Prediction of trade-offs between growth and maturation in *Todarodes pacificus* depending on the environmental conditions

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Hyejin Song, Michio J. Kishi and Yasunori Sakurai
Hokkaido University, Japan
IMPETUS FOR THIS STUDY

• Episodic “regime shifts” involving entire biological communities occur worldwide (Liuch-Belda et al., 1992), and are a key area of research.

• Temperature is thought to be an important causative factor in regime shifts, and many scientists have suggested that species-specific “optimal growth temperature” are important (Climate Effects on Fish and Fishery, Sendai, 2010).

• However, there are multiple, synergistic / interacting factors having indirect effects based on trophodynamics.

• Future climate situations may produce novel combinations of factors - thus ecosystem and full life cycle modeling will be required to make the best possible projections.

(Data derived from the Japan Sea Research Institute, Japan and the National Fisheries Research and Development Institute, Korea).

Sakurai, 2000
Feeding ground with oceanography features

- Tsushima Current
- Mixed water region
- Kuroshio Extension
- Oyashio Front
- Spawning ground
Can we predict trade-offs between growth and maturation corresponding to environmental condition/climate change in *Todarodes pacificus* using a coupled model?

-> *Yes, we can!* (Obama & Kishi)...

- Simulate success or fail of growth and reproduction by the optimum temperature along different migration routes.
- Predict how migration route and spawning area will change due to global warming.
MODEL DESCRIPTION

• **Bioenergetics model** (Rustam, 1988 ; Kishi *et al*., 2009)
  ▫ Captive experimental data during 2006-2010

• **NEMURO** (North Pacific Ecosystem Model for Understanding and Regional Oceanography; Kishi *et al*., 2007)
  • Temperature (average 0-50m depth)
  • Prey density (large and predatory zooplankton biomass)
Bioenergetics Model

\[
\frac{dW}{W \cdot dt} = \left[ C - (R + SDA + F + E + P) \right] \cdot \frac{CAL_Z}{CAL_F}
\]

\(W\): wet weight (g),  \(t\): time (day)
\(C\): consumption (g prey/g fish/day),
\(R\): respiration or losses through metabolism (g prey/g fish/day)
\(SDA\): specific dynamic action or losses due to energy costs of digesting food (g prey/g fish/day)
\(F\): egestion or losses due to feces (g prey/g fish/day)
\(E\): excretion or losses of nitrogenous excretory wastes (g prey/g fish/day)
\(P\): egg production or losses due to reproduction (g prey/g fish/day)
\(CAL_Z\): caloric equivalent of zooplankton (cal/g zooplankton)
\(CAL_F\): caloric equivalent of squid (cal/g squid)
consumption

\[ C = C_e \cdot f_e(T) \]

where

\[ f_e(T) = gCTa \cdot gCTb \]

\[ C_e = \sum_{j=1}^{n} C_j \]

\[ C_j = \frac{\frac{PD_j \cdot v_j}{K_j}}{1 + \sum_{k=1}^{n} \frac{PD_k \cdot v_k}{K_k}} \]

\[ C_{\text{max}} = a_e \cdot W^b_e \]

Thornton & Lessem (1978)

\[ gCTa = \frac{(xk1 \cdot t4)}{(1.0 + xk1 \cdot (t4 - 1.0))} \]

\[ gCTb = \frac{(xk4 \cdot t6)}{(1.0 + xk4 \cdot (t6 - 1.0))} \]

PD \_j: density of prey type j (g wet weight/m^3),

\[ v_j \]: vulnerability of prey type j to predator i

\[ K_j \]: half saturation constant (g wet weight/m^3),

\[ c \]: consumption rate (g/g/day),

\[ C_{\text{max}} \]: maximum consumption rate (g/g/day),

\[ f_e(T) \]: temperature dependence function for consumption

i: predator type

Physical model

Water temp.
Growth & Reproduction potential vs Temperature

Larvae (<15 mm)
Juveniles (15-120 mm)
Young (121-170 mm)
Immature (171-230 mm)
Maturing (>230 mm)
Ripening (>230 mm)
Spawning (>230 mm)

Sakurai et al. (1996)
Personal communication by Sakurai
Kidokoro and Sakurai (2008)
Kidokoro and Sakurai (2008), rearing
Rearing
Rearing
Rearing

Best

Bad
# Optimum Temp. for function

<table>
<thead>
<tr>
<th>MALE</th>
<th>TEMP (°C)</th>
<th>TIME</th>
<th>TEMP (°C)</th>
<th>FEMALE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>te1</td>
<td>te2</td>
<td>te3</td>
<td>te4</td>
</tr>
<tr>
<td>Larvae</td>
<td>1-30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Juveniles</td>
<td>6</td>
<td>17</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>Young</td>
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<tr>
<td>Immature</td>
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<td>21</td>
<td>23</td>
</tr>
<tr>
<td>Maturing</td>
<td>13</td>
<td>15</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>Ripening</td>
<td>13</td>
<td>15</td>
<td>17</td>
<td>23</td>
</tr>
</tbody>
</table>

**Suitable temperature**
- Red: For growth
- Green: For maturation
Trade-offs between growth and maturation; Temperature dependence
Summary of effects of different temperature to growth and maturation of *T. pacificus* by captive experiments during 2006–2009 (p.c. Sakurai)

- **Male (♂)**:
  - 12°C: Lower limit for survival
  - 13°C: High growth & maturing (testis)
  - 15°C: Slow growth with active mating
  - 17°C: Ripening (accessory glands)
  - 19°C: Ripening & spawning

- **Female (♀)**:
  - 12°C: High growth under immature stage
  - 13°C: High growth with maturing (ovary, oviducal glands, nidamental glands)
  - 15°C: Slow growth with active mating
  - 17°C: Ripening (accessory glands)
  - 19°C: Ripening & spawning
- Equations of maturation

1) Gonad W: gonad + nidamental gland + ovary + oviduct

2) Testis W: testis + accessory gland

\[
G = G_r \cdot f_G (T)
\]

\[
G_r = \sum G_j
\]

\[
G_j = \frac{G_{MAX} \cdot \frac{PD_{ij} \cdot v_{ij}}{K_{ij}}}{1 + \sum_{K = 1}^{n} \frac{PD_{ii} \cdot v_{ij}}{K_{ij}}}
\]

\[
G_{MAX} = a_G W + b_G
\]

\[
G_{MAX} = -0.0011W + 0.7795
\]

\[
T_{MAX} = -0.0047W + 0.9807
\]
TEST RUN
CASE: AN CAPTIVE INDIVIDUAL UNDER 13/ 15/ 17/ 19°C
(No food limitation)

✓ Growth

✓ Maturation
Migration routes for the modeling

Cohorts
- Autumn Cohort 1
- Autumn Cohort 2
- Winter Cohort 3
- Winter Cohort 4

Feeding migration
Spawning migration
Body weight along migration route and 1989RS

- **C1, C2**: 86yr < 96yr
- **C3, C4**: 86yr > 96yr

86yr: C3 - C2 - C4 - C1
96yr: C2 - C1 : C3 - C4
Maturation along migration route and 1989RS

86yr < 96yr: C4 - C3 - C1 - C2

C3, C4 had the earlier and better maturation than C1, C2
Temperature along migration route and 1989RS

C1

C2

C3

C4

Temp (°C)

Temp (°C)

growth
Jday
maturation

Jday
Prey density along migration route and 1989RS

C1

C2

C3

C4

Jday

ZP (μM-N)

0

0.000

0.050

0.100

0.150

0.200

0.250

0.300

0.350

0
100
200
300
400

0
100
200
300
400

86
96
DISCUSSION & CONCLUSION

- Autumn cohorts-C1, 2 and winter cohort-C3 showed normal growth due to proper prey density and temperature, but C4 had poor growth; 86yr-winter cohorts / 96yr-autumn cohorts

- All cohorts showed successful maturation in both years. Although the winter cohort occurred the earlier trade-off, it might not successfully reproduce if it didn’t reach the spawning ground.

- Water temperature of migration routes showed the same trend with cool- and warm RS only in autumn cohorts.

This coupled model can be used to changes in growth and maturation depending on environmental conditions that occur in climate regime shifts.