Larval Fish Physiology & Individual-based Models: Exploring Climate Impacts on Early Life Stages of Key Species

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Coupled physical - biological IBMs for marine fish larvae

IBMs allow individuals to have unique characteristics - in the case of pelagic eggs & larvae - environmental conditions in time & space.

(Updated from Tom Miller 2006, WKAMF)
Part I
dendogenus feeding stages
development of eggs & yolksac larvae

Part II
exogenously feeding stages
rates of energy loss & gain by larvae

Part III model application (North Sea)
1-D IBM to 3-D coupled models
demersal gadid vs. pelagic clupeid
(Gadus morhua) (sprattus sprattus)
larval vital rates, temperature & prey availability
Part I: Eggs and Yolksac Larvae (simple IBM’s)

Temperature

- Start
- Next Time Step
- Egg ?
- Yolk Sac ?
- Egg
  - yes
  - $H_{ep} = 1.3T^{1.26}$
- Yolk Sac
  - yes
  - $H_{ys} = 0.4T^{1.26}$
- (1-hr time step)

Climate impacts on:
- Transport
- Habitat connectivity
- Life cycle closure

Drift simulations
Egg Development Rates vs. Temperature

\[ DR = aT^B \]

- \( DR = 1.3T^{1.26} \)
- \( DR = 2.9T^{0.57} \)

Development Rate (% d\(^{-1}\))

Water Temperature (°C)

Atlantic Cod

Sprat
Egg Development Rates for 64 Marine Fish Species

\[ DR = a T^B \]

- **DR** = Development Rate (% d⁻¹)
- **T** = Mean Incubation Temperature (°C)

**Thermal Sensitivity of Egg Development Rate (B value)***

**Development Rate (DR) vs. Mean Incubation Temperature (T)**

*Peck, Chambers, Geffen, data compilation*
Yolksac Larvae: Length-at-hatch
(22 marine species)

Length-at-hatch (mm)

Temperature (°C)

Anarhichas lupus
Bairdiella icistia
Clupea harengus
Eopsetta jordani
Engraulis encrasicolus
Gadus morhua
Gadus macrocephalus
Hippoglossoides elassodon
Limanda ferruginea
Morone americana
Myteroperca rosacea
Melanogrammus aeglefinus
Ophiodon elongatus
Pagellus erythrinus
Rhombosolea tapirina
Pagrus major
Paralichthys dentatus
Parophyrys vetulus
Pseudopleuronectes americanus
Sardinops sagax musica
Sparus aurata
Theragra chalcogramma

(M. Peck, & F. Bils unpublished compilation)
Temperature (°C)

Percentage of Maximum Length-at-hatch (%)

Gadus morhua
Gadus macrocephalus
Theragra chalcogramma
Pagrus major
Sparus aurata
Limanda ferruginea
Paralichthys dentatus
Parophyrys vetulus
Pseudopleuronectes americanus
Eopsetta jordani
Myteroperca rosacea
Melanogrammus aeglefinus
Bairdiella icistia
Anarhichas lupus

Normalized to Max Length-at-hatch

(M. Peck, & F. Bils unpublished compilation)
Best (but difficult) comparison is of individual slopes (more negative slope = most impacted by warming)

Yolk$_{abs}$ = 775.4(±92.8) *e$^{-0.099(±0.005)*T}$

$\text{r}^2 \text{ adj} = 0.702$, $n = 139$, $p<0.0001$

Duration of yolksac period (not „point of no return“)

(M. Peck, & C. Lindemann unpublished compilation)
Part II: Exogenously-feeding larvae
Foraging and Growth Subroutines

START

Next Time Step

1-hr time step

Mortality

= \( f(W/L) \)

Growth

(+ or -)

ENERGY GAIN

= \( f(\text{food, larval size, temperature, light, turbulence}) \)

Forage

\[
C = \frac{\sum m_i \times N_{L_S,i} \times CS_{L_S,i}}{1 + \sum N_{L_S,i} \times HT_{L_S,i}} \times \Delta t
\]

Prey Consumed?

(limited by GER & GutMax)

no

yes

no

no

Prey Consumed?

Assimilation & Digestion

no

yes

no

Forage Consumption

= \( f(\text{Encounter Rate ER}) \)

Capture Success (CS)

Handling Time (HT)

Active Metabolism

Growth (+ or -)

Routine Metabolism

ENERGY LOSS

= \( f(\text{larval size, temperature, foraging...}) \)

Mortality

= \( f(W/L) \)

\( \beta = 0.7(1 - 0.3 e^{-0.003(M_D-M_{MIN})}) \)

\( SDA = 0.11 + 4.91 \times 10^{-7} \times m_i \)

\( R_A = k R_{SM&T} \)

\( R_S = b \times M_D^{0.80} \times \left[ \frac{2.57}{10} \right]^{(T-8)} \)
Rate of Energy Loss by Unfed Marine Fish Larvae
(10 species, all rates adjusted to 8°C)

Rate of Metabolic Losses
(µg larval dry weight d⁻¹)

- Atlantic cod (Gadidae)
- Bay Anchovy (Engraulidae)
- Haddock (Gadidae)
- Herring (Clupeidae)
- Lined sole (Achiridae)
- Mackerel (Scrombidae)
- Plaice (Pleuronectidae)
- Sea bream (Sparidae)
- Spotted seatrout (Sciaenidae)
- Summer flounder (Bothidae)

Larval Fish Dry Weight (µg)

Activity multiplier = 2.5
Q₁₀ adjustment (when needed) = 2.5

(≈10% d⁻¹ ??)
Mechanistic IBM: Foraging and Growth Subroutines

**START**

Next Time Step

Light?

- yes
  - Prey Consumed? (limited by GER & GutMax)

- no
  - Forage

  \[
  C = \frac{\sum m_i \times N_{L_S,i} \times CS_{L_S,i}}{1 + \sum N_{L_S,i} \times HT_{L_S,i}} \times \Delta t
  \]

Prey Consumed?

- yes
  - Assimilation & Digestion
    - \[ SDA_{mi} = 0.11 + 4.91 \times 10^{-7} \times m_i \]
    - \[ \beta = 0.7(1 - 0.3e^{-0.003(M_D - M_{MIN})}) \]

- no
  - Growth (+ or -)
  - Mortality = \( f(W/L) \)

**ENERGY GAIN**

\( = f(\text{food, larval size, temperature, light, turbulence}) \)

**ENERGY LOSS**

\( = f(\text{larval size, temperature, foraging...}) \)

**Routine Metabolism**

\[ R_S = b \times M_D^{0.80} \times 2.57^{\left(\frac{\left(T-8\right)}{10}\right)} \]

**Active Metabolism**

\[ R_A = k \times R_{SM&T} \]

**Assimilation & Digestion**
### Rates of gut evacuation

**Single meal**

- **Constant feeding**
  
  \[ \text{CF} = (2 \text{ to } 5) \times \text{SM} \]

**Temperature**

\[ Q_{10} \approx 2.0 \]

\[ \text{GER} = 1.79 \times SL^{-0.83} \]

**14°C**

### Table: Food Consumption

<table>
<thead>
<tr>
<th>Species</th>
<th>Age</th>
<th>Length</th>
<th>T (°C)</th>
<th>Prey Conc.</th>
<th>Evacuation Rate</th>
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</table>

*estimate based upon range in dry weights (196 to 721 mg)

(Peck & Daewel 2007)
Amount of Prey in Gut Contents

Clupea harengus
Hippoglossoides platessoides
Mallotus villosus
Pleuronectes ferrugineus
Stichaeus punctatus
Pleuronectes americanus
Ulvaria subbifurcata
Liparus sp.

Gadus morhua
Glyptocephalus cynoglossus

GB = 0.064(±0.007)*DM^{0.995(±0.064)}
(n = 97, r^2 adj = 0.712, p < 0.0001)

(Pepin & Penny 2000)
1-D to 3-D Modelling of potential survival & growth
(gadoid vs clupeid larvae)

Temperature-dependent energy loss
(daily, active metabolism, etc.)
vs.
Temperature-dependent energy gain
(prey size, gut evacuation & gut biomass, etc.)

Atlantic Cod

Sprat
3-D coupled model system (NPZD component)

Temperature

Seasonal Zooplankton Dynamics

Year = 1993
all values
depth-averaged

Ecosystem Model
2 Phytoplankton groups
2 Zooplankton groups
3 Nutrient cycles

(C. Schrum, Univ. Bergen)
mechanistic IBM for larval fish

3-D Coupled model system

3D circulation & particle tracking

(Daewel et al. 2008 Fish Ocg.)
But, first some simple 1-D results....

Larval growth when prey is unlimited

Larval length (mm) vs. Time (days)

- 12°C
- 4°C

Atlantic Cod
Sprat
1-D model) temperature-specific prey requirements

- **First-feeding**: 150 - 700 µm prey
- **First-feeding**: 150 - 300 µm prey

**Prey Threshold for Survival**

- Fish don’t eat carbon...
  - (converted to copepods in size classes available to first feeding larvae)
3-D Coupled Model Results: North Sea Cod & Sprat

**Temperature (°C)**
- 1992 (average temperature)
- 1996 (cold year)

**Potential survival (%)**
- 1992 (data provided by Irina Alekseeva)

**Prey biomass (mg C m⁻³)**
- First-feeding to 10 mm SL larvae (Daewel et al. In prep)

**Larval concentration (no. grid cell⁻¹)**

**Time (accounting for drift of eggs & larvae)**
3-D Model Results: North Sea Cod and sprat

Temperature (°C)

- 1992 (average temperature)
- 1996 (cold year)

(data provided by Irina Alekseeva)

Potential survival (%)

First-feeding to 10 mm SL larvae

Larval concentration (no. grid cell⁻¹)

Prey biomass (mg C m⁻³)

First-feeding to 10 mm SL larvae

(Daewel et al. In prep)
Most historic spawning grounds for North Sea cod are still active despite very poor recruitment.
Considerable variation exists in physiological attributes of marine fish early life stages that are directly impacted by climate - examples:

**Eggs**
Change in Development Rate vs Temperature

**Yolksac Larvae**
Change in size-at-hatch vs temperature
Change in the time to end of yolk reserves vs temperature

**Feeding Larvae (inter-specific differences)**
rate of energy loss when unfed
maximum biomass of prey in gut & prey size vs body size

Examine interlinkages among physiological traits & rates that change with body size &/ or temperature
\[ C = G + R + E + F \]
Summary & Conclusions II

Biophysical IBMs can test how species-specific differences in physiological traits may influence severity of climate impacts on early life stage vital rates (e.g., cod vs sprat in North Sea)

**Growth response & temperature**
Similar in larval cod & sprat when provided unlimited prey

**Prey thresholds for survival & growth**
Differ between cod & sprat (cod has larger prey field + higher max. gut content, and species have similar energy losses)

**Match-mismatch and warming**
Fidelity to spawning site & time may lead to severe mismatch between cod larvae & zooplankton production. Sprat appears much less vulnerable to warming.

**Work is ongoing with coupled NPZD-IBM ...**
(e.g., inter-annual (20+ yr) comparison for both species)
Acknowledgements

Data Sets
Franziska Bils
Christian Lindemann
Christof Schneider
Audrey Geffen
Christopher Chambers
Greg Lough:

Co-authors
Ute Daewel (hard at work)
Corinna Schrum

Thanks for your Attention!

Questions?, Comments... ... Lunch?