocean swordfish assessment.

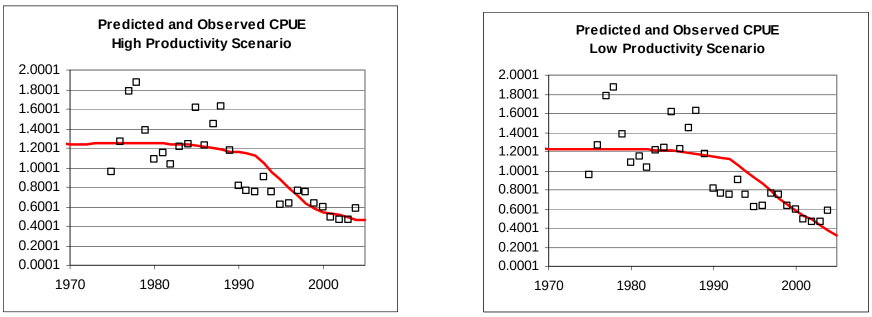

Fig. A3. Comparison of the best high and low productivity Pella-Tomlinson models, fit to the Japanese CPUE series 1975-2004 (areas 3,4,6,7,8). Plots illustrate that the signal to noise ratio in the data does not provide much information for reliably estimating productivity characteristics.