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A Multi Stock Age Structured Tag Integrated Model (MAST) for the Assessment of Atlantic Bluefin Tuna

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Summary
We present a Beta version of a spatial, **M**ulti-stock **A**ge-**S**tructured **T**ag-integrated stock assessment model (MAST) of Atlantic bluefin tuna. MAST models two spawning populations (East and Western) of Atlantic bluefin tuna simultaneously in 4 areas, with quarterly time steps. The model estimates Fmsy and MSY as leading parameters. Each stock has specific growth, maturity and natural mortality parameters. The Western stock is assumed to spawn only in the Gulf of Mexico (GOM, ICCAT area 1) and the Eastern stock in the Mediterranean (MED, ICCAT area 6). Currently, the rest of the Atlantic is divided into two areas with the first being ICCAT area 2 and the second as the combination of ICCAT areas 3 and 4. In the model fish are not permitted to move to the other stock's spawning areas but are otherwise allowed to move between any of the other areas according to estimated movement transition matrices. During spawning periods we assume that movement transition from all areas to the spawning area of a given stock are given by that stock's maturity-at-age ogive. Non-spawning fish during that period move according to movement transition probabilities estimated for non-spawning fish but are not permitted in spawning areas during this period.

We divided each mark-recapture dataset into three groups according to whether or not the marked animal's stock of origin could be designated as Western (1), Eastern (2) or unknown (0). In a few cases with recently marked animals, these designations could be made using genetics but we designated the vast majority as eastern or western fish according whether or not they had been observed in one spawning area or another. In those cases where it was not possible to designate fish to Western or Eastern stocks, we assumed the fish's stock of origin was unknown and could have been either a MED or GOM fish. Mark-recapture data were fit to discreet state-space likelihoods. Here each fish has a mark-recapture history consisting of location (observed in areas 1-3 for GOM fish, or 2-4 for MED fish) or event states (captured in fishing gear g) or not observed (0). When making a stock designation was not possible, the situation was more complicated since observations may be of either a GOM or MED origin fish. In those cases, twice the number of state combinations is possible. Here the tag is assumed to be on either a GOM or MED stock fish in areas 1-4, on a GOM or MED fish caught in fishing gear in areas 1-4, shed or dead etc. In this case, the initial probability of the state given the observation at the first time step is given by proportion of fish vulnerable to the gear and area it was initially marked in. Currently we make designation of length at marking into ages outside the model.

We fitted MAST to ICCAT's indices of abundance for each area as well as conventional mark-recapture data starting in 1950, archival and pop-off satellite tag data. Abundance

indices are fitted using log-normal likelihoods where the predicted vulnerable biomass (or number as applicable for each index) is given by the sum of vulnerable biomasses for each stock, area, and quarter combination. Selectivities are modeled as a function of mean length at age, given by stock-specific von Bertalanffy growth parameters. The joint likelihood function therefore consists of 10 components for CPUE data, and for each stock designation (0, 1, and 2) of each mark-recapture data type (conventional, archival or pop-off).

For a base case fit, we treat gear selectivities as the same between fleets and growth as known and equal and estimate movement parameters, leading recruitment F_{msy} and MSY for both stocks at their posterior mode. We explore four reconstruction scenarios where we fitted the model to the data with Fmsy fixed and estimated and test the performance of the model for these scenarios when down-weighting CPUE likelihoods by 90 %. We show reconstructions for Western and Eastern stocks of total numbers, biomasses.

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Methods

Overview

MAST is spatially explicit, age-structured model of discreet Mediterranean (MED) and Gulf of Mexico (GOM) Atlantic Bluefin tuna spawning populations (or "stocks"). Fish are moved from area to area at quarterly time steps according to stock-specific movement transition probabilities that are estimated by the model. We assume that recruitment occurs in the second quarter and that it only occurs in designated spawning areas. As such, movement transitions to spawning areas are set to the maturity ogive for that stock. In addition we assume that GOM fish and MED fish do not ever use each other's spawning areas. In this way, GOM and MED fish can only overlap in areas 2 and 3 (ICCAT areas 2-5). The master prediction equation of MAST is.

$$N_{i,l',a+1,t+1} = \sum_{l=L_i(1)}^{l=L_i(3)} N_{i,l,a,t}\mu(l,l')e^{-m_i+\sum_g v_{i,a,g}F_{g,t}}$$

Equation 1. Master prediction equation of MAST where predicted numbers N_{t+1} at time $\underline{t}$ of stock i at age a are given by numbers at the previous time step $N_{i,t,a}$, the product of gear vulnerability v of stock i to gear g and fishing rate through all gears ($\sum_g v_{i,a,g}F_{g,t}$) and the movement transition matrix μ.

The movement transition matrix μ consists of from-area rows and to-area columns. Rows must sum to 1 (fish either stay in the area they are or go to other areas). We include all symbols, for state dynamics equations in Table 1 and variable indices in Table 2. Catches by gear and area are converted numerically integrating the fishing mortality until the predicted catches over the time step are within 1 ton of observed catches.

MAST is initialized in the first year with maximum sustainable yield, MSY and the fishing rate at MSY, F_{msy} as leading parameters (Forrest et al. 2008) allowing management parameters to be estimated directly from the data. We model all fleets as having the same asymptotic gear selectivity as a function mean size at age (in quarters) given by

$$v_{i,a} = \frac{1}{1 + e^{-\rho_g(\bar{L}_i - Lh)}}$$

Equation 2 Gear selectivity function for all gears where ρ is the slope of the gear selectivity function, $\bar{L}_i$ is the mean length of stock *i* at age a and *Lh$_i$* is the length at which fish are 50 % vulnerable to the gear. Parameters are given in Table 1.

and hence the same partition of the leading *MSY* and F_{msy}. This is an initial simplification that can be modified later to better reflect gear and regulation changes.

The model is initialized with growth parameters set to those specified by (Parrack and Phares 1979). Set age at maturity for the western stock according (Diaz and Turner 2007) and for the eastern stock we set a_h to 8. We approximate this using a functional form as

$$\varphi_a = \frac{1}{1 + e^{-\lambda(a - a_h)}}$$

Equation 3 maturity φ at age *a* where λ is the slope of the function and age $_{ah}$ is the age at 50 % maturity.

Sampling for basic life-history parameters sometimes occurs from the mixed stock pool. While currently not implemented, the model can use stock composition information and likewise include the effects of sampling from the mixed stock on life-history parameters such as growth, mortality or fecundity, which may or may not have occurred in areas where the stocks are mixing fitting such observations to predicted proportions using multinomial likelihoods. At each time step, we predict number and biomass at age in each area. Therefore the proportion of biomass and numbers of each stock is predicted in each area so that predicted stock composition can be fitted to observations currently being compiled with genetics and otolith microchemistry.

Although we describe a four-area, four-fleet base case above, the model can use multiple areas and fleets. There are multiple versions, including one that has been formulated with a discreet harvest rate occurring at each time step using a single fleet. We present the instantaneous fishing mortality, four-fleet version here.

We use catch by fleet data from ICCAT's TASK 1 database. To translate catches into the designated area groups we summed up the latitude-longitude cell data corresponding to ICCAT areas. We converted the six areas into four by making areas 3, 4 and 5 a single area so that first is ICCAT area 1, the second area ICCAT area 2, the third area being the sum of ICCAT areas 3-5 and the fourth as ICCAT area 6. For the rest of this paper we will refer to these areas 1-4 (1 GOM, 2. Western Atlantic, 3. Eastern Atlantic, and 4. MED). We fitted MAST to a combination ICCAT's 21 CPUE indices by gear and area. We plot catches by area and gear in Figure 1 Catches (in 1000s tones) by area and gear We fitted the indices by summing total predicted numbers at age over which months (reduced to quarters) the index applies to. We fitted the data using a log normal likelihood function using the observation error variances published for each index as the variance term.

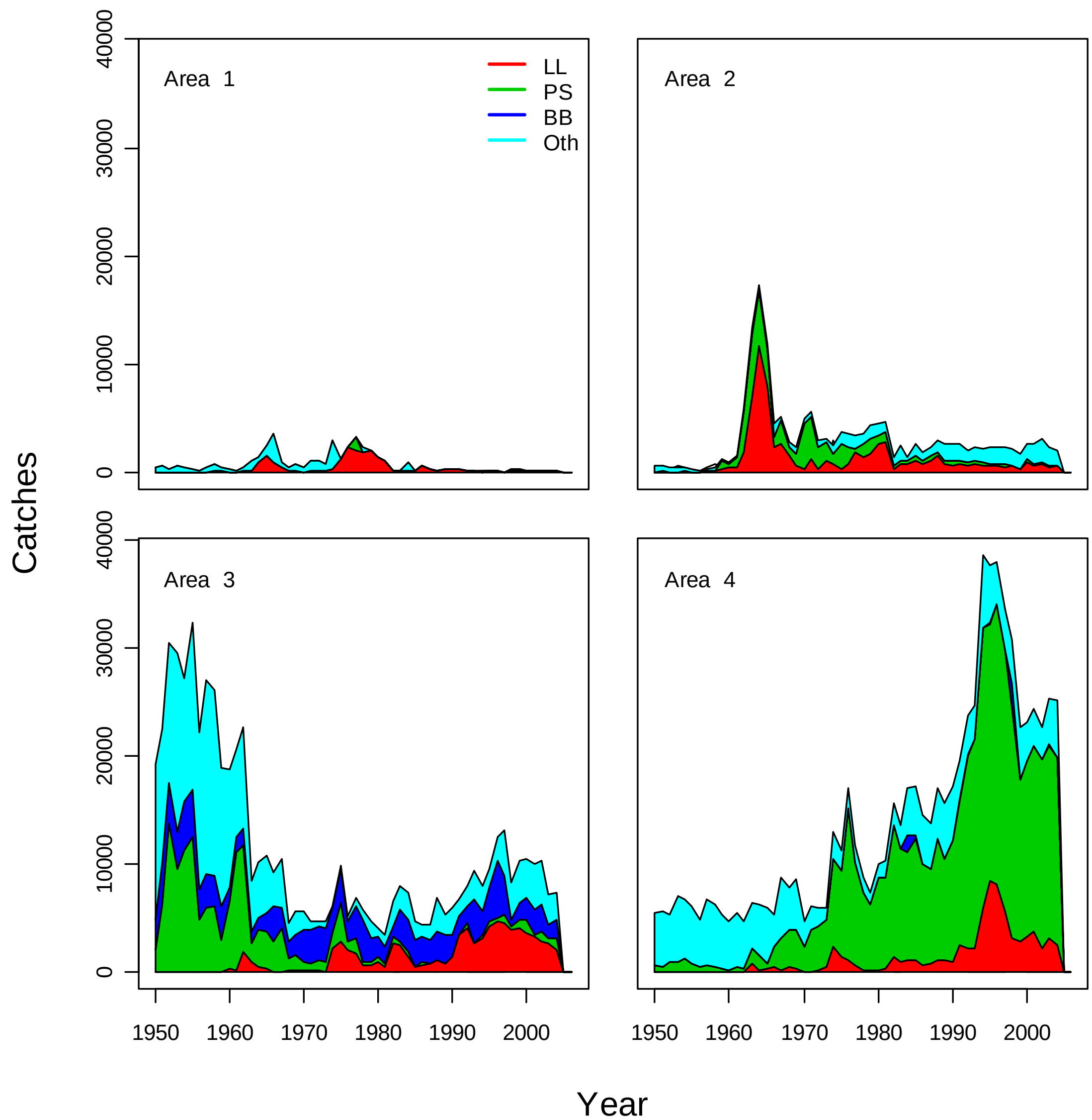

Figure 1 Catches (in 1000s tones) by area and gear

Mark Recapture Data

We use conventional tag data (from 1950 to present) from the ICCAT conventional tag database, archival tag, and pop-up satellite tag data for this analysis. Documentation of archival and satellite tag data is found in (Block et al. 2001, Block et al. 2003, Block et al. 2005).

We divided all mark-recapture datasets into three groups: those that could be designated western stock, eastern stock or unknown. In a few cases these designations could be based on genetics but in the vast majority of cases we made this designation based on whether or not tagged fish were observed in the GOM or in the MED, in which case they were designated as being GOM or MED fish. Thus implicit in this analysis is the assumption that fish from either stock do not use each other's particular spawning areas. We then parsed all mark-recapture observations into histories with initial time at marking, and subsequent observations *o*.

Mark-Recapture Likelihoods

MAST uses nine different discreet state-space likelihoods (De Valpine and Hastings 2002) to model mark-recapture data. We will give an overview of the method here but encourage readers to consult this reference for underlying theory and details. We chose this method in order to use all location-state information for each tag time series, rather than just start and end points. Strictly speaking we model tags, not fish, through discreet states for each model time step. We discuss the designation of these states below.

Seasonal and age dependencies of movement rates are incorporated in the estimation by (1) assigning each fish of stock *i* an apparent age-at-first-capture based on its length and (Parrack and Phares 1979) and then assigning fish to a particular age group whose movement parameters are assumed to be the same. Currently length-to-age conversions are applied to both stocks with the same growth parameters external to the model to reduce computational burden but it is possible to do so in the model according to estimated stock-specific growth parameters, and propagate age-assignment and growth uncertainty in this conversion forward. The data do not permit estimating movement transition matrices for each age groups so we divide movement parameters into three groups corresponding to ages 1-3, 4-8 and 9+ assuming that movement is similar between those groups.

Whether tags be conventional, archival or pop-up types, we have a recapture history of the form $Y_t=\{0,o,0,0,\ldots,o,0,\ldots\}$ where for each possible sampling date an observation $y_t=0$ denotes no recapture and a $y_t=l$ denotes at least one recapture in location l. In addition to location-state events we define capture gears *g* for conventional and archival tags that define gear used to recover the tag.

We calculate the likelihood $P(Y_t)$ of each history using the recursive method reviewed in (De Valpine and Hastings 2002) where $P(Y_t)$ is represented as

$$P(Y_t) = P(Y_{t-1})P(y_t|Y_{t-1}).$$

Equation 4. Probability of mark-recapture histories

To use this representation, we note that the probability of an event *k*, in a recapture history $P(y_t|Y_{t-1})$ can be written as

$$P(y_t|Y_{t-1})=\Sigma_s P(s_t|Y_{t-1})P(y_t|s_t,Y_{t-1})$$

Equation 5 Probability of observation y_t given the state up until time *t-1*.

where s_t represents possible tag states (s_t={ on dead fish, on live fish in location 1, alive in location 2,..,}) and $P(y_t|s_t,Y_{t-1})$ is the observation probability of y_t given that the fish is in state s_t. Representation for $P(y_t|Y_{t-1})$ in terms of states s_t expresses the problem of calculating it as two simpler problems, calculation of location state probabilities $P(s_t|Y_{t-1})$ and observation probabilities $P(y_t|s_t)$.

For different combinations of stock-designation and tag type, possible states and observation probabilities are modeled differently. We describe these differences in some detail below. In general however, tag states are assumed to be: attached to living fish in permitted stock areas (i.e. on GOM fish in areas 1-3 or on a MED fish in areas 2-4); attached to a recently captured fish on the deck of a fishing vessel in areas; shed or dead.

Archival Tag State-Space Likelihood Fish Having Stock Designations
In those cases where fish stock of origin is assumed known, tag states are assumed to be either on a living fish of stock *i* in stock areas, captured in fishing gear, shed, or attached to a dead fish. Given a matrix L_i of permitted areas ($L_i(1,2,3)$ for the GOM stock and $L_i(2,3,4)$ for the MED stock) we define 8 states, the observation probabilities given these states ($p(y_t|s_t)$) and the state probabilities given all observations up until *t*, $P(s_t|Y_{t-1})$ and summarize how these values area computed in tables Table 3 for $p(y_t|s_t)$ and Table 5.

Observation probabilities given the state $p(y_t|s_t)$ can be easily defined when there is an observation ($o>0$) in a capture history. If the tag is 'observed' in areas 1-3 ($s=1$ *to* 3), it remains implanted in the fish, with the tag still recording geopositions. In this case, the observation probabilities are given by the (possibly time or area-dependent) probability of getting a geoposition γ. If the fish is observed captured ($s=4$-6) in areas $L_i(1,2,3)$, then $p(y_t|s_t)$ is the reporting rate *R* for fleet *g*. Observation probabilities for shed or dead state are typically set to zero. Since each event is mutually exclusive (i.e. tags cannot be on a living swimming fish and also on the deck of a fishing boat or dead or shed), when an observation is made the probabilities of all other $p(y_t|s_t)$ are null. When no observations are made, $p(y_t|s_t)$ for states 1-3 are set to the compliment of the capture probabilities (1-γ), the compliment of the possible time and fleet varying reporting rate (1-R) for states 4-6 and to 1.0 for states 7-8.

Computation of $P(s|Y_{t-1})$ for each *s* are more complex. The sequence of fates for each fish is assumed to be movement, shedding, natural mortality then fishing mortality. Since in this case stock designation is assumed known, the probability that the tag is on a fish from stock *i* in the release area is 1. At the next time step we calculate $P(s_{t+1}|Y_t)$ (which is $P(s_t|Y_{t-1})$ for the next time step) according the equations listed in Table 3. The computations can be understood using the following example. In order for a tag to be on a fish in area *s*`, the fish may have been alive in other areas (given by $P(s_t|Y_{t-1})$ ), then moved from area *l* to area *l*` according to the estimated movement transition matrix for that fish $\mu_{l,l`}$, survived natural mortality and fishing ( $e^{-(m_{t-1}+\sum_g v_{g,t-1}F_{g,i,t-1})}$ ) and finally did not shed its tag $(1-D_{t-1})$. The probability of the state is given by Equation 5 by summing across all transitions from *s* to *s*`. The parameter μ is the estimated movement transition matrix consisting of from-area rows, and to-area columns. Diagonals of μ are the probability that the fish stays where it is. Mathematically this is example is represented by the first row in Table 5 with all other model states in subsequent rows. Note that MAST does not permit fish to spontaneously return from dead or shed states to living states - so transitions from dead to dead states are set to 1. Similarly transition probabilities from shed or dead states to s=1-3 are set to zero. The log-likelihood then simply the sums of the log of the probability of the entire capture history given by equation 1.

Conventional Tags with Stock Designations
Modeling state transitions for conventional tags is identical to archival except with shedding rates D corresponding to the tag type k. However modeling $p(y_t|s_t)$ is modeled differently for obvious reasons if the tag is still on the fish in areas L_i then the probability of observing it is zero. A few conventional tags were re-released alive, or with a new tag, in which case $P(s_{t+1}|Y_t)$ is set to 1 for the area released. With conventional tags, $p(y_t|s_t)$ is simply 1 in the area that it was observed (with all observation probabilities set to zero). We show how $p(y_t|s_t)$ is designated in Table 4.

PSAT Tag State-Space Likelihood Fish Having Stock Designations
Computation of the likelihoods for pop-off tags having stock designations is the same except that we add an additional state for the tag popping π and where D in this case is a combined shedding/malfunction probability instead of a shedding rate for archival tags . Computation of $p(y_t|s_t)$ is listed in Table 7 and of the state probabilities in Table 8. Note here that γ and D refer to the specific tag type. We created an additional type of observation type when a pop-off event occurred (k=10). The probability such an event is the probability that the fish survived fishing and natural mortality, and tag failure and that the tag popped off. We model the probability the tag popped off given the programmed pop-off date π as being normally distributed with mean programmed pop-off date μ_π and the estimated pop-off date standard deviation σ_π.

$$\pi_t \sim N(\mu_\pi, \sigma_\pi)$$

Equation 6 Probability of a pop-off event.

We model the state just as we did for archival tags but with the addition of the popped-off state Table 8.

Archival Tag State-Space Likelihood for Fish Having Without Stock Designations
Modeling movement trajectories for fish of unknown stock of origin is more complex. Recall that when the stock of origin is known, the probability of the state at the first time step is trivial (tag is on a fish of stock i in the area where it was marked). However if the stock of origin is unknown, then the tag could be on a GOM fish or on a MED fish. Therefore for each state transition we must model whether or not the tag is on a GOM or a MED fish, moving and dying according to stock-specific-natural mortality, fishing mortality (due to possible differences in size at age) and movement transitions. We include these model equations in table Table 9 for archival and conventional tags and in for PSAT tags in Table 10.

CPUE Index and Parameter Fitting Scenarios
We fitted the model to available indices listed in Table 15 and to all available mark-recapture data. We ran two scenarios where we allowed Fmsy and MSY to be estimated freely with no likelihood re-weighting. For the second set we down-weighted CPUE likelihoods by 90 %. We summarize runs conducted and parameter estimates in Table 14.

Likelihood Minimization

We use prior densities for all estimated parameters listed in Table 12. The joint posterior then consists of 16 log-normal likelihood for CPUE data, three 3 multinomial likelihoods for each stock designation of archival tags, 3 multinomial likelihoods for each stock designation of PSAT tags and 3 multinomial likelihood likelihoods for conventional tag data. Fitting was done using conjugant gradient fitting algorithm provided by AD model builder, which is a C++ library that does automatic differentiation. AD model builder is proprietary software used under license by the Fisheries Center at the University of British Columbia. Full documentation of it and trial versions can be obtained at http://otter-rsch.com/admodel.htm.

Results

We remind readers that fits and reconstructions here are mainly to illustrate that what outputs and analysis the model is capable of and not to have provided actually estimates of current and historical biomass and numerical reconstructions.

This first-fitting enterprise illustrates some of potential problems that might be anticipated with future applications of this model. One major issue is the strong correlation between the leading parameters of each stock. While total MSY of both stocks generally consistent (Table 14) and ranging between 25 and 29 kt, they trade off with respect to the proportion of the total biomass that belongs to each stock. That said, estimates of MSY are reasonable consist with MSY estimates derived from single species assessments. This strong correlation between the leading parameters of each stock also produces problems for the non-linear minimization because the model can find equally likely explanations of the data by moving fish from each stock around so as to best fit CPUE indices.

In the model's current formulation, the model has difficulty converging with CPUE likelihoods fully weighted in joint likelihood. We are not currently sure why this is the case but the two information sources appear to contradict each other in some way. Several simplifications that we have made during model development, in particular time-invariant gear-selectivity functions and reporting rates may be to blame for this conflict but additional investigations need to be conducted to determine if this is the case or not. Upon more close examination we could not conclude that model runs that were run with CPUE and mark-recapture data can be reliably said to have converged.

In addition to these problems, some ICCAT indices apply to smaller areas than the model currently employs meaning that some areas are treated to represent much larger areas than they actually do. For example, Gulf of St, Lawrence indeces are fit to the models predictions for the entire Western Atlantic. More areas, or more sensible definitions of the areas might need to be applied.

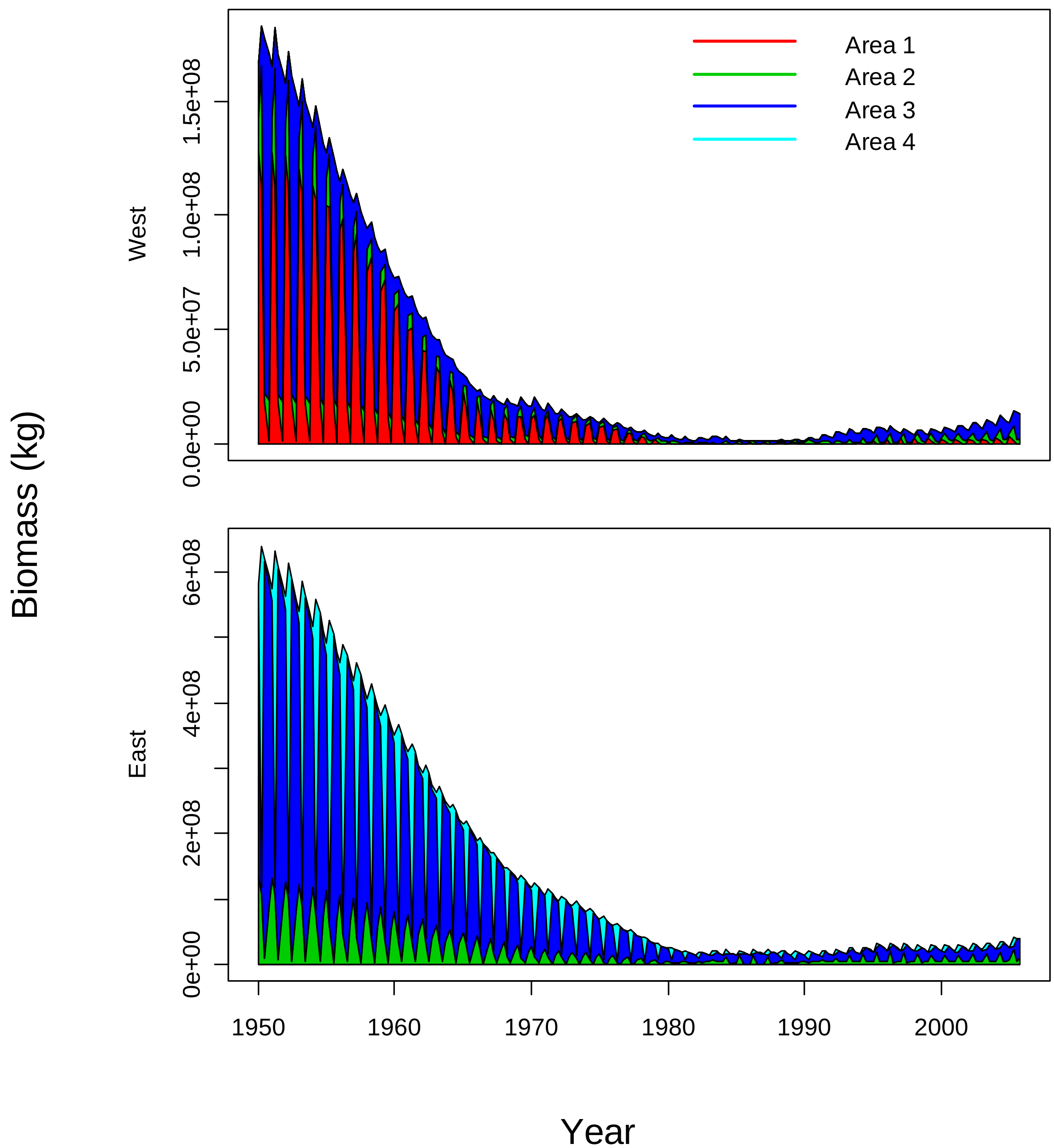

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Figure 2 Reconstructed total biomass for Western (top) and Eastern (bottom) stocks for scenario 3, based on fits with Fmsy free and CPUE likelihoods downweighted by 90 %.

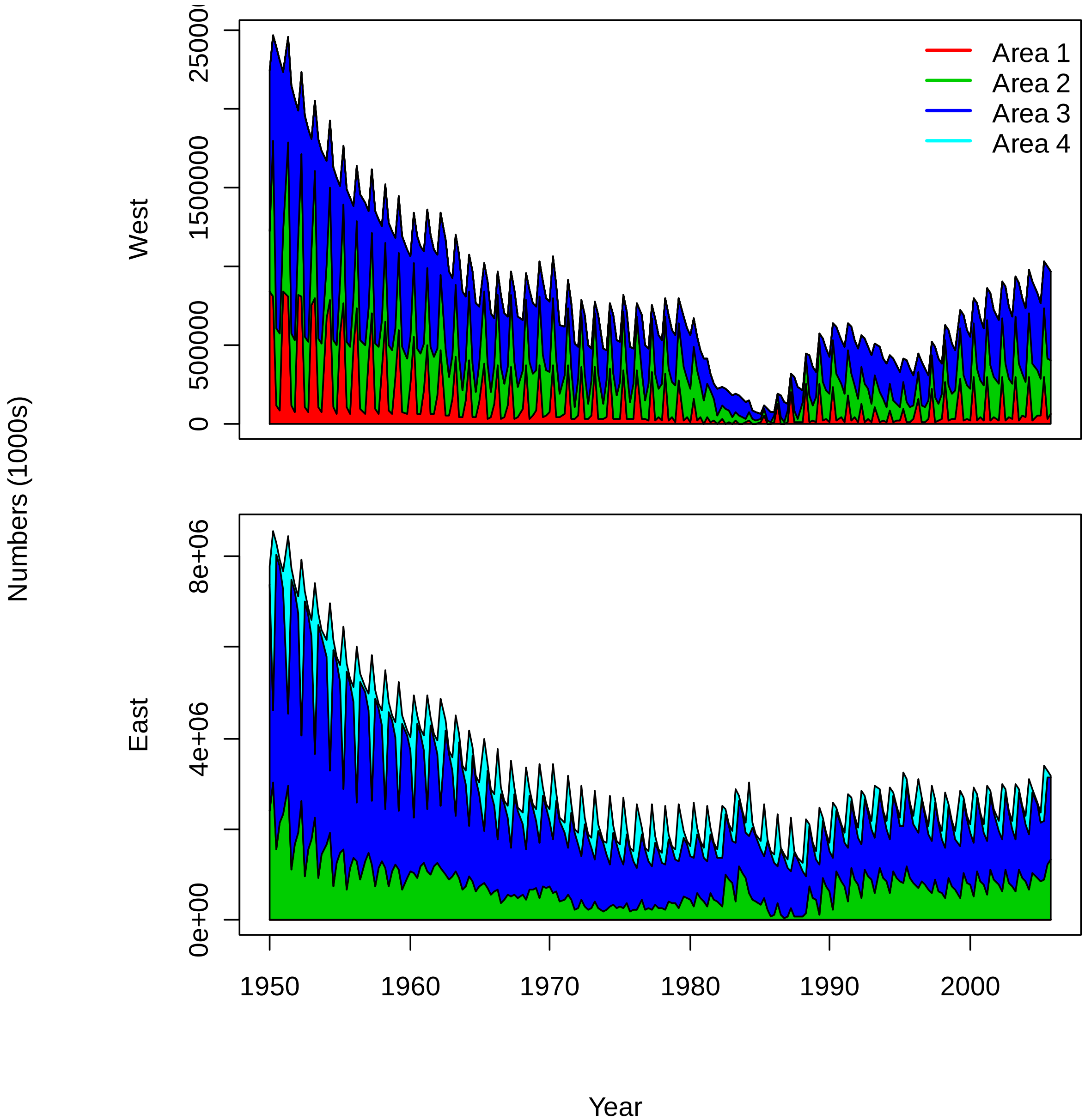

Figure 3 Reconstructed numbers (1000s) for scenario 3 based on fit based on fits with Fmsy free and CPUE likelihoods downweighted by 90 %.

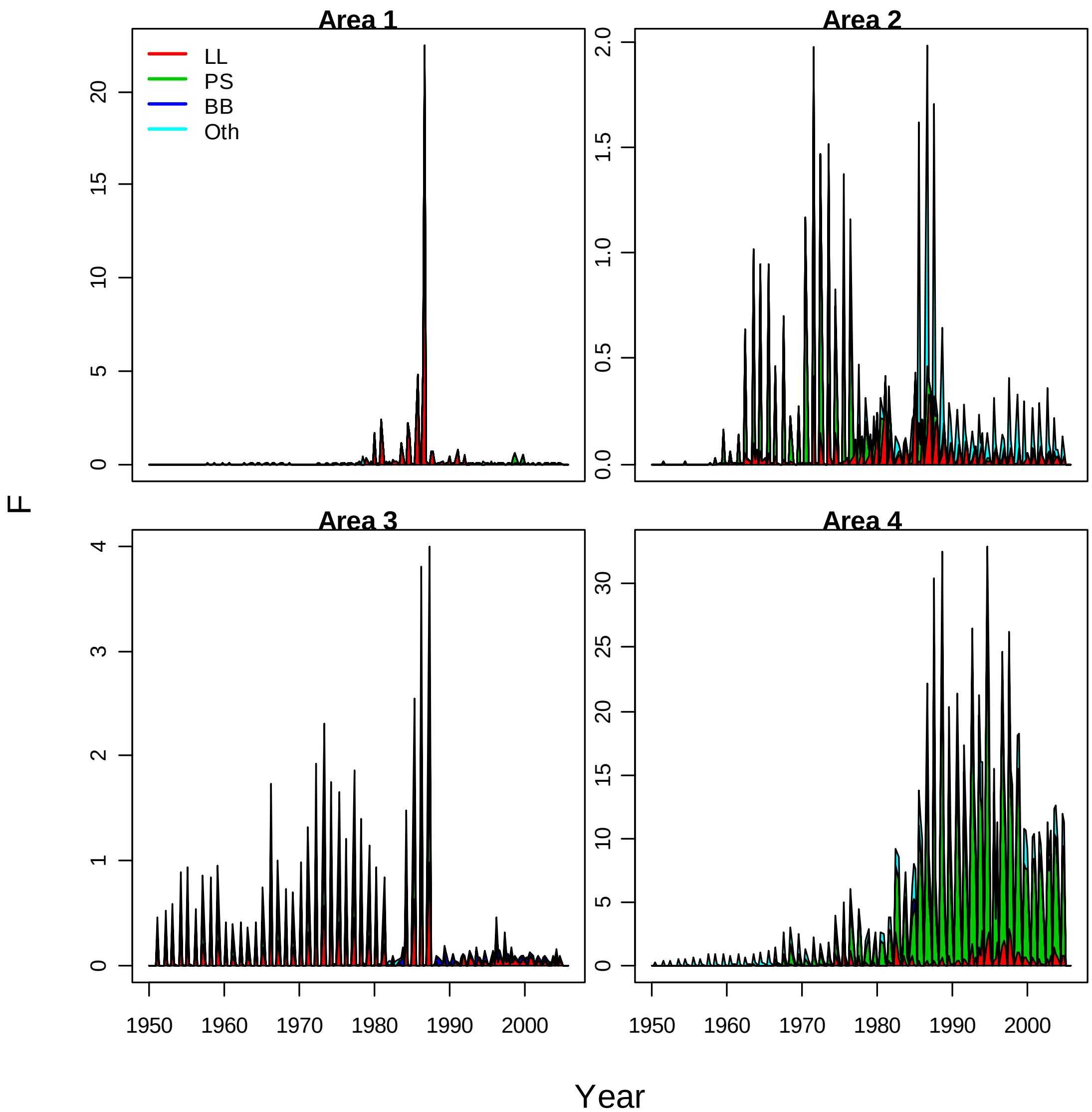

Figure 4 Reconstructed fishing mortalities (yr^{-1}) by area and gear for scenario 3 based on fit based on fits with Fmsy free and CPUE likelihoods downweighted by 90 %.

While it was possible to estimate Fmsy for scenario 3, it tended to produce unreasonably high values for this parameter. Note that given current assumptions of growth and gear selectivity, values of Fmsy in the order of 0.1-0.11 correspond to slopes of origin of the stock recruitment function.

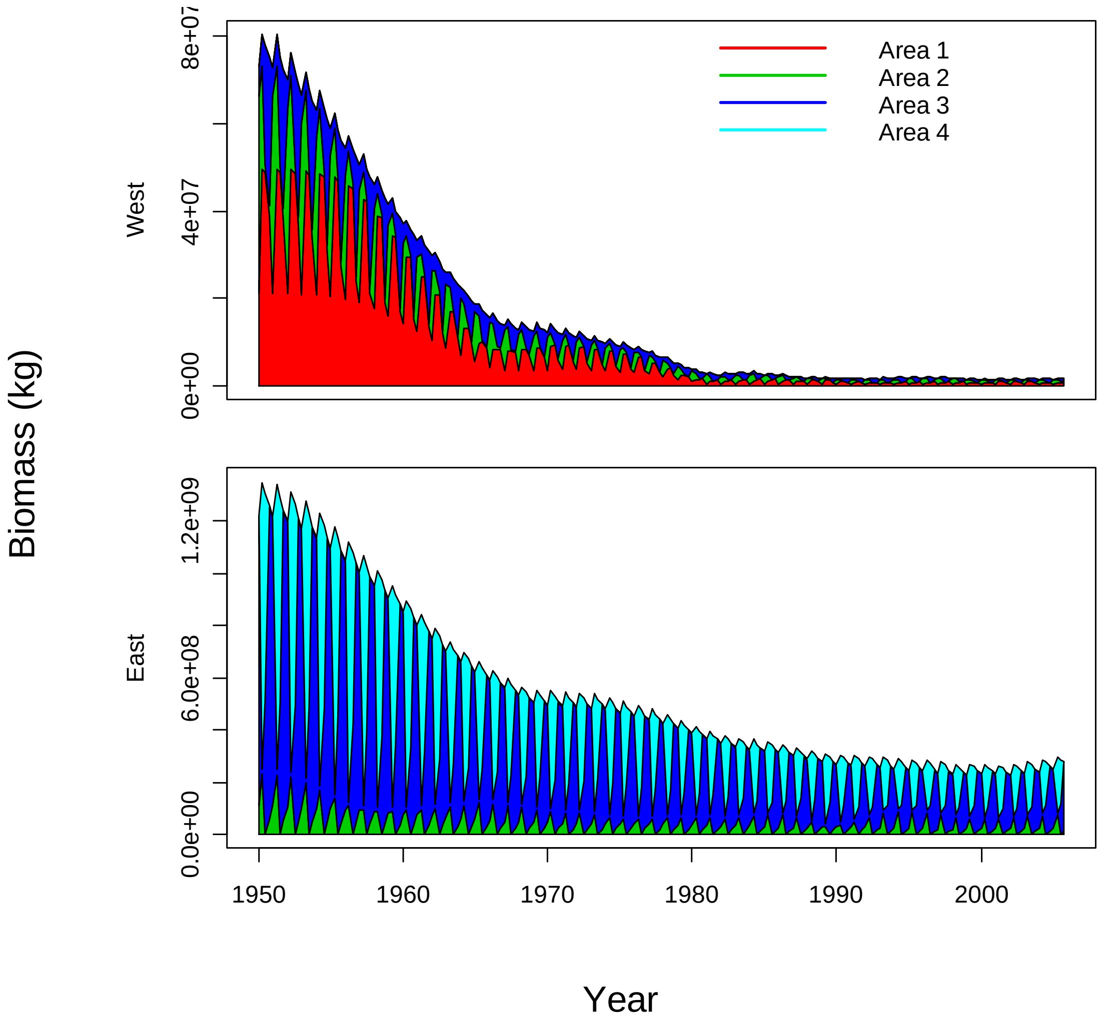

Figure 5 Reconstructed biomass for scenario 4 with Fmsy fixed at 0.05.

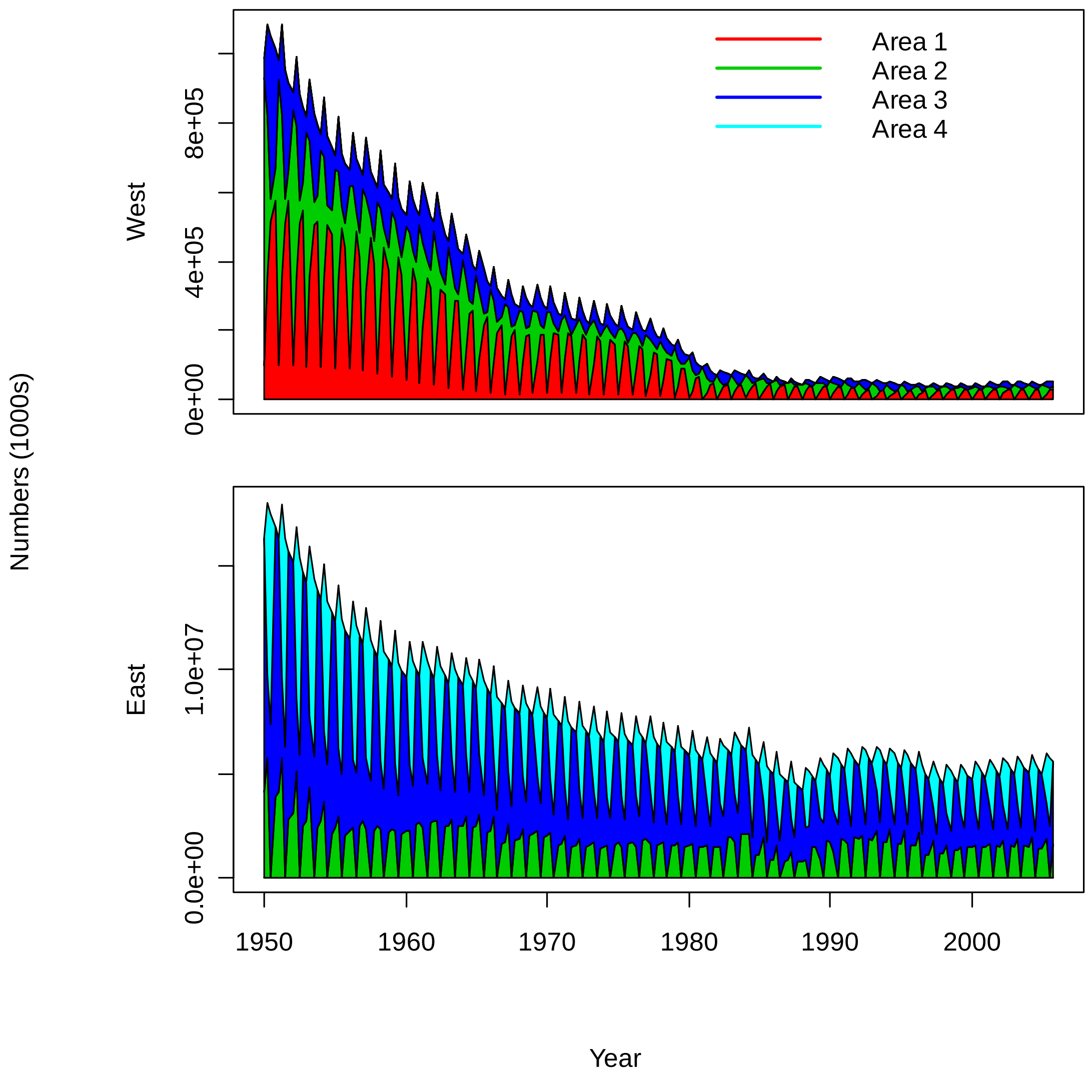

Figure 6 Reconstructed total numbers for scenario 4 with Fmsy fixed at 0.05

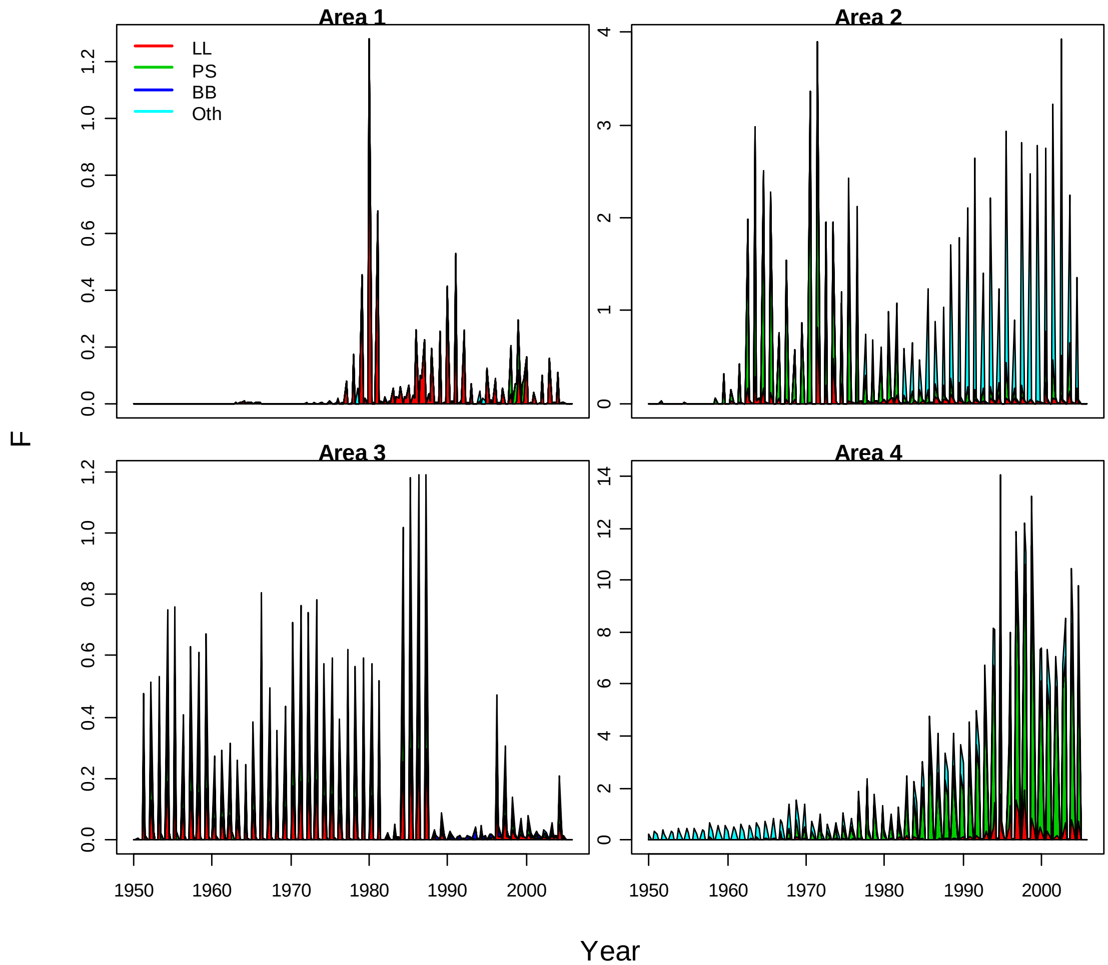

Figure 7 Reconstructed F by area and gear for scenario 4 with Fmsy fixed at 0.05

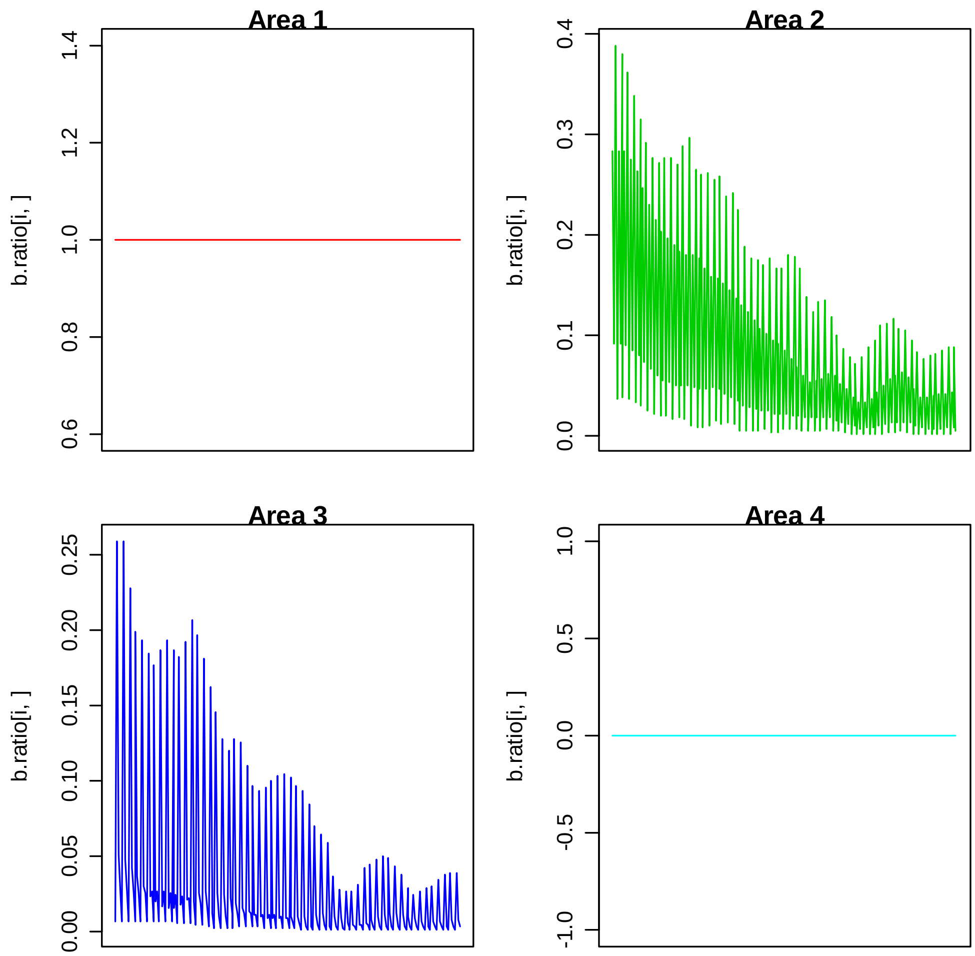

Figure 8 Reconstruction proportions of Western stock to total biomass for scenario 4 with Fmsy fixed to 0.05.

Discussion

Estimates of MSY were quiet similar to existing assessments but having two stock moving presents statistical catch-at-age models such as MAST with many possible ways of explaining the data and the relative weighting of different data sources has a big effect on MAST's predictions. The major explanation for this is that there are very few data that can be used to describe stock-specific movement trajectories since the vast majority of mark-recapture observations consist of fish that have undesignated stocks of origin (see Table 16). As a result, the model can move fish around in order to best fit CPUE indices with little penalty for producing unreasonable GOM or MED stock sizes. One desperately needed item is to assign stock of origin for tagged fish, to the extent possible and to sample historical and current catch samples for relative stock numbers. This information can be readily include into MAST as a set of multinomial observations to predicted stock compositions like Figure 8 Reconstruction proportions of Western stock to total biomass for scenario 4 with Fmsy fixed to 0.05. Additional weighting schemes should be employed to further test the model's sensitivity to such likelihood weighting of various kinds. It would also be useful to have longer CPUE time-series for times before the 1970's VPA assessment start point. While the VPA cannot use them, it should prove useful to fit them with this model to help properly characterize the population dynamics earlier in the time series.

Individual estimates of MSY can differ by a lot, in particular for the Western stock where MSY differs by a factor of nearly double (Table 14). That said, mixing between stock is predicted to be high meaning that defining stock-specific quotas might better be replaced by determining area-specific fishing mortalities that both stocks can support, across a range of mixing rates and stock sizes.

While finer spatial dynamics are possible with MAST, the existing model stretches the limit of conventional 32 bit operating systems since a lot of memory is required to store derivative information needed in order to calculate Hessian and covariance matrices. The memory footprint is about 1.1 gigabytes. In addition to the memory burden, the model is slow - the current four area model requires at least an hour to converge.

While we have been critical of the problems associated with CPUE indices here our own analysis of mark-recapture data begs a thorough examination of potential biases by mark-recapture programs used to date. Indeed some of the same criticisms applied to how CPUE data do not representatively sample the potential fish distribution apply to mark-recapture data also. To a large extent, tags of all types have been put on fish only over a very limited spatial distribution. Given that the stocks are distributed over much of the Atlantic Ocean over a tiny sample of the possible sampling universe. In addition, we have only sampled those fish having movement trajectories that allowed them to captured and marked, and subsequently recaptured making our sample one only of those fish whose movement trajectories resulted them getting captured in fishing gear (at least for the initial capture phase). A related matter to examine here is how time and area-dependent reporting rate will affect our interpretation of stock movement. These are matters that still require considerable examination in the form of simulation testing.

Including additional analysis of tag-reporting rates, and better characterizing gear-selectivity, and how it has changed over the course of the fishery are the next most important matters to attend to in the development MAST. While we recognized it to be an issue from the very beginning that simplification of gears into a single gear type with an asymptotic shape was not representative of the current state of affairs this simplification was necessary to get the model off the ground. To deal with the latter, it would be useful to build this model conditioned on effort, rather than on catches. In this way, dynamics producing CPUE hyperstability could be modeled and tested. We initially explored the use of the TASK-II dataset for this purpose but it was in complete. Modeling the dynamics conditioned on effort would help deal with changes in effort distribution as well as smaller spatial scale dynamics.

We emphasize that this model is still very much in the development phase. We present it here to introduce the methodology and development progress but we do not intend that its results be forwarded for the purpose of target setting. Until we have simulation tested the performance of MAST with these across a range of scenarios, we encourage readers to consider our results preliminary. Nevertheless we feel that the approach is promising.

Modeling Atlantic bluefin population dynamics at finer scale offers several advantages over traditional one or even two boxes. Firstly this approach is a more realistic representation of the stock dynamics and it is better suited to analyzing the performance of various different spatial policy options. With MAST it will be possible to examine the effects of smaller scale temporal and spatial closures, accounting for estimates of seasonal movement rates by stock between the management areas of interest. In addition to this, the model now has the basic architecture to accommodate both the stock mixing issue and also reaching back further in time to estimate historical biomasses.

Parameter Name	**Symbol**	***Value stock 1 (GOM)***	***Value stock 2 (MED)***
Asymptotic size	L_∞	*313cm*	*313cm*
von Bertalanffy growth parameter	K	*0.09* yr^{-1}	*0.09* yr^{-1}
Age at theoretic zero length	t_o	*0.96 yr*	*0.96 yr*
Gear selectivity length at half selectivity (all gears)	L_h	*{50,50,50,50}cm*	*{50,50,50,50}cm*
Gear selectivity slope (all gear)	P	*{0.1 0.1 0.1 0.1}*	*{0.1 0.1 0.1 0.1}*
Maturity at age	Φ	-	-
Age at half maturity	a_h	*11 yr*	*8 yr*
Slope of the maturity ogive	Λ	*2*	*2*
Length-weight converstion coefficient	A	*36.285*	*36.285*
Length-weight conversion exponent	B	*0.3381*	*0.3381*
Length-weight conversion equation	$L=\alpha W^b$	-	-
Natural mortality rate	*M*	*0.13* yr^{-1}	*0.13* yr^{-1}

Table 1 Model variables and symbols.

Indices	**Symbol**
Stock	i
Year	y
Age	a
Gear	g
Quarter	qa
Time	t
State	s
Area	l
Tag type	k

Table 2 Table of indeces for population dynamics equations

State Index	Tag State s_t	Observation Probabilities $p(y_t\|s_t)$ where	Observation Probabilities $p(y_t\|s_t)$ where
1-3	On fish area i	γ	1-γ
4-6	Captured in fishing gear g in area l	R	1-R
7	Shed	0	1
8	Dead	0	1

Table 3. Probability of observations given the state (*p(yt|st)*, by state index for archival tags

State Index	Tag State s_t	Observation Probabilities $p(y_t\|s_t)$ where k>0	Observation Probabilities $p(y_t\|s_t)$ where k>0
1-3	On fish in areas L_i	0	0
4-6	Captured in fishing gear g in area l	R	1-R
7	Shed	0	1
8	Dead	0	1

Table 4 $p(y_t|s_t)$ for conventional tags

State Index	Tag State s_t	State Probabilities $p(s_t Y_{t-1})$
1-3	On fish areas L_i	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(s=1)}^{L_i(s=3)} \mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
4-6	Captured in fishing gear g in area l	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} \mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,l,t-1}})(1-D_{t-1}) + \sum_{s=4}^{6} P(s_t \mid Y_{t-1})$
7	Shed	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} \mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,i,t-1}})D_{t-1} + P(s_t = 7 \mid Y_{t-1})$
8	Dead	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} \mu(l,l')P(s_t \mid Y_{t-1}) e^{-(\sum_g v_{i,g,t-1}F_{g,i,t-1})}(1-e^{-m_{i,t}})(1-D_{t-1}) + P(s_t = 8 \mid Y_{t-1})$

Table 5. Probability of the state given the data $P(s_{t+1}|Y_t)$ until time t-1 for archival tags in fish of known stock origin.

State Index	Tag State s_t	State Probabilities $p(s_t Y_{t-1})$
1-3	On fish areas L_i	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1})e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
4-6	Captured in fishing gear g in area l	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1})e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,l,t-1}})(1-D_{t-1}) + \sum_{s=4}^{6} P(s_t \mid Y_{t-1})$
7	Popped off	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} \pi\mu(l,l')P(s_t \mid Y_{t-1})e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
8	Shed	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1})e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{g,t-1}F_{g,i,t-1}})D_{t-1} + P(s_t = 8 \mid Y_{t-1})$
9	Dead	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1})e^{-(\sum_g v_{g,t-1}F_{g,i,t-1})}(1-e^{-m_{i,t}})(1-D_{t-1}) + P(s_t = 9 \mid Y_{t-1})$

Table 6 . Probability of the state given the data $P(s_{t+1}|Y_t)$ until time t-1 for PSAT tags in fish of known stock origin.

State Index	Tag State s_t	Observation Probabilities $p(y_t \mid s_t)$ where	Observation Probabilities $p(y_t \mid s_t)$ where
1-3	On fish areas L_i	γ	1-γ
4-6	Captured in fishing gear g in area i	1	1-R
7	Shed	0	1
8	Pop off	1	0
9	Dead	0	1

Table 7 $p(y_t \mid s_t)$ **for PSAT tags**

Table 8 Probability of the state given the data $P(s_{t+1} \mid Y_t)$ **until time t-1 for PSAT tags in fish of known stock origin.**

State Index	Tag State s_t	State Probabilities $p(s_t Y_{t-1})$
1-3	On GOM fish areas $l=L_i$	$P(s_{t+1}\mid Y_t)=\sum_{l=L_1(1)}^{L_1(3)}\mu(l,l')P(s_t\mid Y_{t-1})e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
4-6	On MED fish areas $l=L_i$	$P(s_{t+1}\mid Y_t)=\sum_{l=L_2(1)}^{L_2(3)}\mu(l,l')P(s_t\mid Y_{t-1})e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
7-9	On GOM (i=1) Fish Captured in fishing gear g	$P(s_{t+1}\mid Y_t)=\sum_{l=L_i(1)}^{L_i(3)}\mu(l,l')P(s_t\mid Y_{t-1})e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,l,t-1}})(1-D_{t-1})+\sum_{s=7}^{9}P(s_t\mid Y_{t-1})$
10-12	On MED (i=2) fish Capture in fishing gear g	$P(s_{t+1}\mid Y_t)=\sum_{l=L_i(1)}^{L_i(3)}\mu(l,l')P(s_t\mid Y_{t-1})e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,l,t-1}})(1-D_{t-1})+\sum_{s=10}^{12}P(s_t\mid Y_{t-1})$
13	Shed on GOM (i=1)	$P(s_{t+1}\mid Y_t)=\sum_{l=L_i(1)}^{L_i(3)}\mu(l,l')P(s_t\mid Y_{t-1})e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,i,t-1}})D_{t-1}+P(s_t=7\mid Y_{t-1})$
14	Shed on MED (i=2)	$P(s_{t+1}\mid Y_t)=\sum_{l=L_i(1)}^{L_i(3)}\mu(l,l')P(s_t\mid Y_{t-1})e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,i,t-1}})D_{t-1}+P(s_t=7\mid Y_{t-1})$
15	Dead GOM (i=1)	$P(s_{t+1}\mid Y_t)=\sum_{l=L_i(1)}^{L_i(3)}\mu(l,l')P(s_t\mid Y_{t-1})e^{-(\sum_g v_{g,t-1}F_{g,i,t-1})}(1-e^{-m_{i,t}})(1-D_{t-1})+P(s_t=9\mid Y_{t-1})$
16	Dead on MED (i=1)	$P(s_{t+1}\mid Y_t)=\sum_{l=L_i(1)}^{L_i(3)}\mu(l,l')P(s_t\mid Y_{t-1})e^{-(\sum_g v_{g,t-1}F_{g,i,t-1})}(1-e^{-m_{i,t}})(1-D_{t-1})+P(s_t=9\mid Y_{t-1})$

Table 9 Model of archival tag states put on fish of unkown origin.

State Index	Tag State s_t	State Probabilities $p(s_t Y_{t-1})$
1-3	On GOM fish areas l=L_i	$P(s_{t+1} \mid Y_t) = \sum_{l=L_1(1)}^{L_1(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
4-6	On MED fish areas l=L_i	$P(s_{t+1} \mid Y_t) = \sum_{l=L_2(1)}^{L_2(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
7-9	On GOM (i=1) Fish Captured in fishing gear g	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,l,t-1}})(1-D_{t-1}) + \sum_{s=7}^{9} P(s_t \mid Y_{t-1})$
10-12	On MED (i=2) fish Capture in fishing gear g	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,l,t-1}})(1-D_{t-1}) + \sum_{s=10}^{12} P(s_t \mid Y_{t-1})$
13	Popped off on GOM (i=1)	$P(s_{t+1} \mid Y_t) = \sum_{l=L_1(1)}^{L_1(3)} \pi\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
14	Popped off on MED (i=2)	$P(s_{t+1} \mid Y_t) = \sum_{l=L_1(1)}^{L_1(3)} \pi\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1}+\sum_g v_{i,g,t-1}F_{g,l,t-1})}(1-D_{t-1})$
15	Shed on GOM (i=1)	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,i,t-1}})D_{t-1} + P(s_t = 7 \mid Y_{t-1})$
16	Shed on MED (i=2)	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(m_{i,t-1})}(1-e^{-\sum_g v_{i,g,t-1}F_{g,i,t-1}})D_{t-1} + P(s_t = 7 \mid Y_{t-1})$
17	Dead GOM (i=1)	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(\sum_g v_{g,t-1}F_{g,i,t-1})}(1-e^{-m_{i,t}})(1-D_{t-1}) + P(s_t = 9 \mid Y_{t-1})$
18	Dead on MED (i=1)	$P(s_{t+1} \mid Y_t) = \sum_{l=L_i(1)}^{L_i(3)} (1-\pi)\mu(l,l')P(s_t \mid Y_{t-1}) e^{-(\sum_g v_{g,t-1}F_{g,i,t-1})}(1-e^{-m_{i,t}})(1-D_{t-1}) + P(s_t = 9 \mid Y_{t-1})$

Table 10 Table of modeled tag state for PSAT tags attached to fish of unknown origin

Parameter Description	**Units**	**Symbol**
Maximum sustainable yield	kg/ yr	*MSY*
Fishing rate to achieve MSY	yr^{-1}	F_{msy}
Fishing mortality	yr^{-1}	*F*
Natural mortality	yr^{-1}	*M*
Movement transitions	$yr/4^{-1}$	μ
Recapture History	-	*Y*
Recapture Observation	-	*y*
State	-	*s*
Probability of observation given the state and all data until t-1	-	$P(y_t \vert s_t, Y_{t-1})$
Probability of the state given all data up until time *t-1*	-	$P(s_t \vert Y_{t-1})$

Table 11 Table of symbols for mark-recapture likelihoods

Parameter	*Symbol*	*Prior*
Maximum sustainable yield (*kt* {stock1, stock 2}	*MSY*	{N~(5,10), N~(25, 50)}
Fishing rate to yield msy (/yr) {stock1, stock 2}	*Fmsy*	{ N~(5,10), N~(25, 50)}
Movement parameters	μ	Beta(2,2)
Probability of a geoposition	γ_g	Beta(2,2)
Standard Deviation of pop-off quarter given programmed pop-off	σ_π	N~(1,5)

Table 12 Prior densities used for base-case model fitting

Scenario Number	Fmsy estimation	CPUE likelihood weighting
1	Free	0.5
2	Fixed at {0.05,0.05}	0.5
3	Free	0.1
4	Fixed at {0.05,0.05}	0.1

Table 13 Fitting scenarios used for preliminary fitting.

		Value				**Fit Or Fixed**			
Parameter Name	**Symbol**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Fishing mortality producing MSY (/yr)	F_{msy}	NA	NA	GOM=0.120 MED=0.122	GOM=0.08 MED=0.08	Fit	Fixed	Fit	Fixed
Maximum sustainable yield (kilotonnes)	*MSY*	NA	NA	GOM=6.63 MED=23.34	GOM=3.62 MED=21.5	Fit	Fixed	Fit	Fixed
Archival and PSAT probability of geoposition	γ_g	NA	0.662	0.65	0.675	Fit	Fixed	Fit	Fixed
Reporting R conventional tag	Rc	0.12	0.12	0.12	0.12	Fixed	Fixed	Fixed	Fixed
Reporting Rate Archival and PSAT	Ra	0.20	0.20	0.20	0.20	Fixed	Fixed	Fixed	Fixed
Conventional Tag shedding rate /yr	Dc	0.12	0.12	0.12	0.12	Fixed	Fixed	Fixed	Fixed
Archival Tag shedding Rate /yr	Da	0.12	0.12	0.12	0.12	Fixed	Fixed	Fixed	Fixed
Standard deviation of pop-off date (quarters)	σ_π		1.46	4.81	1.36	Fit	Fit	Fit	Fit
Mean pop-off date given predicted popoff date (quarter)	μ_π	0	0	0	0	Fixed	Fixed	Fixed	Fixed

Table 14 Estimated parameters and corresponding values for each scenario run.

CPUE Index
CAN GLS
CAN SWNS
US RR >195
JLL Area 2
JLL GOM
GOM Larval Zero Inflated
US PLL GOM
SP BB1
SP BB2
SP BB3
SP BB4
SP BB5
SP BB 7-15
SP BB 15-25
SPBB All
SP Trap

Table 15 Table of CPUE indices fitted with for base run.

Mark-recapture data type	Number of modeled tags
GOM Archival Tags	10
MED Archival Tags	13
Undesignated Archival Tags	29
GOM PSAT Tags	17
MED PSAT Tags	14
Undesignated PSAT Tags	114
GOM Conventional	1965
MED Conventional	92
Undesignated Conventional	43791

Table 16 Summary of mark-recapture data used.

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