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Introduction of a spatially-structured model of Pacific Bluefin Tuna

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Abstract

A two-area spatially structured model is introduced for Pacific bluefin tuna. Movement is estimated to explain the proportion at length and CPUE from the Eastern Pacific area. A series of increasingly more complex and realistic models were developed with all model results indicating similar population dynamics. The most parsimonious model results are compared to those of the current stock assessment. Although a full range of diagnostics was not reviewed for the spatially structured model, the limited set of diagnostics indicated it was well behaved. Results of the spatially structured model were similar to the current stock assessment. The spatially structured model was not sensitive to small changes in juvenile M and changes to adult M were consistent with changes to population productivity. A spatially structured model appears to be possible with the current data, however parsimony may favor the existing stock assessment model.

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Introduction

Pacific bluefin tuna (*Thunnus thynnus*) exhibit a complex life history that extends over much of the North Pacific Ocean. Spawning takes place in the Western Pacific Ocean (WCPO) around the East China Sea and the Sea of Japan (Sund et al. 1981). Age-1 bluefin migrate to the Eastern Pacific (EPO) where they may stay until at least age 4 (Bayliff 1993; Bayliff 1994). Forcing factors behind the migration are not fully understood, but prey availability may play an important role (Polivina 1996).

The International Scientific Committee’s (ISC) Pacific bluefin tuna working group has experimented with using different population dynamic models that relie upon alternative data treatments and process assumptions to assess stock status. Early attempts to assess stock status were undertaken using an adaptation of Virtual Population Analysis (VPA). The method was abandoned because VPA relies on accurate ages to reconstruct cohorts but virtually no production ageing had ever been completed.

In 2006, an initial age structured and length-base model (Piner et al. 2006) was introduced as an alternative modeling approach, in which age-specific information is derived from length observations using an integrated growth curve. In 2008, the working group completed the first accepted assessment using a fully integrated analysis (Stock Synthesis II). In 2009 the assessment was updated using a newer version of Stock Synthesis (SS3) and an updated natural mortality schedule. In 2010, results from an update of the SS3 model with data through 2008 (Ichinokawa et al. 2010) was accepted and presented to the ISC Plenary.

Although the use of age-structured and length based models fit to data with less “pre-processing”, other modeling issues remained. Notably the model showed poor residual patterns resulting from fitting poorly to the Eastern Pacific Ocean (EPO) purse seine CPUE (Aires-da-Silva et al. 2007). This mis-fitting indicates that those data are inconsistent with other data or structural assumptions in the current assessment model. One hypothesis is that the proportion of bluefin that migrate to (or remain in) the EPO changes over time (Polivina 1996) and thus catchability is non-constant. Under this hypothesis, the EPO purse seine index aliases year-specific availability in addition to changing relative abundance. Modeling trans-Pacific movement within the assessment model would allow the explicit estimation of the availability component, making the assumption of constant catchability more reasonable.

Another issue was the model appeared to be overly sensitive to small changes in M (~0.01-0.03-^{1yr}). This sensitivity resulted in model estimates of Spawning Stock Biomass (SSB) that were much larger than expected for relatively small changes in M. It may be that this sensitivity is related to the mis-specification of the model regarding the EPO fisheries.

The objectives of this paper are to present results of a spatially structured model that introduces the process of movement to help explain EPO data. This first attempt at incorporating spatial structure would be done using a model that was as similar to the base case assessment (Ichinokawa et al. 2010) as possible and with the spatial dynamics (including movement) modeled with the most parsimonious model. We determine if the additional process both improved fit to EPO CPUE indices, and eliminated the model sensitivity to changes in juvenile and adult M.

Materials and methods

In this study we used the model as described by Ichinokawa et al. (2010) and referred to as BASE in this paper. The model referred to as MOVE is the most parsimonious of the spatial models tested and included the following changes from that BASE model:

a. Spatially explicit areas: Divide fisheries (catch, CPUE and size composition) into 2 areas: WCPO (area 1) and EPO (Fisheries 8 and 9 into area 2).
b. Recruitment: Age 0 fish recruit only to area 1.
c. Movement: Movement is governed by a functional form to reduce parameters (similar to natural mortality functional form in SS). Model estimates a movement parameter (rate) at age 1 and age 4 (nodes). Movement of age 0 is assumed not to occur (rate=0). Movement rates of age 2 and 3 fish are interpolated values between estimates at each node. Movement rate for ages 5+ are the same as estimated for the second node (age 4). Estimate movement nodes only for movement from WCPO to EPO. All surviving fish in the EPO are assumed to return to the WCPO during the season 1 of next year.). All movement is assumed to occur in season 1.Year-specific movement is allowed from 1970-2005 via estimation of deviations around the base movement rates. Deviates have an assumed S.D =0.2.
d. Selectivity: Assume selectivity of EPO fisheries is asymptotic and age-based.
e. Data: Fit to (lambda =1.0) CPUE series 25 and 26 (EPO PS). Do a simple iterative reweighting of those CPUE series, but not any other likelihood component.

We compared model results from the MOVE model to the BASE model and a 3rd model that is identical to BASE model except that the EPO data is substantially down-weighted (referred to as DOWN). In the DOWN model, EPO USPS CPUE fleet 24 lambda =0 and set EPO PS fleet 8 size comp lambda= 0.01. We also ran sensitivity analysis of changes in juvenile M vectors (Table 1) and adult M (Table 2) to determine if the MOVE model was sensitive to changes in Juvenile and Adult M.

We also compare results of the MOVE model to more fully parameterized movement models where the complete deviate time series is estimated 1952-2005 (MOVE2) and where all 4 nodes (movement to and from EPO) in addition to the complete deviate time series estimated (MOVE3).

Results

Although no formal convergence testing (random starting and phasing) was conducted, the MOVE model did not have any parameters on bounds and both the hessian and gradient indicated convergence. The log-likelihood components obtained from the MOVE and BASE models are given in Table 3. Figures 1-3 display the improved fits to the EPO PS fleet CPUE.

The estimated age selectivity pattern of EPO fisheries indicates that age 1 is 60% selected and age 2+ is fully selected(Figure 4). Predicted biomass in each area is given in Figure 5.

The MOVE model was similar in dynamics to the BASE model and the DOWN model (Figure 6). The predicted dynamics from the MOVE model was not sensitive to small changes in juvenile M (Figure 7) and responded predictably to changes in adult M (Figure 8). As assumed productivity of the stock increased, the unfished biomass estimates declined and ending biomass increased (Table 2 and Figure 6).

Adding more realism (and complexity) to the parameterization of movement beyond the MOVE model marginally improved model fit but did not alter model results (Table 4). Estimating deviates from the start of the model (MOVE2) improved model fit and may be somewhat statistically justified (2.2 likelihood unit improvements for each additional parameter). Estimating the full movement of fish both to and from the EPO (MOVE3) also improved model fit, but not enough to statistically justify the additional100^+ parameters (0.76 likelihood unit improvement for each additional parameter).

Discussion

The MOVE model is an overly simplified movement model that allows year-specific changes in available biomass in the EPO to test if the assumption of constant EPO catchability produced misfitting that skewed model results. The oversimplification of movement in the MOVE model avoids the confounding of estimating both retention of fish in the EPO and movement to the EPO. Although this parameterization prevents the separation of movement from retention for ages > 1 (age 0 does not move), it does provide estimates of age-specific biomass in the EPO area that best matches the data and other process assumptions. However, in that parameterization there could be difficulties if too large a proportion of fish were foundIt is clear that the inclusion of year-specific movement provides better fit to the EPO CPUE, but not a fundamentally different estimate of the population dynamics. Importantly, the addition of the movement process (and its additional 70+ parameters) did not produce equivalent results as simply down-weighting the EPO data. This result implies that the rate of exchange in the model is driven by data in both areas. An alternative process to movement would be the use of time varying catchabilty and selectivity. Although this avenue was not explored, fitting to the EPO data via the movement process is preferable as year-specific catchability is equivalent to down-weighting that data.

Adding movement (plus fitting two additional CPUE indices) improved the individual fits to nearly all CPUE series but only some of the length composition while degrading others. Most notably there was significant loss of fit to the EPO PS Length Composition. The degradation to EPO length is partially explained by estimated movement deviates starting in 1970 as length composition data extends back to the start of the model. Movement prior to this period is a single value that best fit the data. Perhaps more importantly, the more restrictive selectivity pattern assumption (logistic) resulted in the degraded fits to the length composition. It may be that some level of domed shaped selectivity (or retention) is occurring in the EPO, however estimating the descending limb of the selectivity function would be confounded in this model with movement. Perhaps more likely is that some level of retention of fish in the EPO may improve model fits to the size composition. Direct observations of the movement process will greatly assist in estimating this component of a spatial model. We should also note that standardized CPUE from the Mexican PS are included in the model but are not precisely fit. However, there is considerable noise in that index that is unlikely to reflect changes in actual abundance. We may interpret this mis-fitting as an indication that the additional process of year-specific movement has not removed all model tension such that we are only modeling the noise.

It was the goal of this paper to explore a model that used movement and spatial structure to explain the data. As part of this goal, our intention was to pursue a model that was a close approximation of the current base case so that comparisons could be made. One notable deviation to the base case was the modeling of EPO selectivity as age-based. We thought this consistent with our hypothesis of movement as age based as well. However, the length based process may still be a better choice. We also retained the single block (1988-1989) of time varying selectivity to the EPO fisheries to explain the occurrence of very large fish in that year. However, in a model with movement used to explain the EPO data, it is probably more consistent to assume time invariant selectivity and simply allow the movement to explain this data.

Despite being a relatively constrained spatially structured model, the MOVE model did not suffer from the sensitivity to small changes in juvenile M and changes to adult M produced model behavior that was expected. In other words, increasing or decreasing adult M changed the productivity of the hypothetical population resulting in model dynamics that were consistent. However, in a single run (which run?) the model converged on a local rather than global minimum. Results of that run included an unusually large rescaling of biomass and if those results had been taken at face value would have indicated unusual sensitivity to changes in juvenile M. In all cases, further exploration found model solutions that were better fits and more consistent based on likelihood profiles. Results of these “better fit” models did not show unusual biomass scaling issues.

Perhaps equally importantly the increased process used to fit the EPO data did not change the general result of higher recruitment at the end of the series. It is of some concern that the increasing catches of both age 0 and juveniles (ages 1-3) towards the end of the series could be biasing the estimates of recruitment high via model mis-specification. This would impact our view of both stock resilience and the sustainability of the current fishing practices. If the increase recruitment at the end of the series is due to misspecification, the most likely cause is the constraint of the assumed temporally constant selectivity pattern and increasing EPO fishery on juveniles. Based on the number of parameters, this model appears to have more relative freedom via movement, but the degraded fit the size composition might imply that the assumption of constant asymptotic selectivity is problematic. It remains to be seen if the increased recruitment at the end of the time series is real or an effect of the more restrictive assumption of asymptotic selectivity in the EPO.

To Move or not to move? That does appear to be the question. The results suggest that a spatially –structured model is feasible even without direct observations on movement (tagging data). However, the use of spatial definition of fisheries and flexible selectivity pattern appear to produce similar answers. Parsimony would certainly favor the latter model and realism the former. However, if tagging data were available, a spatially-structured model may be preferable.

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Table 1. Vectors of age-specific Natural Mortality used in the sensitivity analysis of juvenile M, total model likelihood and estimates of unfished spawning biomass (SSB0).

age	Run1	2	3	4	5	6	MOVE	7	8	9	10	11	12
0	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
1	0.44	0.43	0.42	0.41	0.4	0.39	0.386	0.38	0.37	0.36	0.35	0.34	0.33
2	0.31	0.3	0.29	0.28	0.27	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25
3	0.3	0.29	0.28	0.27	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
4+	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
like	5354	5353	5356	5356	5357	5354	5357	5356	5355	5357	5354	5353	5356
SSB0	477059	486651	498229	506356	515528	527996	531051	533058	534081	538595	539724	544653	547354

Table 2. Vectors of age-specific Natural Mortality used in the sensitivity analysis of Adult M, total model likelihood and estimates of unfished spawning biomass (SSB0).

	MOVE	very low 1	low 2	high 3[1]	higher 4[1]	Very high 5[1]
M	1.6	1.6	1.6	1.6	1.6	1.6
age 0	0.386	0.39	0.39	0.39	0.39	0.39
age 1	0.25	0.26	0.26	0.275	0.3	0.325
age 2	0.25	0.25	0.25	0.275	0.3	0.325
age 3+	0.25	0.2	0.225	0.275	0.3	0.325
Tot like	5357	5402	5372	5326	5287	5261
SSB0 (mt)	531051	679698	589851	474610	454829	443500

[1] Note that when increasing adult M, that juvenile M also had to be increased for some age-classes to avoid larger tuna having higher mortality.

Table 3. Likelihoods components by fleet for the model with movement (MOVE) and the current BASE model. Values in parenthesis indicate a likelihood degradation compared to the other model, values in not in parenthesis the opposite.

Fleet:	1	2	3	4	5	6	7	8		11	14	15	20	23	24	25	26
MOVE																	
Catch λ	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
Catch_like:	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
Surv_ λ	0	0	0	0	0	0	0	0		5	5	5	1	5	1	1	1
Surv_like:	0	0	0	0	0	0	0	0		-12	-27	-22	-1	-4	-23	48	7
Length_ λ	1	1	1	1	1	1	1	1		0	0	0	0	0	0	0	0
Length_like:	(909)	(538)	822	845	(161)	(689)	176	(1506)		0	0	0	0	0	0	0	0
BASE																	
Fleet:	1	2	3	4	5	6	7	8		11	14	15	20	23	24	25	26
Catch_ λ	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
Catch_like:	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
Surv_I λ:	0	0	0	0	0	0	0	0		5	5	5	1	5	1	0	0
Surv_like:	0	0	0	0	0	0	0	0		(-11)	-27	(-21)	(1)	(-1)	(84)	(335)	(76)
Length_ λ	1	1	1	1	1	1	1	1		0	0	0	0	0	0	0	0
Length_like:	907	501	(834)	(847)	160	675	(180)	643		0	0	0	0	0	0	0	0

Table 4. Results of model runs that include increasing complexity in the parameterization of the spatial dynamics.

	MOVE	MOVE2	MOVE3
dev years	1970-2005	1952-2005	1952-2006
# nodes est	2	2	4
# parms	161	197	307
Total LIKELIHOOD	5355.88	5275.61	5245.08
SSB0	531051	533626	535421

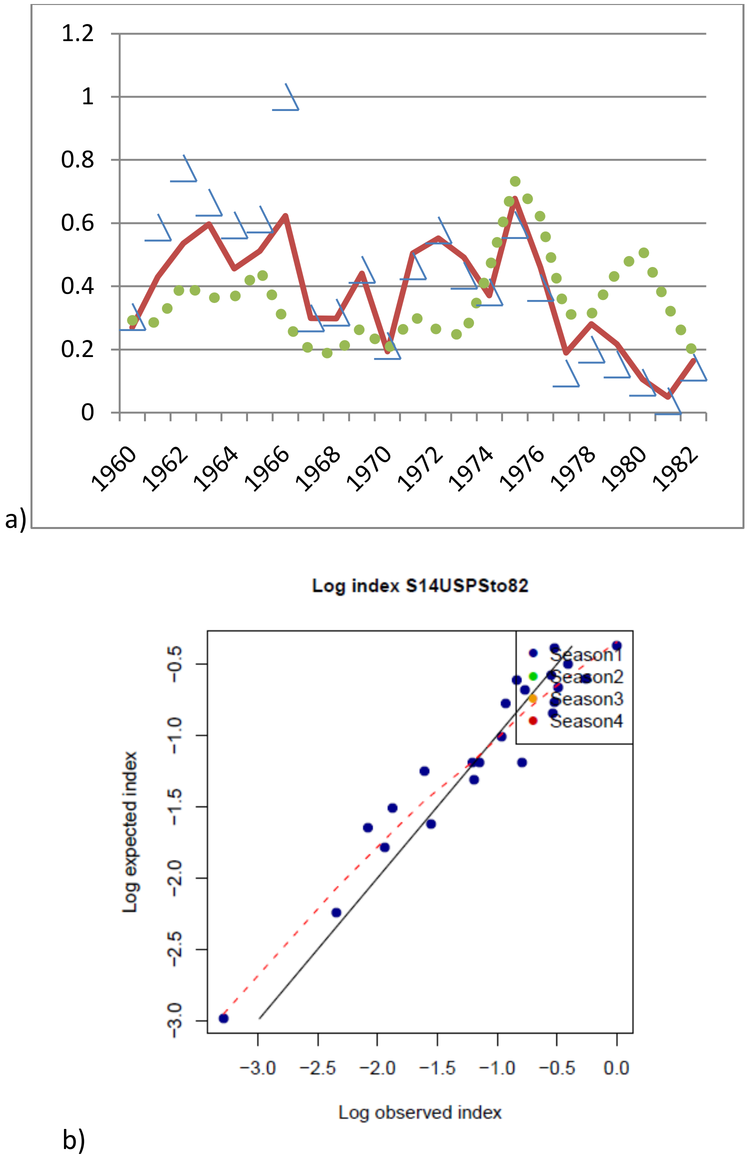
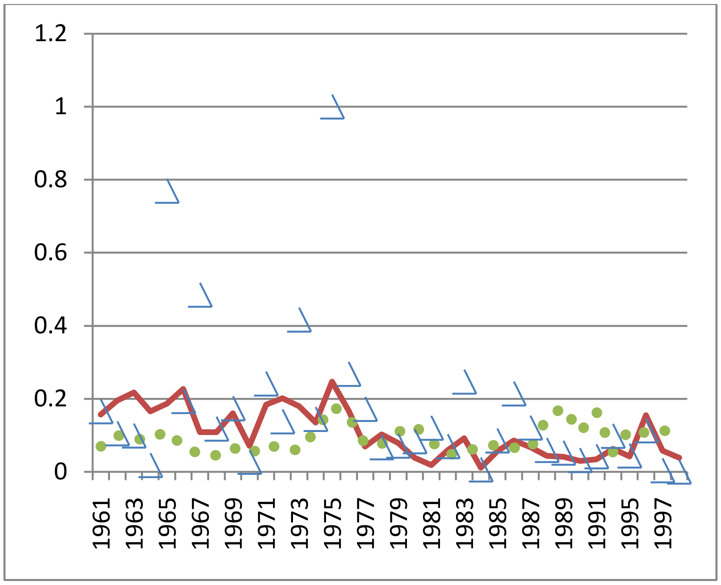
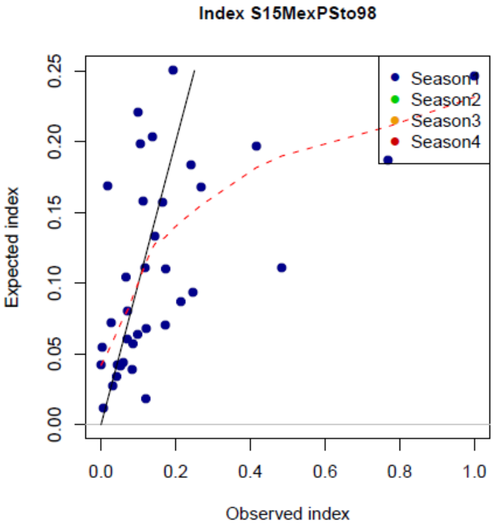


Figure 1. Fit to EPO PS CPUE from the US fleet 1960-1982. a) Observed values are given (Δ) and the expected from the Movement model (MOVE) are depicted as a solid line while the expected from the current assessment (BASE) is given as a dashed line. b) Plot of CPUE expected and observed from the MOVE model. The line indicates perfect agreement.



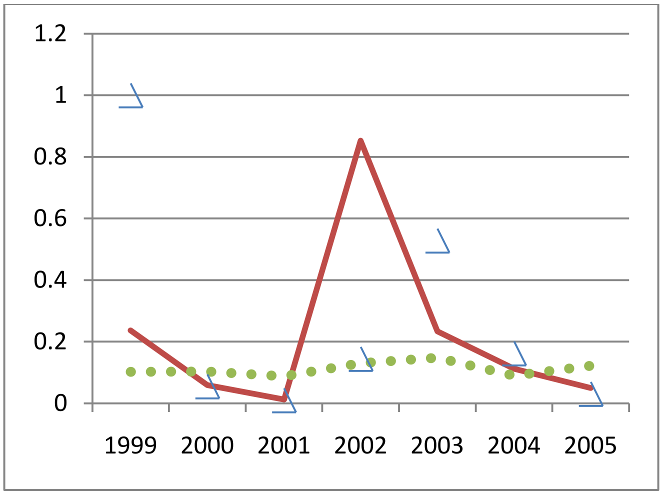
a)



b)

Figure 2. Fit to EPO PS CPUE from the Mexican fleet 1961-1998. a) Observed values are given (Δ) and the expected from the Movement model (MOVE) are depicted as a solid line while the expected from the current assessment (BASE) is given as a dashed line. b) Plot of CPUE expected and observed from the MOVE model. The line indicates perfect agreement.

a)



b)

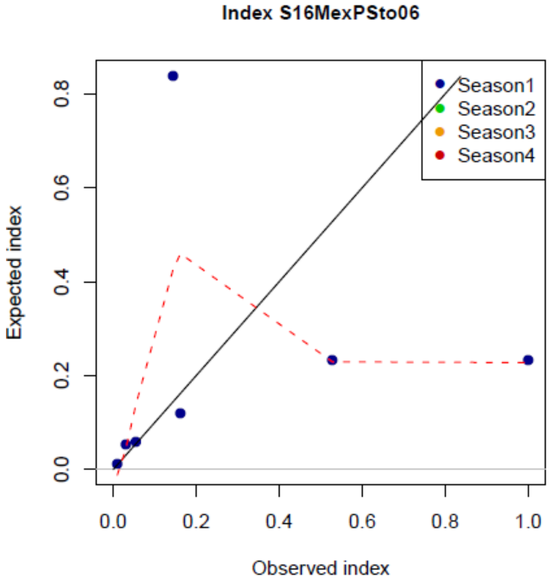


Figure 3. Fit to EPO PS CPUE from the Mexican fleet 1999-2005. a) Observed values are given (Δ) and the expected from the Movement model (MOVE) are depicted as a solid line while the expected from the current assessment (BASE) is given as a dashed line. b) Plot of CPUE expected and observed from the MOVE model. The line indicates perfect agreement.

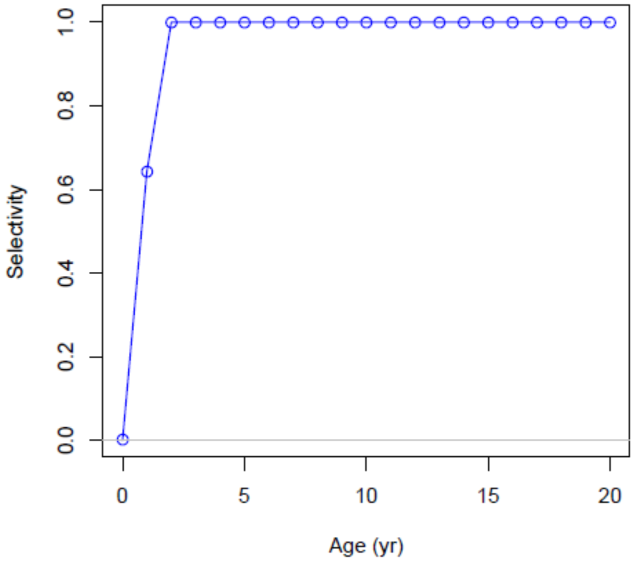


Figure 4 . Estimated Age selectivity for EPO fisheries

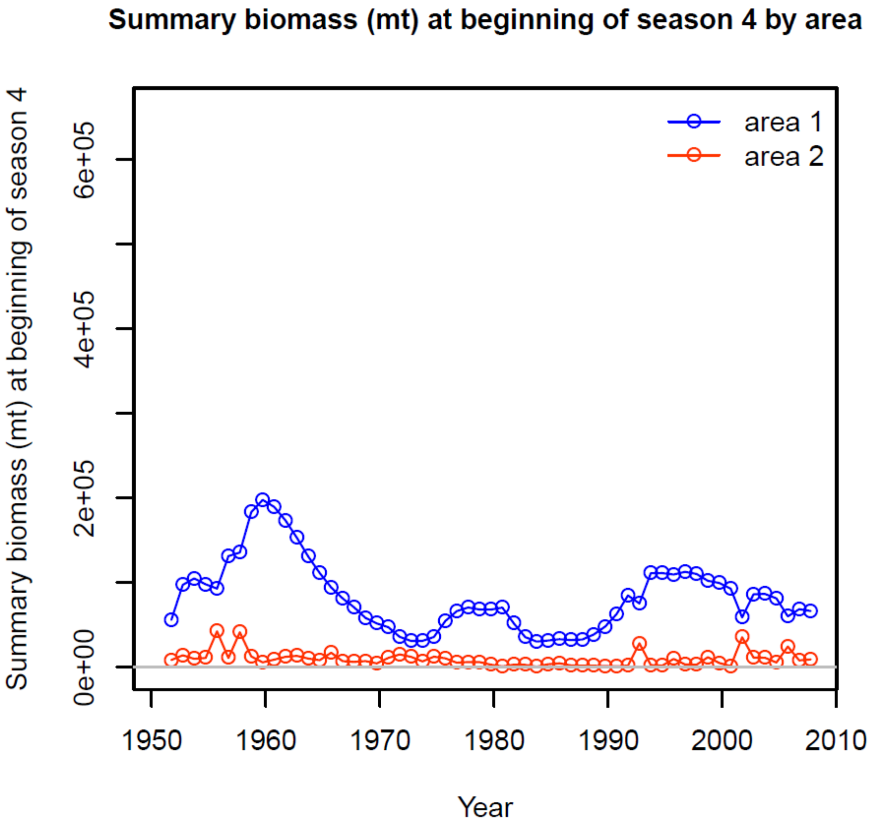


Figure 5. Estimated age 1 biomass in WCPO (area 1) and EPO (area 2) 1950-2008.

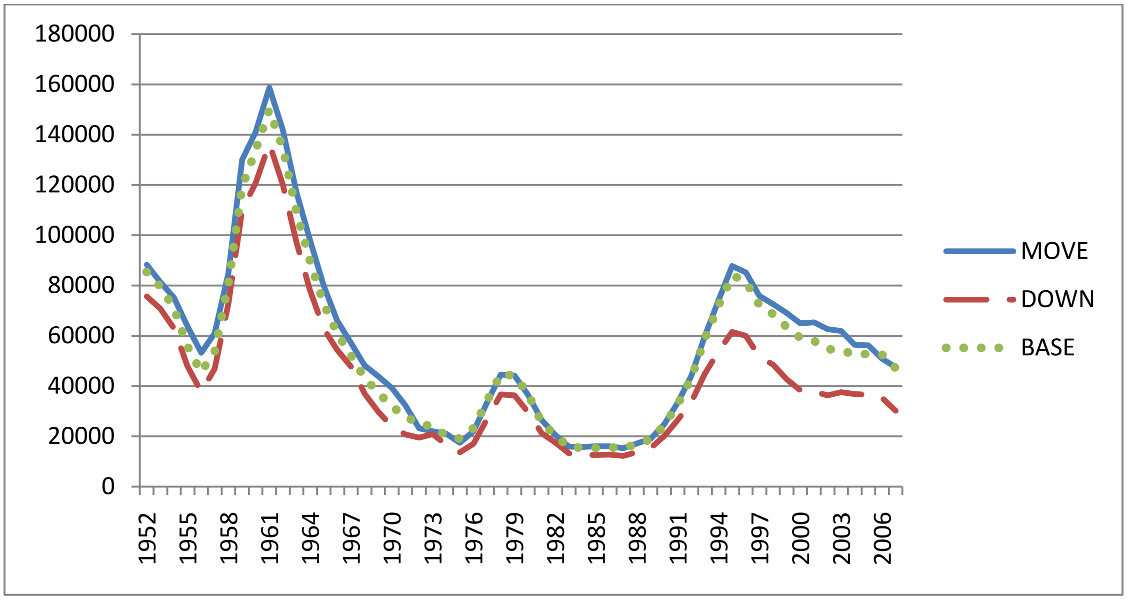


Figure 6. Estimated spawning biomass series from the MOVE model (solid line), BASE stock assessment (dotted line) and DOWN model (dashed).

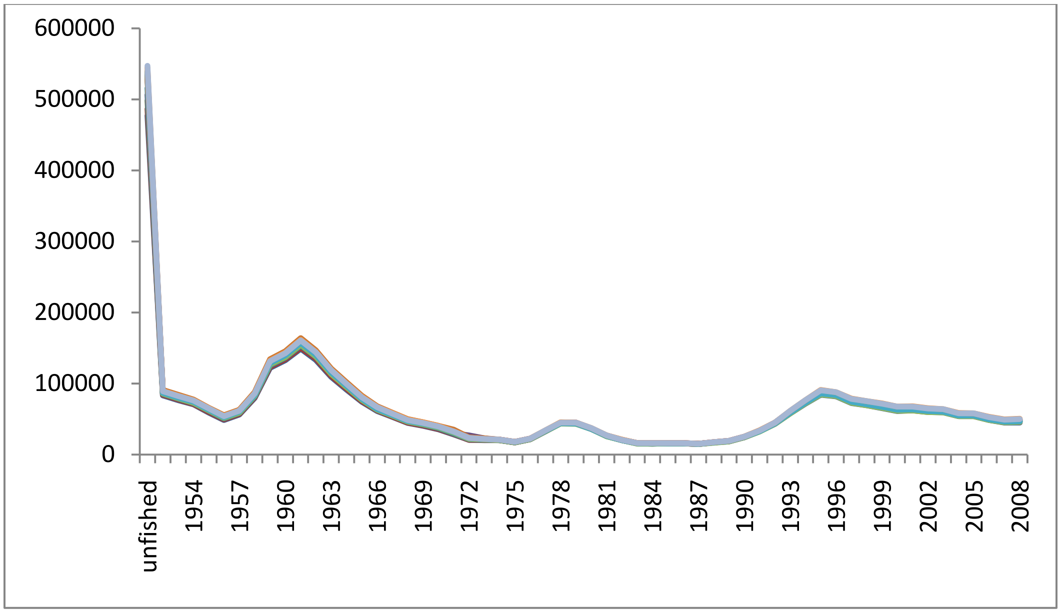


Figure 7. Estimated spawning biomass from the model with movement (MOVE) with minor changes in juvenile M.

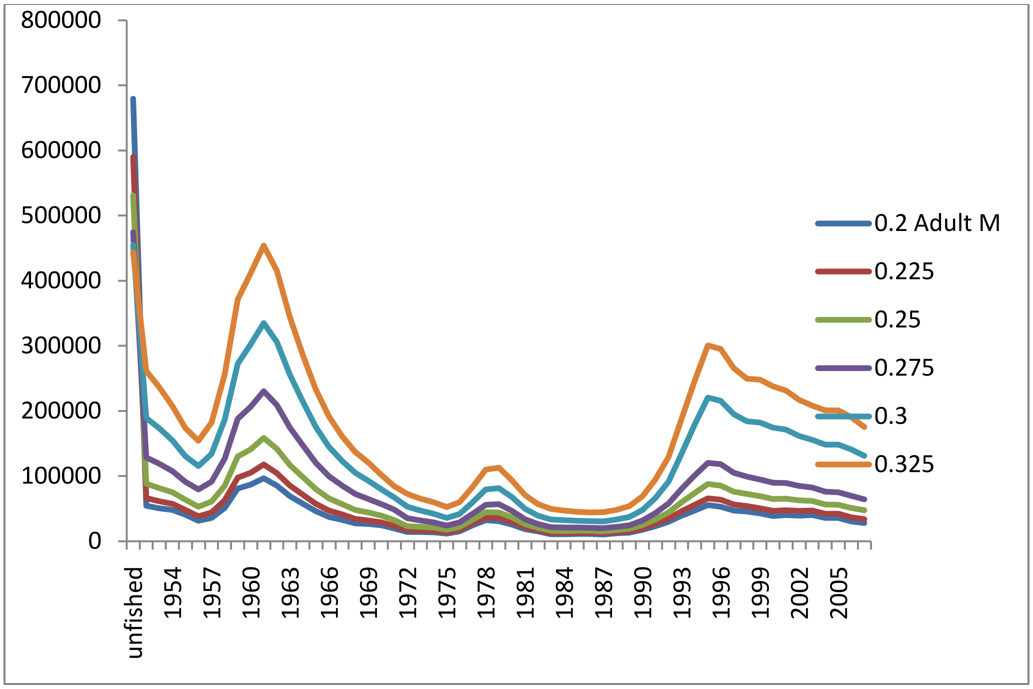


Figure 8. Estimated spawning biomass from the model with movement (MOVE) with changes in adult M.