Inna Senina, John Sibert

Progress in parameter estimation for Spatial Population and Ecosystem Dynamics Model (SEAPODYM) applied to Pacific skipjack

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Pelagic Fisheries Research Program
http://www.soest.hawaii.edu/PFRP/
Objectives

Explore the model. What mechanisms control population migrations and abundance? Which model parameters to consider for estimation?

Provide efficient computational tool for searching optimal model parametrization in order to make the model suitable for decision making and management in large pelagic predators fishery.

Perform necessary testing of the developed software.

Estimate model parameters.
How it works

**Input**
3-layer monthly data:
- Temperature,
- Ocean currents
1-layer monthly data:
- Chlorophyll
3-layer quarterly data:
- Dissolved oxygen

**Fisheries data**

**Sub-model**
Recruites
of forage populations

**Coupled model**
6 forage populations: epipelagic, mesopelagic migrant and non-migrant, bathypelagic active-migrant, migrant and non-migrant
Tuna age classes:
- 3 juvenile age classes,
- 15 adult age classes

**Output**
Tuna population distribution
Predicted catch
Habitat approach

Spawning habitat index, September 2004

Juvenile habitat index, March 2004

Six-months adult skipjack habitat index, July 2004

4-years adult skipjack habitat index, July 2004
Mathematical model

\( F_n, n = 1..6 \) are densities of mature forage populations

\( J_0 \) is density of tuna larvae; \( J_k, k = 1, 2 \) are juvenile monthly-based age classes

\( N_a, a = 1..15 \) are densities of adult quarterly-based age classes of tuna

The top level of the model is:

\[
\begin{aligned}
J_0^t &= \kappa I_s \\
J_k^t &= q_{k-1} J_{k-1}^{t-1} + (1 - q_k) J_k^{t-1}, \quad k = 1, 2 \\
N_0^t &= q_k J_2^{t-1} + (1 - q_0) N_0^{t-1}, \\
N_a^t &= q_{a-1} N_{a-1}^{t-1} + (1 - q_a) N_a^{t-1}, \quad a = 1..15 \\
\frac{\partial F_n}{\partial t} &= -\vec{v} \nabla F_n + \nabla (\sigma \nabla F_n) - (\lambda_n + \omega_n) \cdot F_n \\
\frac{\partial J_k}{\partial t} &= -v_0 \nabla J_k + \nabla (\sigma \nabla J_k) - g_k(I_j(P, F, T_0, N)) \cdot J_k \\
\frac{\partial N_a}{\partial t} &= -\tilde{v} \nabla N_a + \nabla (D_a \nabla N_a - (\chi \nabla I_a, N_a)) - f_a(I_a(P, F, T, O)) \cdot N_a
\end{aligned}
\]
Table 1: Parameters of habitat indices

<table>
<thead>
<tr>
<th>N</th>
<th>Parameter</th>
<th>Function(s)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\sigma_0$</td>
<td>$\Phi(T_0), I_s, I_j$</td>
<td>determines the range of SST in spawning and juvenile’s habitat index</td>
</tr>
<tr>
<td>2</td>
<td>$T_{0opt}$</td>
<td>$\Phi(T_0), I_s, I_j$</td>
<td>optimal SST in spawning and juvenile’s habitat index</td>
</tr>
<tr>
<td>3</td>
<td>$\alpha$</td>
<td>$I_{sp}$</td>
<td>constant determining the impact of ratio $P/F$ on spawning habitat index</td>
</tr>
<tr>
<td>4</td>
<td>$\sigma$</td>
<td>$\Phi(T), I_a$</td>
<td>determines the range of $T$ in feeding habitat index</td>
</tr>
<tr>
<td>5</td>
<td>$T_{opt}$</td>
<td>$\Phi(T), I_a$</td>
<td>optimal temperature is the function of age</td>
</tr>
<tr>
<td>6</td>
<td>$\theta$</td>
<td>$\Psi(O), I_a$</td>
<td>coefficient defining slope of oxygen function</td>
</tr>
<tr>
<td>7</td>
<td>$O_{cr}$</td>
<td>$\Psi(O), I_a$</td>
<td>oxygen concentration threshold</td>
</tr>
</tbody>
</table>
### Table 2: Parameters of mortality functions

<table>
<thead>
<tr>
<th>N</th>
<th>Parameter</th>
<th>Function(s)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$M_{p_{max}}$</td>
<td>$M_p, g, f$</td>
<td>tuna mortality rate due to predation</td>
</tr>
<tr>
<td>2</td>
<td>$\beta$</td>
<td>$M_p, g, f$</td>
<td>slope coefficient in tuna predation mortality</td>
</tr>
<tr>
<td>3</td>
<td>$M_{s_{max}}$</td>
<td>$M_s, g, f$</td>
<td>tuna mortality rate due to scenescence</td>
</tr>
<tr>
<td>4</td>
<td>$\xi$</td>
<td>$M_s, g, f$</td>
<td>parameter defining dependence of natural mortality on tuna age</td>
</tr>
<tr>
<td>5</td>
<td>$\zeta$</td>
<td>$M_s, g, f$</td>
<td>the mean age at which $M_s$ is age-independent</td>
</tr>
<tr>
<td>6</td>
<td>$\epsilon$</td>
<td>$g, f$</td>
<td>variability of tuna mortality with habitat index</td>
</tr>
</tbody>
</table>

#### Scenescence mortality

- Threshold age = 30 months
- 20 months

#### Total mortality

- Habitat index values: 0.1, 0.15, 0.2, 0.25, 0.3
Parameters of movement

Table 3: Parameters defining tuna movement

<table>
<thead>
<tr>
<th>N</th>
<th>Parameter</th>
<th>Function(s)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$D_{max}$</td>
<td>$D_a$</td>
<td>maximal diffusion coefficient</td>
</tr>
<tr>
<td>2</td>
<td>$\gamma$</td>
<td>$D_a$</td>
<td>parameter defining rate of decrease of D with habitat index</td>
</tr>
<tr>
<td>3</td>
<td>$MSS$</td>
<td>$U, V$</td>
<td>maximal sustainable speed of the adult tuna</td>
</tr>
</tbody>
</table>

Diffusion coefficient:

$$D_a = D_{max} \left(1 - \frac{I_a}{\gamma + I_a}\right) \left(1 - \rho \frac{\partial I_a}{\partial x}\right)$$

Velocity of directed movement:

$$U = \chi \frac{\partial I_a}{\partial x}, \quad V = \chi \frac{\partial I_a}{\partial y}, \quad \text{where} \quad \chi = \frac{MSS}{G_{max}}$$
The Method

\[ \mathbf{X} = (M_{p_{\text{max}}}, \beta, M_{s_{\text{max}}}, \xi, \zeta, \epsilon, \sigma_0, T_{0_{\text{opt}}}, \alpha, \sigma, T_{\text{opt}}, \theta, O_{cr}, D_{\text{max}}, \gamma, M_{SS}, \kappa) \]

\[ C_{t_{\text{pred}}} = \sum_a \sum_f s q E_f(x, y, t) N_a(x, y, t) W_a \]

\[ C_{t_{\text{obs}}} = \sum_f C_f(x, y, t) \]

The objective is:

- to minimize the functional:

\[ L(X|C) = \frac{N_{\text{obs}}}{2} \ln \sum_{\Omega, t} (C_{t_{\text{pred}}} - C_{t_{\text{obs}}})^2 \rightarrow \min \]

The technique is:

- to solve forward task to get the solution of the model
- to make inverse run to compute gradients of cost function with respect to variable parameters
- test adjoint code

\[ \frac{\partial L}{\partial X_i} = \lambda_i \approx \frac{L(X_i + \delta X_i) - L(X_i)}{\delta X_i} \]
### Very first results

<table>
<thead>
<tr>
<th>N</th>
<th>Parameter</th>
<th>Function</th>
<th>Initial</th>
<th>t = 49</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$M_{p,\text{max}}$</td>
<td>predation mortality</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>$\beta$</td>
<td>predation mortality</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td>3</td>
<td>$M_{s,\text{max}}$</td>
<td>scenscence mortality</td>
<td>0.167</td>
<td>0.49</td>
</tr>
<tr>
<td>4</td>
<td>$\xi$</td>
<td>scenscence mortality</td>
<td>-0.267</td>
<td>-0.99</td>
</tr>
<tr>
<td>5</td>
<td>$\zeta$</td>
<td>scenscence mortality</td>
<td>30</td>
<td>31.7</td>
</tr>
<tr>
<td>6</td>
<td>$\epsilon$</td>
<td>scenscence mortality</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>$\sigma_0$</td>
<td>spawning/juvenile index</td>
<td>2</td>
<td>1.04</td>
</tr>
<tr>
<td>8</td>
<td>$T_{\text{0,\text{opt}}}$</td>
<td>spawning/juvenile index</td>
<td>30</td>
<td>26.5</td>
</tr>
<tr>
<td>9</td>
<td>$\alpha$</td>
<td>spawning habitat index</td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>$\sigma$</td>
<td>feeding habitat index</td>
<td>3</td>
<td>0.69</td>
</tr>
<tr>
<td>11</td>
<td>$T_{\text{opt}}$</td>
<td>feeding habitat index</td>
<td>26</td>
<td>32</td>
</tr>
<tr>
<td>12</td>
<td>$\theta$</td>
<td>feeding habitat index</td>
<td>-10</td>
<td>-27.4</td>
</tr>
<tr>
<td>13</td>
<td>$O_{\text{c,r}}$</td>
<td>feeding habitat index</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>14</td>
<td>$D_{\text{max}}$</td>
<td>adult tuna diffusion</td>
<td>15000</td>
<td>67317.5</td>
</tr>
<tr>
<td>15</td>
<td>$\gamma$</td>
<td>adult tuna diffusion</td>
<td>0.04</td>
<td>$\approx$ 0</td>
</tr>
<tr>
<td>16</td>
<td>$\text{MSS}$</td>
<td>directed movement speed</td>
<td>1</td>
<td>0.52</td>
</tr>
<tr>
<td>17</td>
<td>$\kappa$</td>
<td>spawning</td>
<td>300</td>
<td>1000</td>
</tr>
</tbody>
</table>
Population distributions

Juvenile age classes distribution with initial parametrization

With estimated parameters

Adult age classes distribution with initial parametrization

With estimated parameters
Predicted vs. observed catch

Skipjack predicted and observed catch at January 1980

Catch predicted with initial parametrization

Catch predicted with estimated parameters

Spatial correlations between skipjack predicted and observed catch
Is it possible to avoid spinup in optimization model?

Building the population

B Juv. skj

B Young skj

B Rec skj

B Adult skj

Time
0   e+00 6   e+05
0 1500000
0 600000
Conclusions

Adjoint method is feasible for Seapodym

Future plans

What movement model is more appropriate? Skip spinup?
Include catchability coefficients to the estimation procedure.
Minimize likelihood taking into account only data for Western Pa-
cific ocean.
Provide more reasonable constraints.
Perform parameter estimations for different time periods and initial
conditions.
Test different likelihood functions.
Apply mixed-resolution approach within the optimization frame-
work.