Predicting marine ecosystem responses to environmental variation:

*Now is the time to merge bioenergetics and movement ecology*

Kenneth Rose
Horn Point Laboratory
Cambridge, Maryland
Today

• Organisms will move in response to climate change

• Progress on movement
  – Observations
  – Modeling

• Status of bioenergetics

• Need and opportunities for merging

• Next steps
<table>
<thead>
<tr>
<th>Reference</th>
<th>Publication year</th>
<th>Region</th>
<th>LME</th>
<th>Type</th>
<th># Species</th>
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Progress: Movement Data

REVIEW SUMMARY

ECOLOGY

Aquatic animal telemetry: A panoramic window into the underwater world


Science 348: 1255642, 2015
Fig. 2 Aquatic telemetry to understand the movements of animals in four dimensions: horizontal (2D), vertical (depth), and over time.

Nigel E. Hussey et al. Science 2015;348:1255642

Published by AAAS
Top panel of Fig. 4 Multidisciplinary aquatic telemetry approaches.

Nigel E. Hussey et al. Science 2015;348:1255642
Energy Consumed = Respiration + Waste + Growth

Growth (Somatic + Reproduction)

Environmental Influences (temperature, oxygen)

Food Consumption

Respiration (SMR + AMR + SDA)

Waste (urine & feces)

Heart Rate

Internal Milieu

Imagery

Acceleration

FS Positioning

EMG

Remote bioenergetics measurements in wild fish: Opportunities and challenges

Steven J. Cooke a,*, Jacob W. Browncombe a, Graham D. Raby b, Franziska Broell c, Scott G. Hinch d, Timothy D. Clark e, Jayson M. Semmens f
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Recent advances in telemetry for estimating the energy metabolism of wild fishes

J. D. Metcalfe*,†, S. Wright*,‡, C. Tudorache§ and R. P. Wilson‡
Fish Personalities

... whereas environments with less predictable food abundance do not always meet costs of high activity and therefore passive or shy individuals can grow as fast as, or even faster than, active or bold individuals.

Zavorka et al. 2015. Behavioral Ecology 26: 877-884
Progress: Movement Modeling

- Many approaches have been proposed
  - \(X(t+1) = X(t) + V_x(t)\)
  - \(Y(t+1) = Y(t) + V_y(t)\)
  - \(Z(t+1) = Z(t) + V_z(t)\)
  - Determine the cell

- Quite confusing because of non-standard descriptions and terminology for \(V_x\), \(V_y\), and \(V_z\)
  - Random walk
  - Run and tumble
  - Event-based
  - Restricted-area
  - Kinesis
  - ANN
A movement ecology framework that integrates four existing paradigms for studying organismal movements.

Major Issue

• If we are to use these methods to simulate management actions and climate change, then the methods must predict responses to changes in cue(s)
Loop over time steps
Loop over fish
Movement
Growth
Mortality
Genetic Algorithm
Test on novel grid

Loop over generations

Simplified Hypothetical Species

Scale
Grid: 540 x 540 cells
Cells: 5 m²
Time step: 5 minute
Generation: 30 days
Initial size = 73.3 mm
Initial worth = 100 fish
3000 super-individuals
Model Processes

Growth (mm 5-min\(^{-1}\))

\[ G = G_{\text{max}} \cdot G_{r,c} \]

\[ L(t+1) = L(t) + G \]

\[ W(t+1) = a \cdot L(t+1)^b \]

Movement

\[ X(t+1) = X(t) + V_x(t) \]

\[ Y(t+1) = Y(t) + V_y(t) \]

\[ \text{cell location } (r,c) \]

Mortality (5-min\(^{-1}\))

\[ M = M_{\text{max}} \cdot M_{r,c} \cdot M_L \]

\[ S(t+1) = S(t) \cdot e^{-M} \]

\[ M_L = 1 - \frac{L_i - 73.3}{L_{\text{max}} - 73.3} \]

Reproduction

\[ E = 55 \cdot S(30) \cdot (421.84 \cdot W(30) + 304.79) \]
GA Calibration

• 3000 strategy vectors of parameter values
  – Start with random values for everyone

• Every 30-day generation, select 3000 individuals:
  – $P(\text{selection}) = \frac{E_i}{\Sigma E}$
  – Mutate each vector: 6% of parameters, ±0.25

• Use these 1000 vectors for the next generation

• Continue until egg production levels off

• Parameter values should have converged
Restricted Area Search

- Rank cells in a $D_{\text{hood}}$ cell radius by habitat quality ($Q_{c,r}$)
  
  $Q_{c,r} = (1 - \delta) * (G_{c,r} + n) - \delta * (M_{c,r} * M_L + n)$

- $n = \left(1 - \frac{1.42}{\sqrt{(c-xcell)^2 + (r-ycell)^2}}\right)$

- Compute $\Theta = $ toward the cell with the highest $Q_{c,r}$

- $V_x(t) = (SS + RV_1 \cdot R_{\text{dist}}) \cdot \cos(\theta + RV_2 \cdot R_{\theta})$

- $V_y(t) = (SS + RV_1 \cdot R_{\text{dist}}) \cdot \sin(\theta + RV_2 \cdot R_{\theta})$

- GA evolves: $\delta, R_{\theta}, R_{\text{dist}}, D_{\text{hood}}$
Kinesis – Robert Humston

- Velocities are the sum of inertial (f) and random (g)

- Compute random swim speed: \[ \varepsilon_x = \mathcal{N}\left(\frac{1.0}{\sqrt{2}}, 0.5\right) \]

- Compute habitat quality: \[ Q_{c,r} = (1 - \delta) \cdot G_{c,r} - \delta \cdot M_{c,r} \cdot M_L \]

- Compute f and g weighted by how close habitat quality \( Q_{c,r} \) is to the optimal habitat \( Q_{\text{opt}} \)
  \[
  f_x = \text{Vel}_x(t - 1) \cdot H_1 \cdot e^{-0.5 \left( \frac{Q_{c,r} - Q_{\text{opt}}}{\sigma_Q} \right)^2}
  
  g_x = \varepsilon_x \cdot \left( 1 - H_2 \cdot e^{-0.5 \left( \frac{Q_{c,r} - Q_{\text{opt}}}{\sigma_Q} \right)^2} \right)
  
  \]

- GA evolves \( Q_{\text{opt}}, \sigma, H_1, H_2, \delta \)
Calibration – Fitness Convergence

Restricted area, Kinesis, Event-based, Run-tumble
Last day of 300\textsuperscript{th} generation
10 Individuals

hood

kinesis

event

levy

Legend:

1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Pathways

Grid1

Grid2

Grid3

Grid4

Number of Cells Encountered

Movement Sub-model

hood  kinesis  event  levy
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<td>Enrique N. Curchitser</td>
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<td>Jerome Fiechter</td>
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<td>Kate Hedstrom</td>
<td>Institute of Marine Science - University of Alaska</td>
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<td>Miguel Bernal</td>
<td>FAO – Rome</td>
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<td>Vera Agostini</td>
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Fiechter et al. 2015. The role of environmental controls in determining sardine and anchovy population cycles in the California Current: Analysis of an end-to-end model. Progress in Oceanography 138: 381-398.
Provided by: Salvador E. Lluch-Cota based on Schwartzlose et al. 1999
Fully-Coupled Model Within ROMS

Regional Ocean Circulation Model

NPZ Component (multiple)

Floats Component

Climate Coupling

Data Assimilation

Fish IBM

Sardines

Anchovies

Predators

Fishing Fleet
Model 1: ROMS

- Grid:
  - 10 km
  - 42 levels

- 900 s

- Run duration: 50 years (1959-2009)
Model 2: NEMURO
Environmental Cues for Movement (Kinesis)

Temperature (°C) - Gaussian

P-Value (C/C_{max}) – Holling Type III

INERTIA
RANDOM
TOTAL

Sardine Spatial

(E&YS – $10^{12}$; 1000 MT)
Hypoxia - Gulf of Mexico
LaBone, E., D. Justic, K.A. Rose, and H. Huang. almost. Exposure of fish to hypoxia in the northern Gulf of Mexico: Effects of allowing fish to move vertically....
Bioenergetics

- Wisconsin formulation
- Dynamic Energy Budget
- Anchovy examples
Fish Bioenergetics 4.0:
An R-based Modeling Application

Users Manual
Initial conditions.
Loop over years in run.
Loop over days in year (Jan 1 to Dec 31).
Loop over time steps (3600 sec) in each day.
If midnight then add new super-individuals as eggs.
If midnight then loop over boats.
Daily selection of cells to harvest.
Update worths of caught sardine.
Next boat.
Loop over time steps (900 sec) in an hour.
Hydrodynamics
NEMURO–NPZ
Next 900 sec.
Determine fish individuals (by species) in each cell.
Loop over cells in grid.
Loop over anchovy and sardine individuals in cell.
Loop over albacore individuals in cell.
Horizontal movement and consumption of albacore.
Update worths of eaten anchovy and sardine.
Next albacore.
If midnight then egg release and set-up horizontal movement.
Impose midnight horizontal movement.
Vertical movement (L, J, A).
Growth and fecundity via egg batches.
Natural and starvation mortality.
Age and clean old individuals.
Next year.

\[
W_{t+\Delta t} = W_t + \left[ (A \cdot C - R) \cdot W_t \cdot \left( \frac{e_f}{e_z} \right) - E \right] \cdot \frac{\Delta t}{86,400}
\]

\[
A = \min(a_s \cdot W^{b_s}, A_M)
\]

\[
C_m = a_c W^{b_c} F(T)
\]

\[
C_j = \frac{C_m W \left( \frac{Z_j \cdot V_{s_j}}{K_{s_j}} \right)}{1 + \sum_{k=1}^{3} \left( \frac{Z_k \cdot V_{s_j}}{K_{s_k}} \right)}
\]

\[
R = a_r W^{b_r} \cdot G(T) \cdot a_a \cdot 5.258
\]

\[
G(T) = e^{R_Q \cdot (T - T_r)}
\]

\[
a_a = e^{d_r \cdot U_B \cdot L/10}
\]
Disconnect

• Movement cues
  – Sometimes projected growth
  – Often temperature or other habitat variable

• Selection (optimization) of speed, direction, or destination

• Trajectory (journey)

• Bioenergetics consequences

• Routine type movement maybe OK but not for GCC
Necessity or Opportunity

• Merge movement with the bioenergetics

• Consistency (two-way)

• Journey and destination affect bioenergetics the same way as used in movement

• Project responses to major changes in cues
Next Step

• Time for synthesis and algorithm development and testing

• Working group or workshops?

• Fish and Fisheries ↔ Movement Ecology

• NOAA, PICES, ICES, ESA, AFS, CERF