Predicting marine ecosystem responses to environmental variation: ***Now is the time to merge bioenergetics and movement ecology***

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Cambridge, Maryland

Today

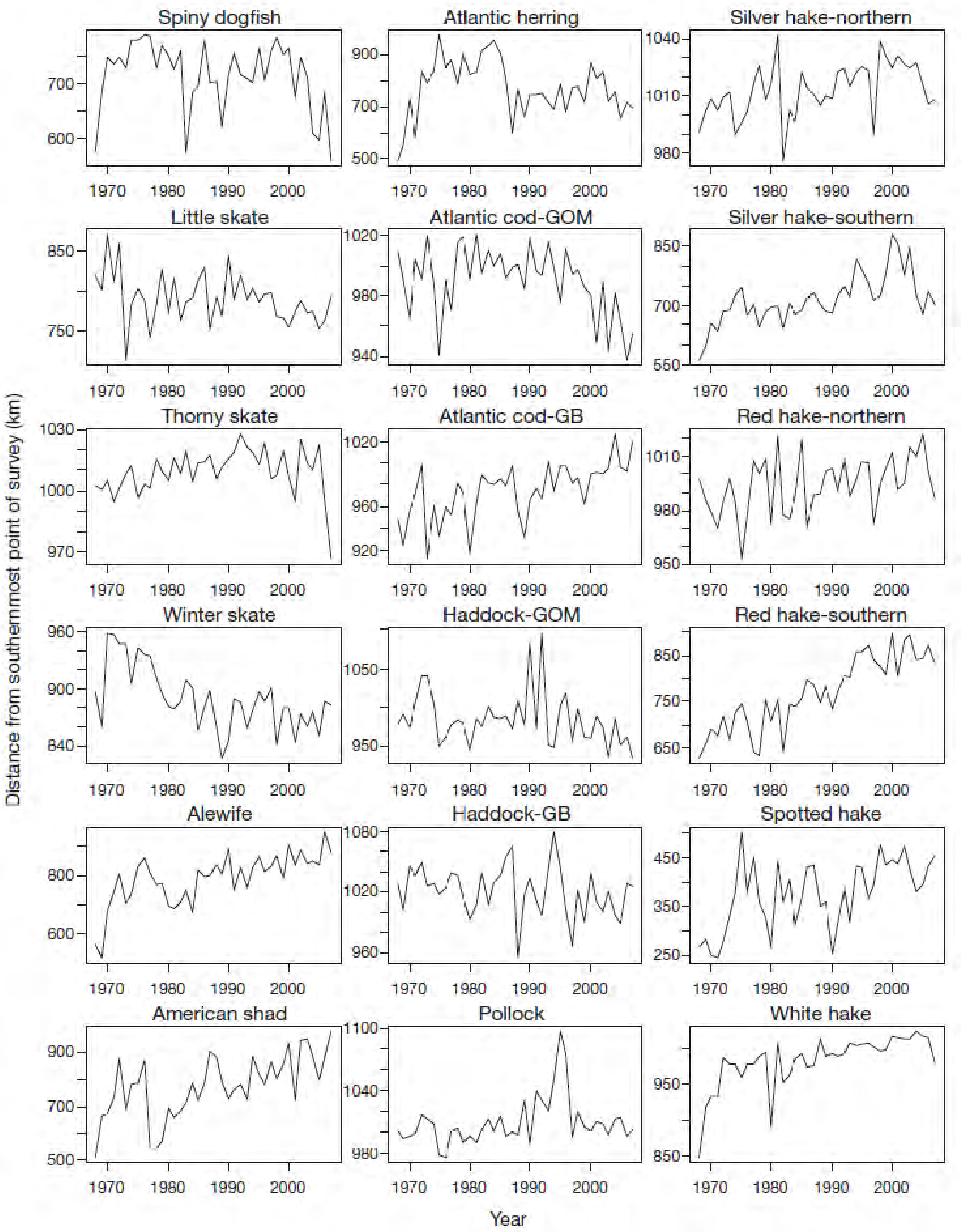
- Organisms will move in response to climate change

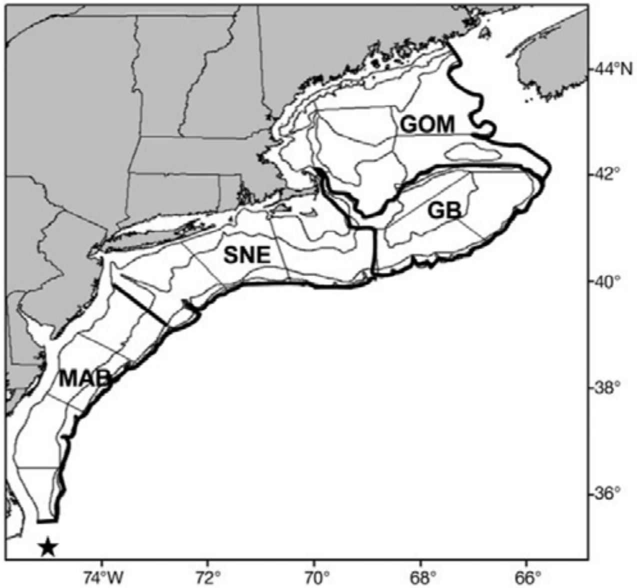
- Progress on movement
  - Observations
  - Modeling

- Status of bioenergetics

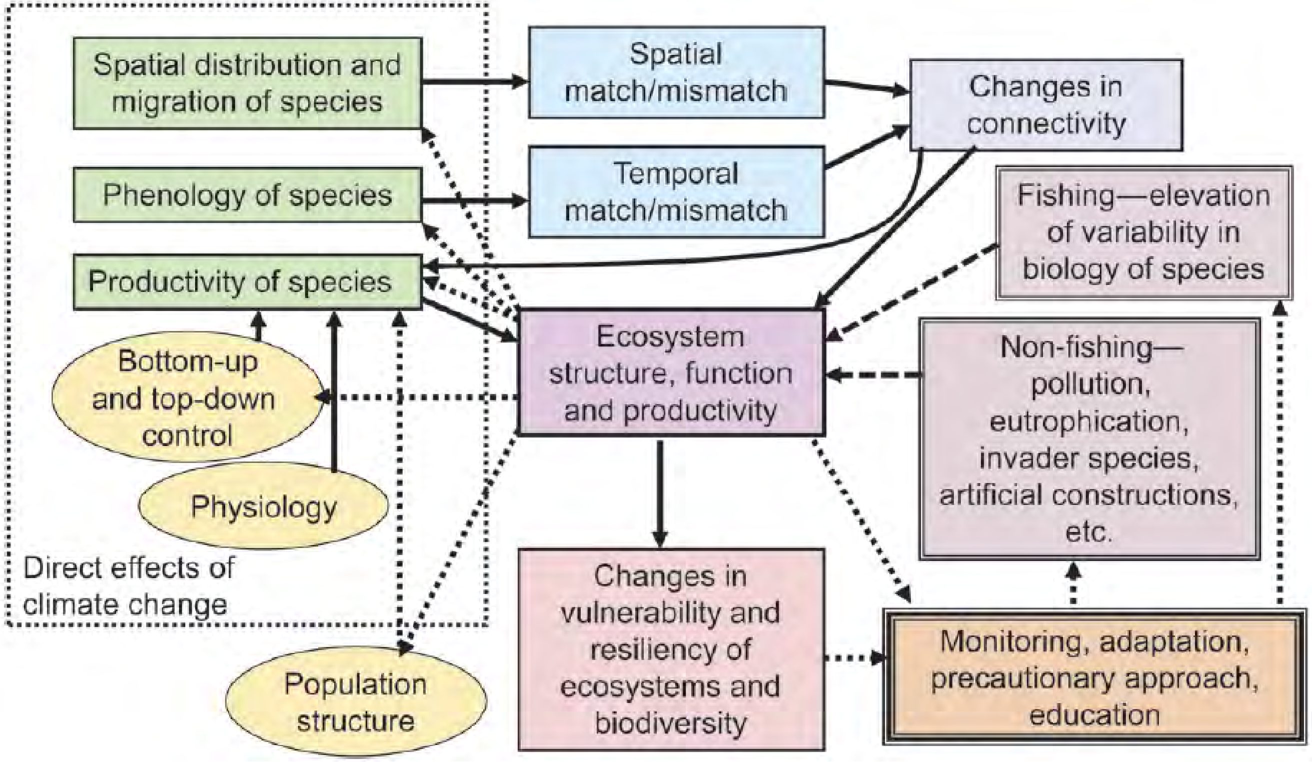
- Need and opportunities for merging

- Next steps





Nye et al. 2009. Marine Ecology Progress Series 393: 111-129.



Hollowed et al. 2013. ICES Journal of Marine Science 70: 1023-1037.

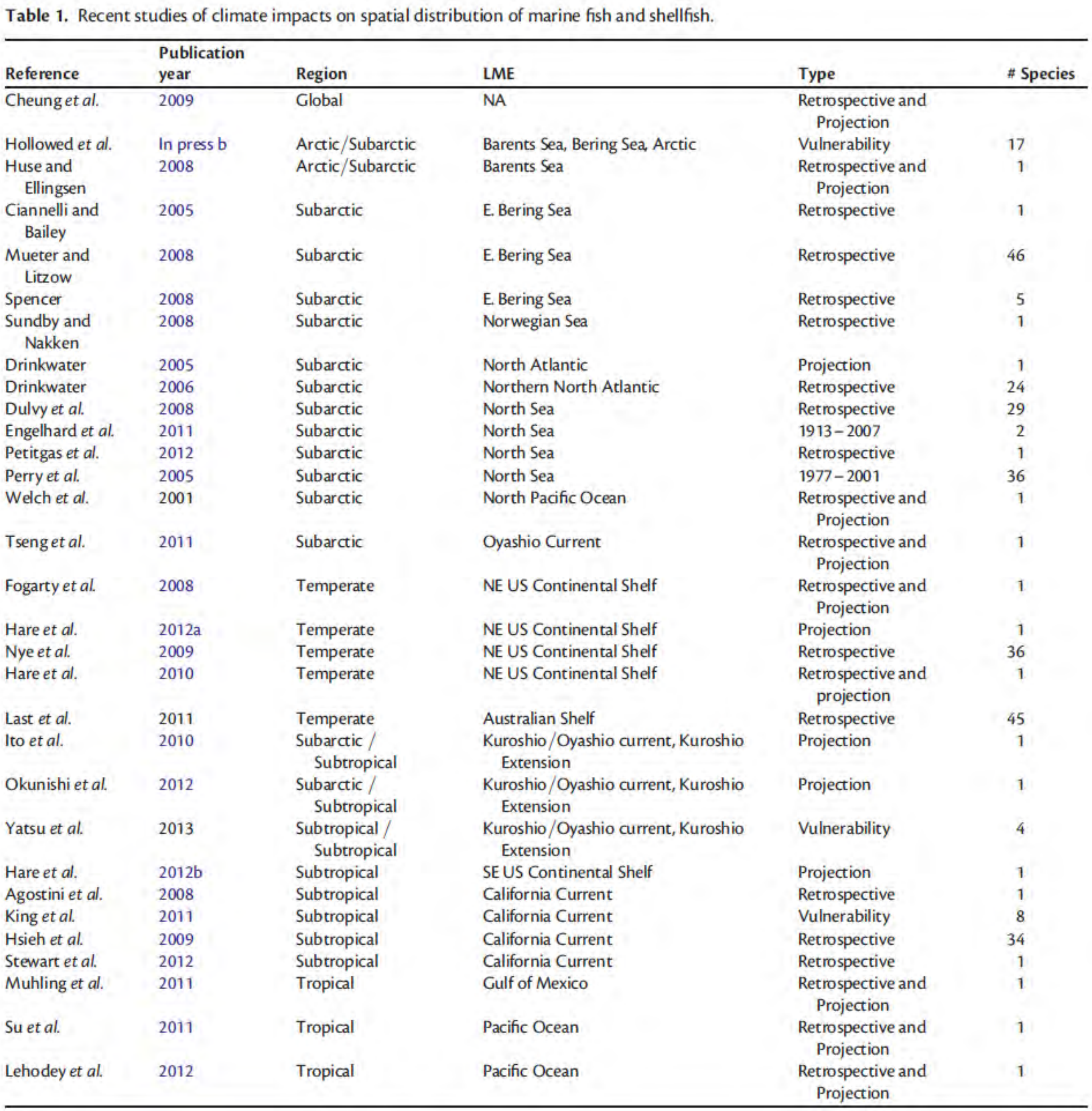
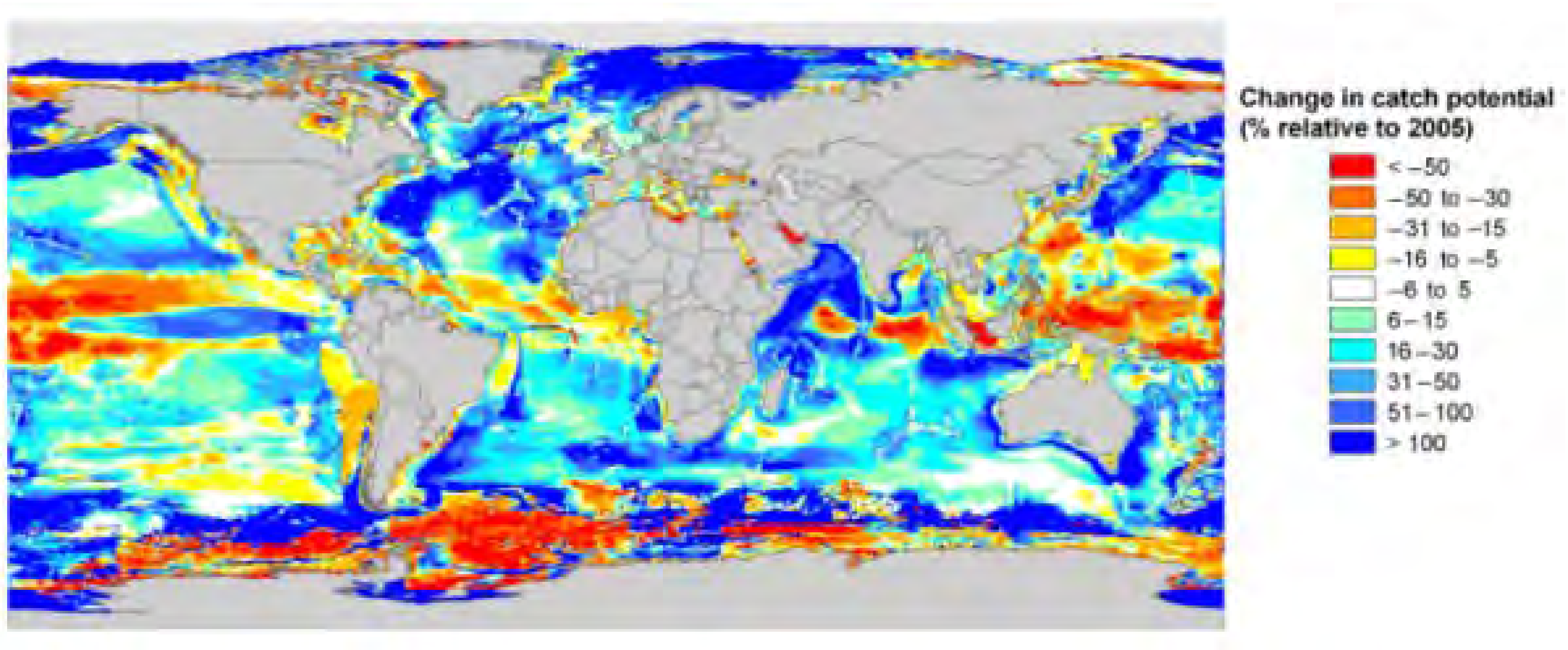


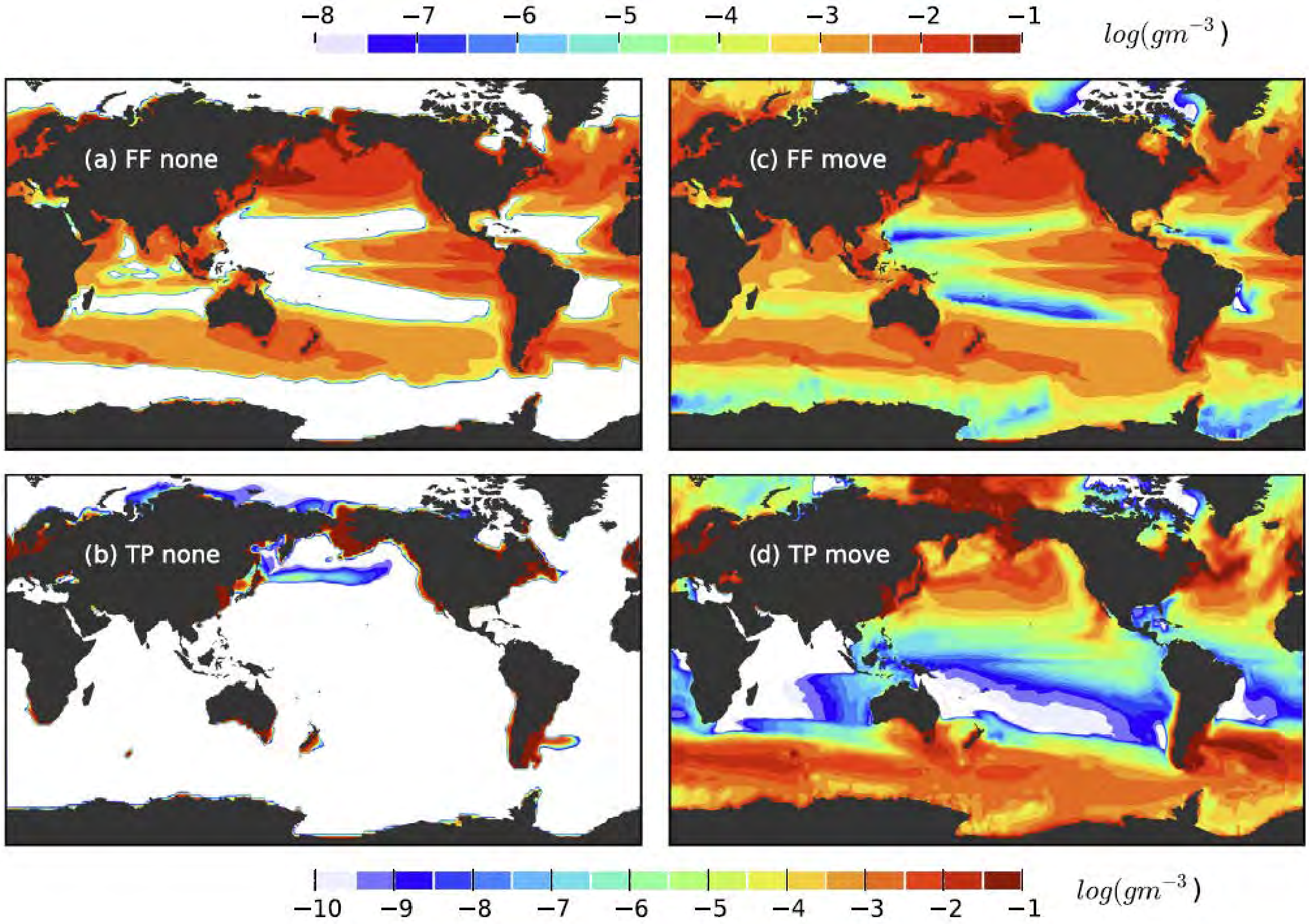
Table 1. Recent studies of climate impacts on spatial distribution of marine fish and shellfish.

Reference	Publication year	Region	LME	Type	# Species
Cheung *et al.*	2009	Global	NA	Retrospective and Projection	
Hollowed *et al.*	In press b	Arctic/Subarctic	Barents Sea, Bering Sea, Arctic	Vulnerability	17
Huse and Ellingsen	2008	Arctic/Subarctic	Barents Sea	Retrospective and Projection	1
Ciannelli and Bailey	2005	Subarctic	E. Bering Sea	Retrospective	1
Mueter and Litzow	2008	Subarctic	E. Bering Sea	Retrospective	46
Spencer	2008	Subarctic	E. Bering Sea	Retrospective	5
Sundby and Nakken	2008	Subarctic	Norwegian Sea	Retrospective	1
Drinkwater	2005	Subarctic	North Atlantic	Projection	1
Drinkwater	2006	Subarctic	Northern North Atlantic	Retrospective	24
Dulvy *et al.*	2008	Subarctic	North Sea	Retrospective	29
Engelhard *et al.*	2011	Subarctic	North Sea	1913–2007	2
Petitgas *et al.*	2012	Subarctic	North Sea	Retrospective	1
Perry *et al.*	2005	Subarctic	North Sea	1977–2001	36
Welch *et al.*	2001	Subarctic	North Pacific Ocean	Retrospective and Projection	1
Tseng *et al.*	2011	Subarctic	Oyashio Current	Retrospective and Projection	1
Fogarty *et al.*	2008	Temperate	NE US Continental Shelf	Retrospective and Projection	1
Hare *et al.*	2012a	Temperate	NE US Continental Shelf	Projection	1
Nye *et al.*	2009	Temperate	NE US Continental Shelf	Retrospective	36
Hare *et al.*	2010	Temperate	NE US Continental Shelf	Retrospective and projection	1
Last *et al.*	2011	Temperate	Australian Shelf	Retrospective	45
Ito *et al.*	2010	Subarctic / Subtropical	Kuroshio/Oyashio current, Kuroshio Extension	Projection	1
Okunishi *et al.*	2012	Subarctic / Subtropical	Kuroshio/Oyashio current, Kuroshio Extension	Projection	1
Yatsu *et al.*	2013	Subtropical / Subtropical	Kuroshio/Oyashio current, Kuroshio Extension	Vulnerability	4
Hare *et al.*	2012b	Subtropical	SE US Continental Shelf	Projection	1
Agostini *et al.*	2008	Subtropical	California Current	Retrospective	1
King *et al.*	2011	Subtropical	California Current	Vulnerability	8
Hsieh *et al.*	2009	Subtropical	California Current	Retrospective	34
Stewart *et al.*	2012	Subtropical	California Current	Retrospective	1
Muhling *et al.*	2011	Tropical	Gulf of Mexico	Retrospective and Projection	1
Su *et al.*	2011	Tropical	Pacific Ocean	Retrospective and Projection	1
Lehodey *et al.*	2012	Tropical	Pacific Ocean	Retrospective and Projection	1

Hollowed et al. 2013. ICES Journal of Marine Science 70: 1023-1037.

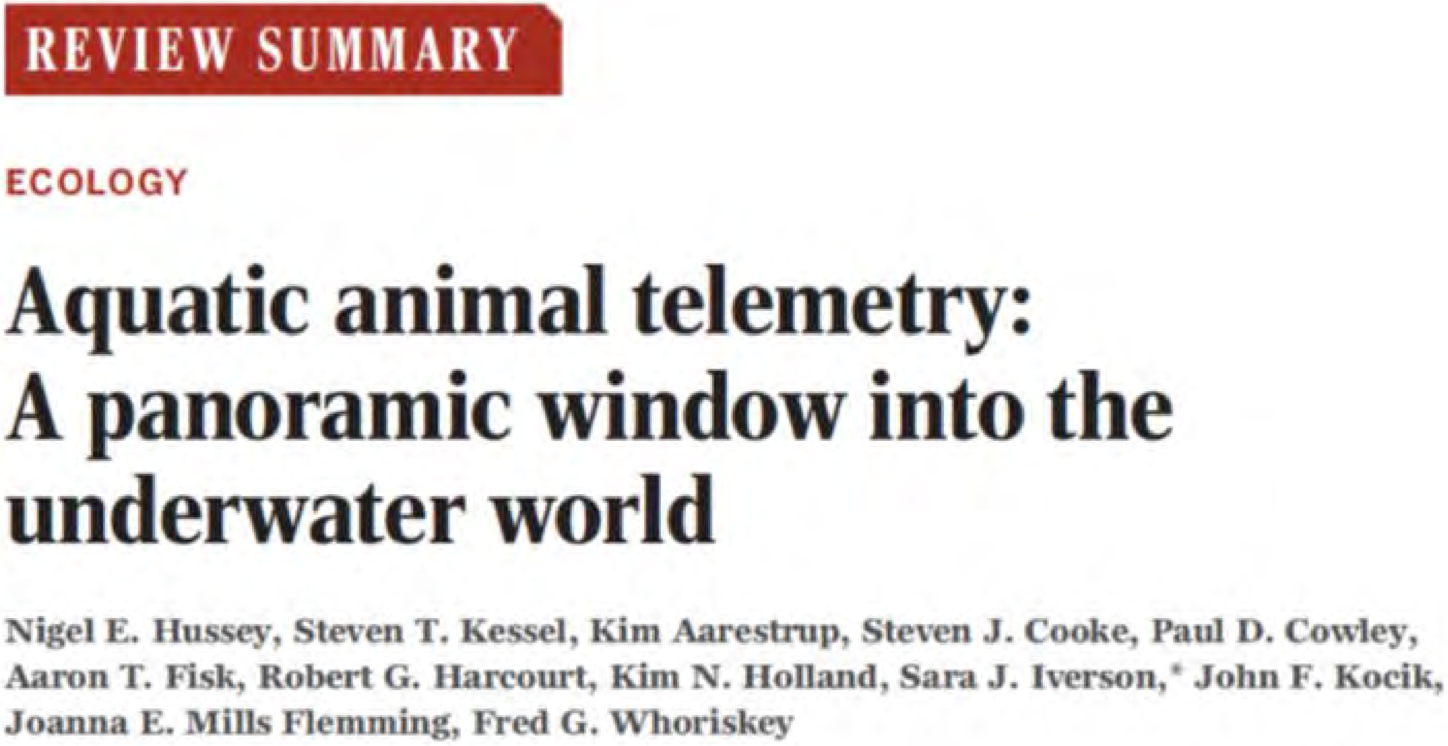


Cheung et al. 2010. Global Change Biology 16: 24-35.



Watson et al. 2015. Progress in Oceanography 138: 521-532.

Progress: Movement Data



REVIEW SUMMARY

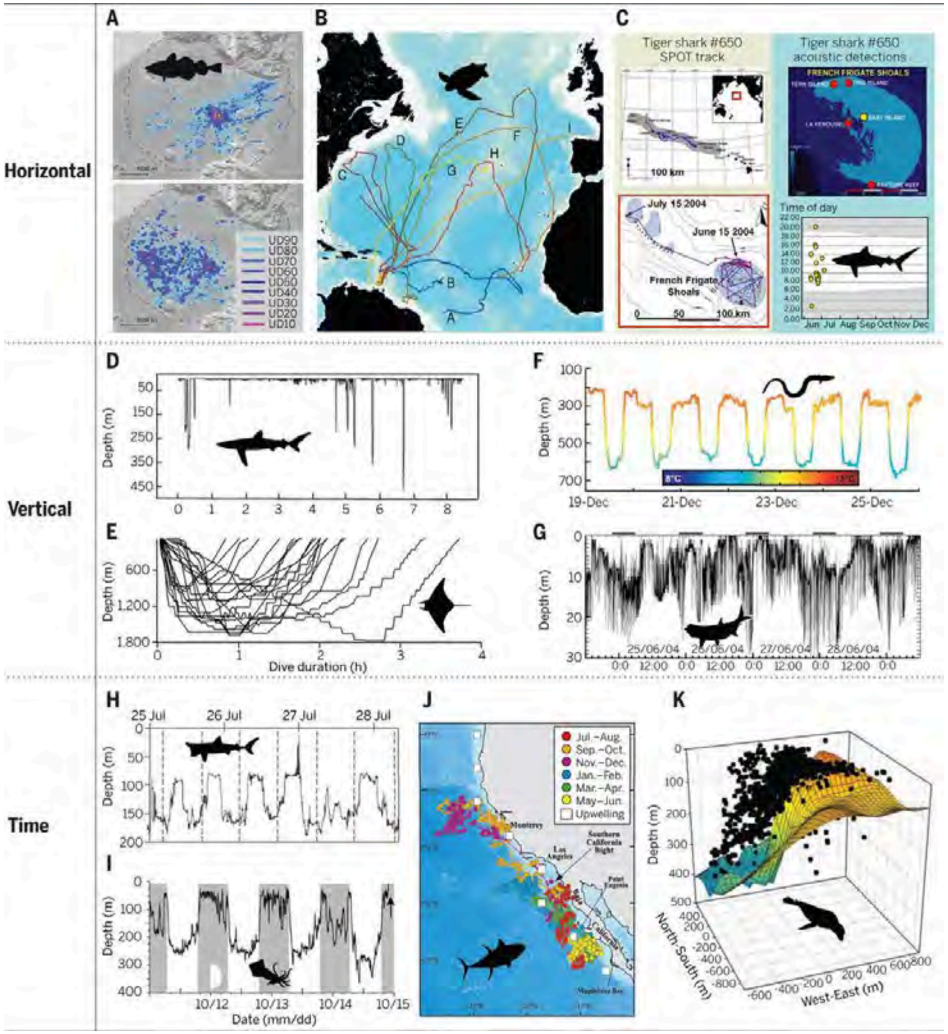
ECOLOGY

Aquatic animal telemetry: A panoramic window into the underwater world

Nigel E. Hussey, Steven T. Kessel, Kim Aarestrup, Steven J. Cooke, Paul D. Cowley, Aaron T. Fisk, Robert G. Harcourt, Kim N. Holland, Sara J. Iverson,* John F. Kocik, Joanna E. Mills Flemming, Fred G. Whoriskey

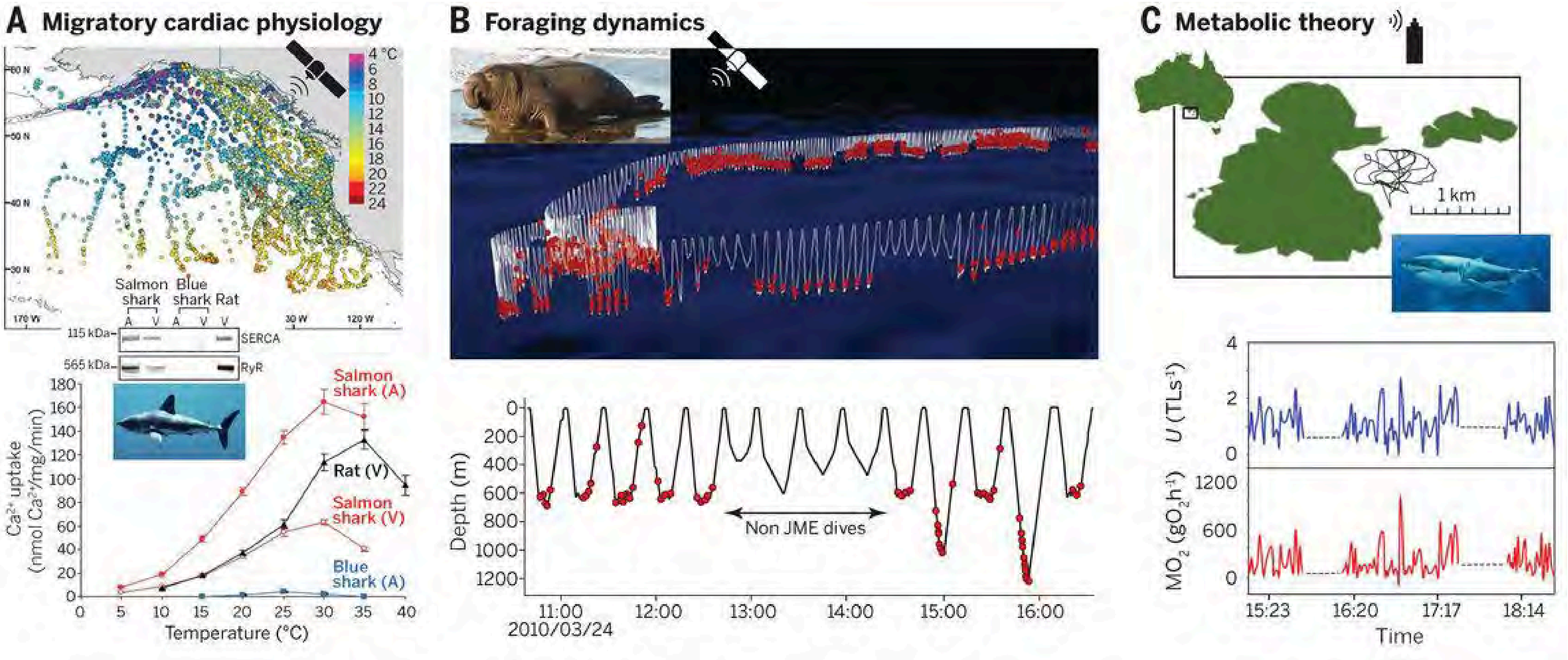
Science 348: 1255642, 2015

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

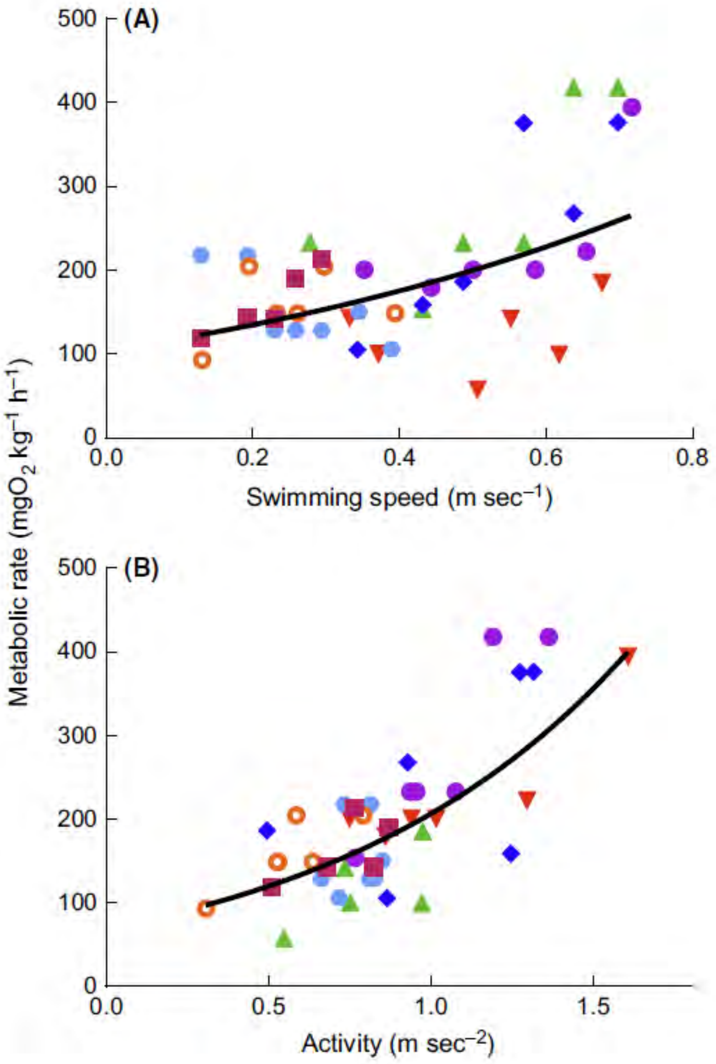


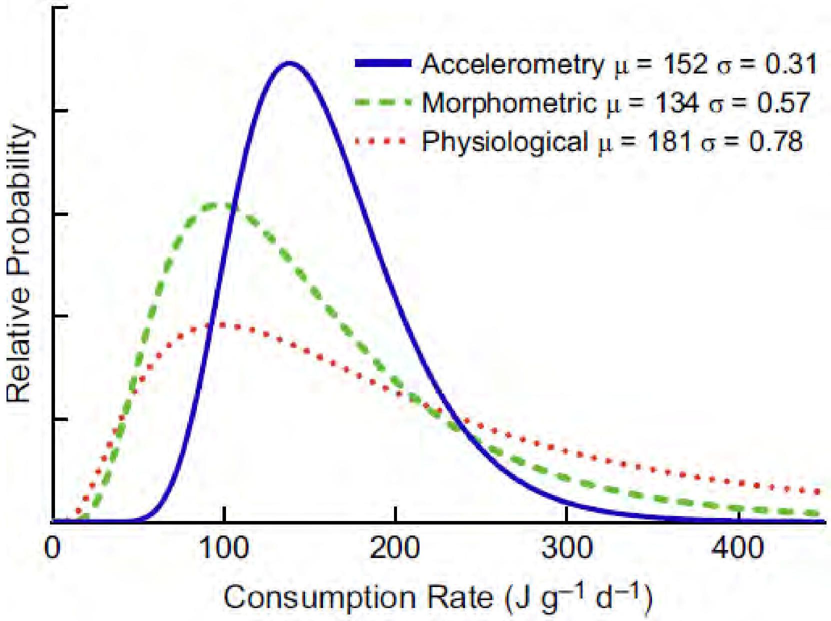
Nigel E. Hussey et al. Science 2015;348:1255642

Top panel of Fig. 4 Multidisciplinary aquatic telemetry approaches.

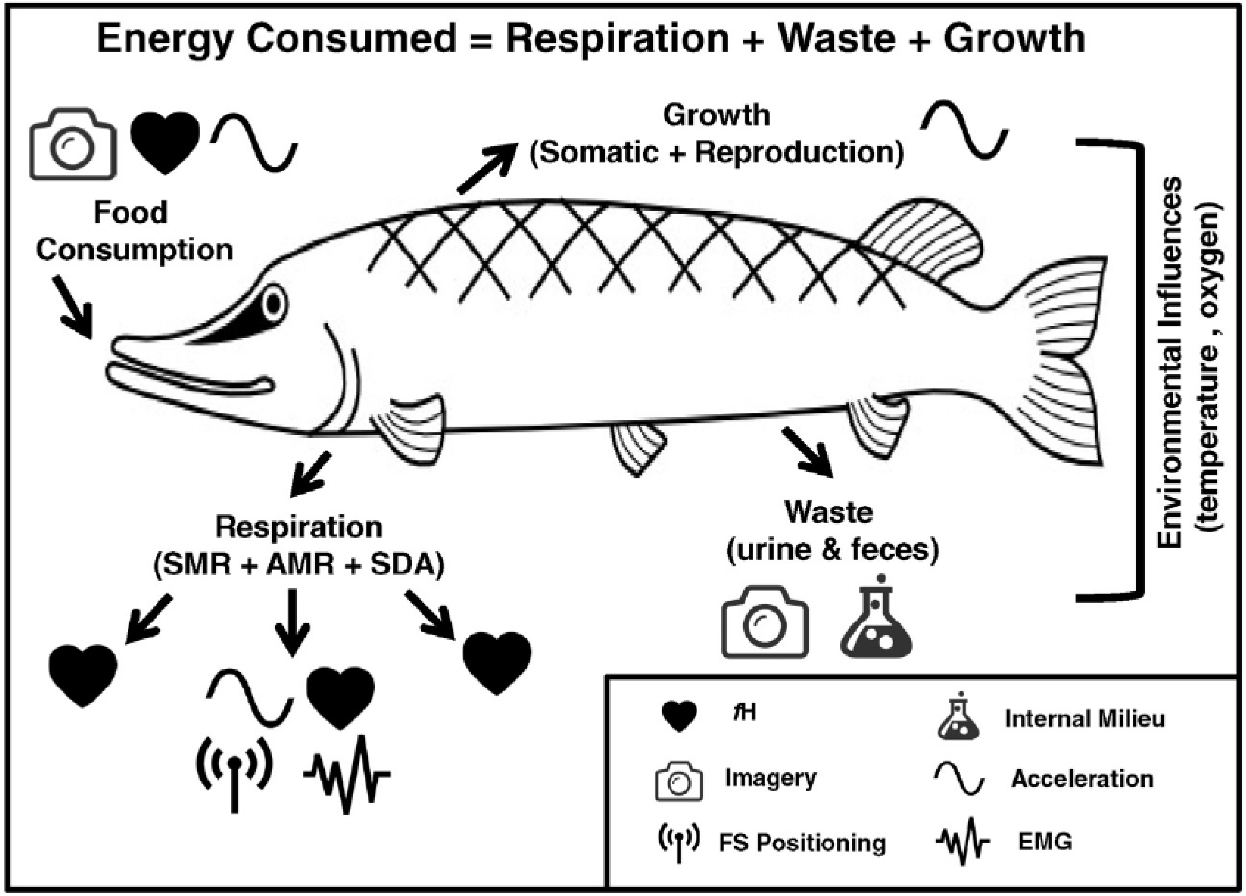


Nigel E. Hussey et al. Science 2015;348:1255642





Brodie et al. 2016. Ecology and Evolution 6: 2262-2274.



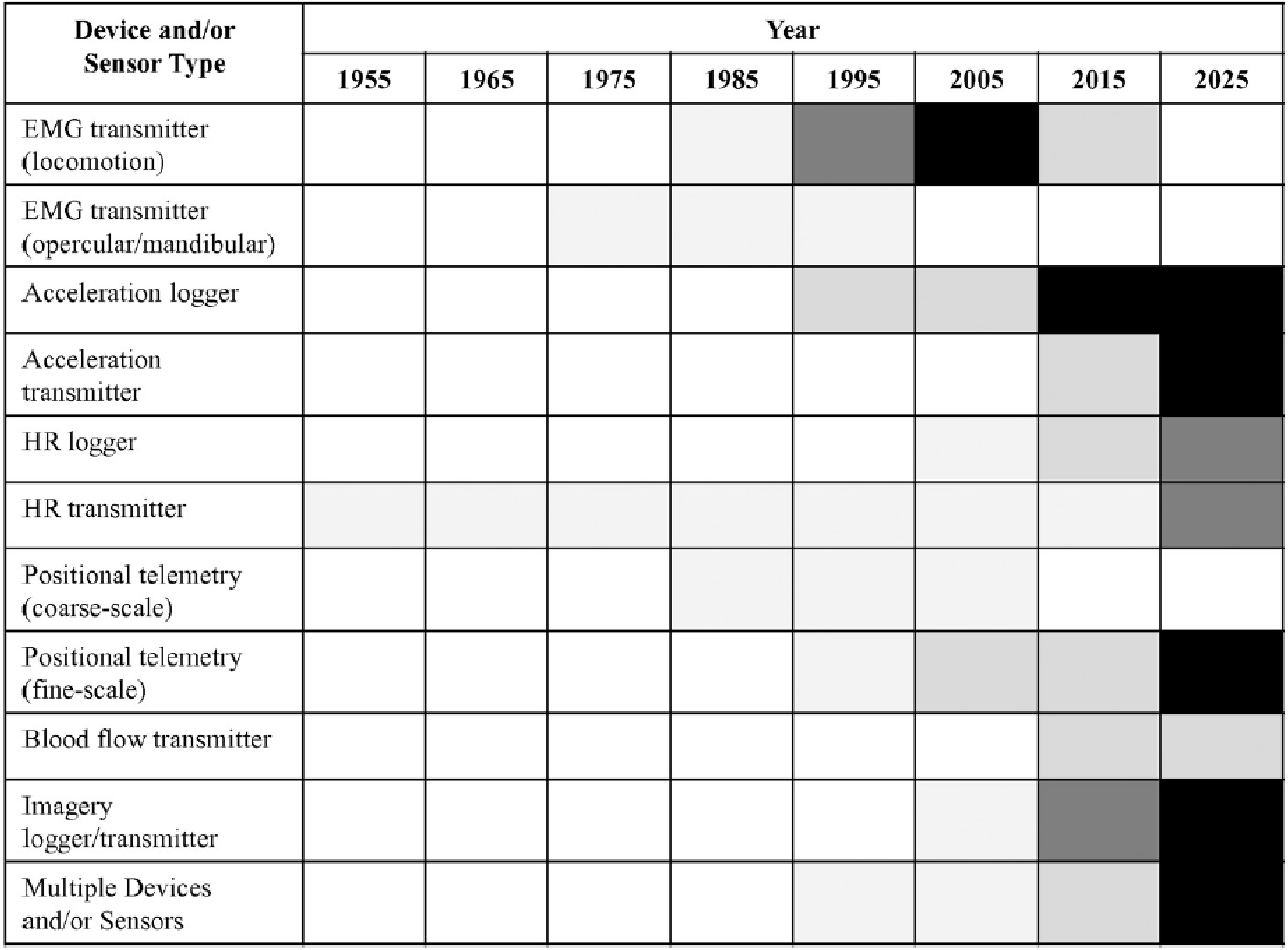
Contents lists available at ScienceDirect

Comparative Biochemistry and Physiology, Part A

journal homepage: www.elsevier.com/locate/cbpa

Remote bioenergetics measurements in wild fish: Opportunities and challenges☆

Steven J. Cooke[a,*], Jacob W. Brownscombe[a], Graham D. Raby[b], Franziska Broell[c], Scott G. Hinch[d], Timothy D. Clark[e], Jayson M. Semmens[f]



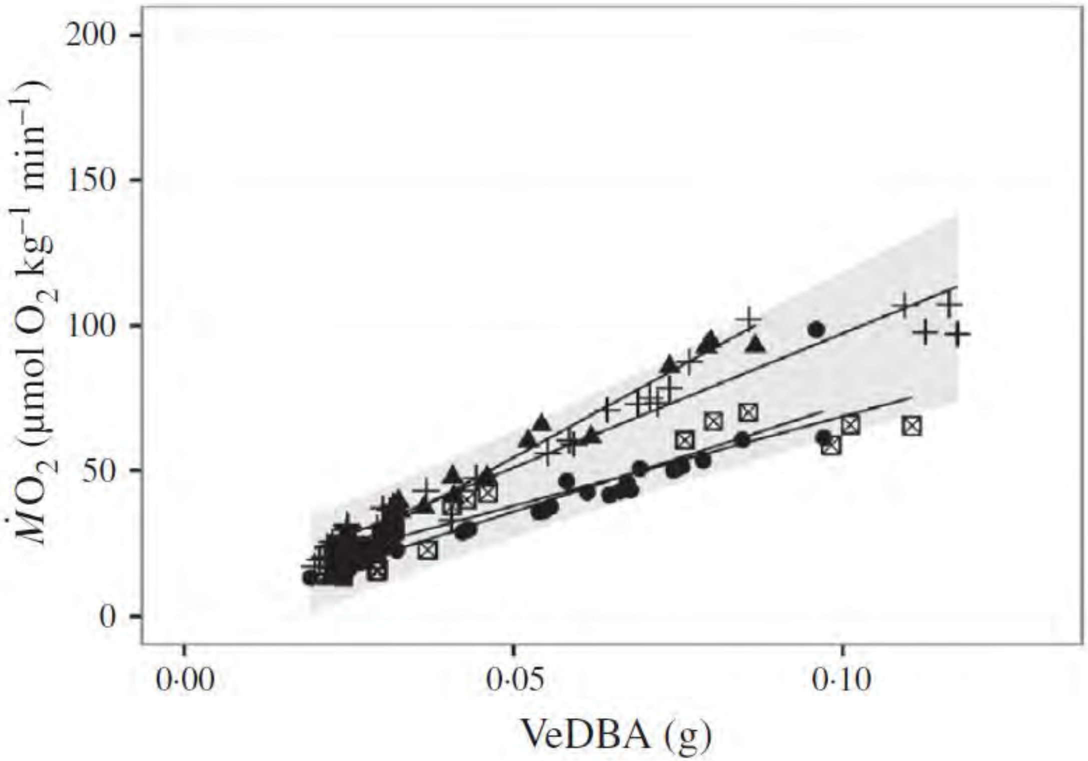
Device and/or Sensor Type	Year							
	1955	1965	1975	1985	1995	2005	2015	2025
EMG transmitter (locomotion)				░	▓	█	▒	
EMG transmitter (opercular/mandibular)			░	░	░			
Acceleration logger					▒	▒	█	█
Acceleration transmitter							▒	█
HR logger						░	▒	▓
HR transmitter	░	░	░	░	░	░	░	▓
Positional telemetry (coarse-scale)				░	░	░		
Positional telemetry (fine-scale)					░	▒	▒	█
Blood flow transmitter							▒	▒
Imagery logger/transmitter						░	▓	█
Multiple Devices and/or Sensors					░	░	▒	█

Cooke et al. 2016. Comparative Biochemistry and Physiology A 202: 23-37.

Journal of Fish Biology (2016) **88**, 284–297
doi:10.1111/jfb.12804, available online at wileyonlinelibrary.com

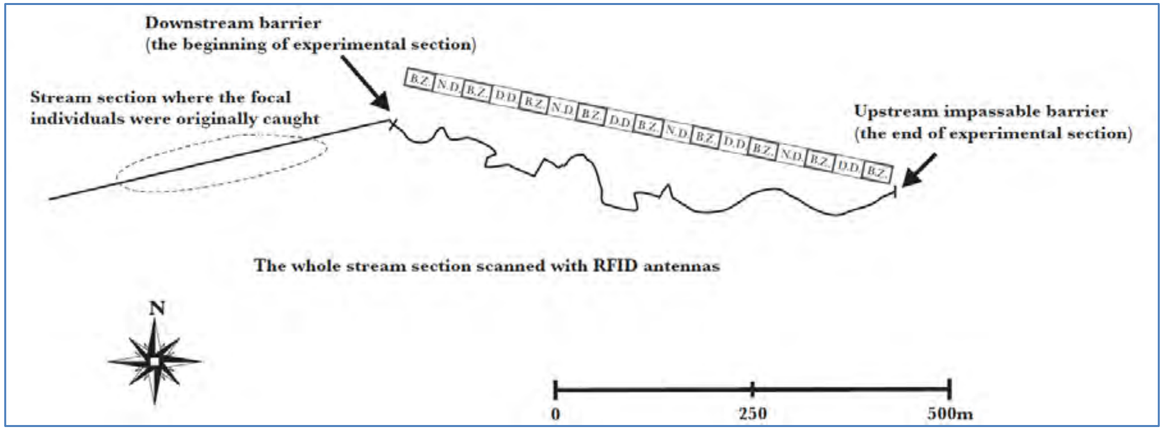
Recent advances in telemetry for estimating the energy metabolism of wild fishes

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



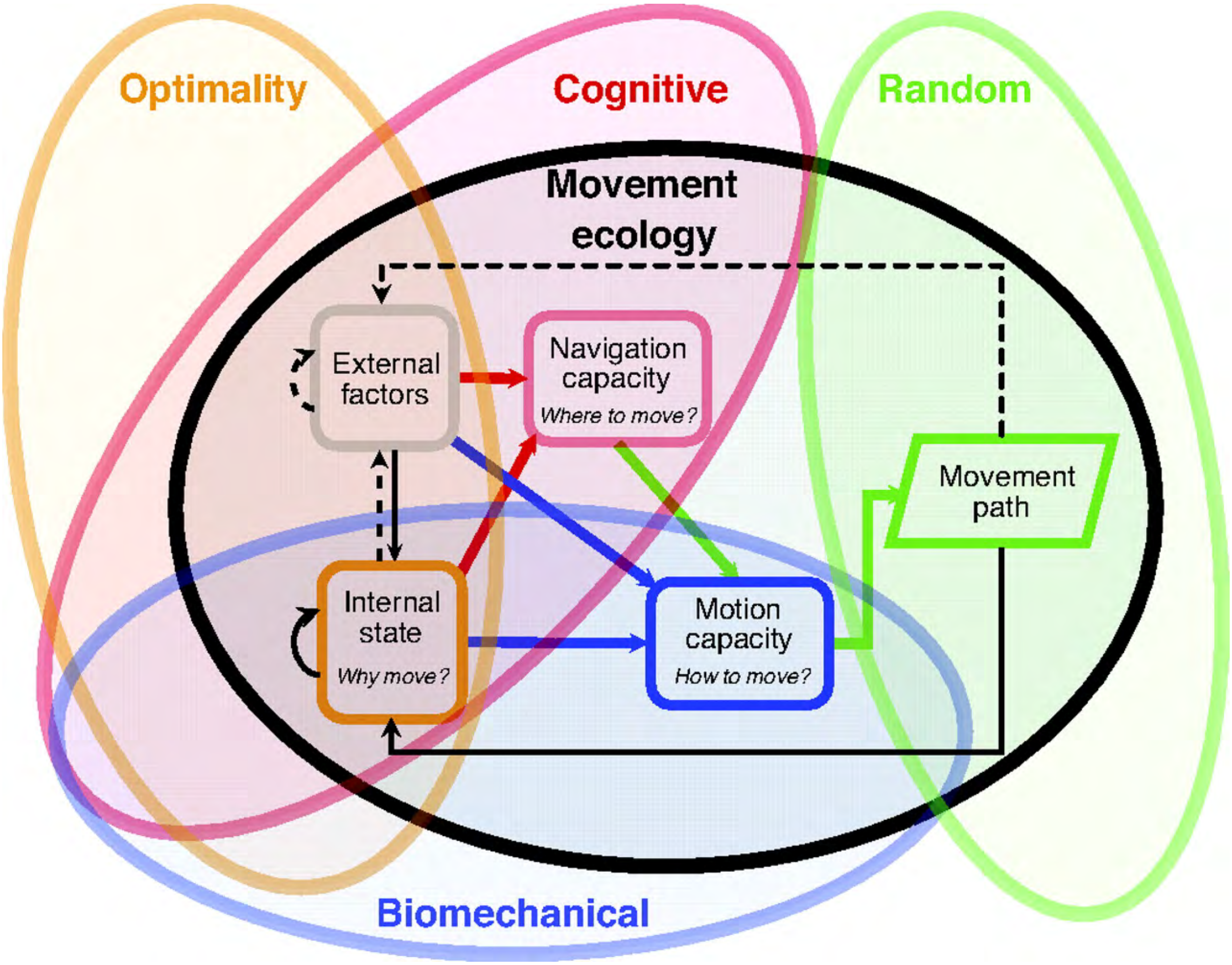
Zavorka et al. 2015. Behavioral Ecology 26: 877-884

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

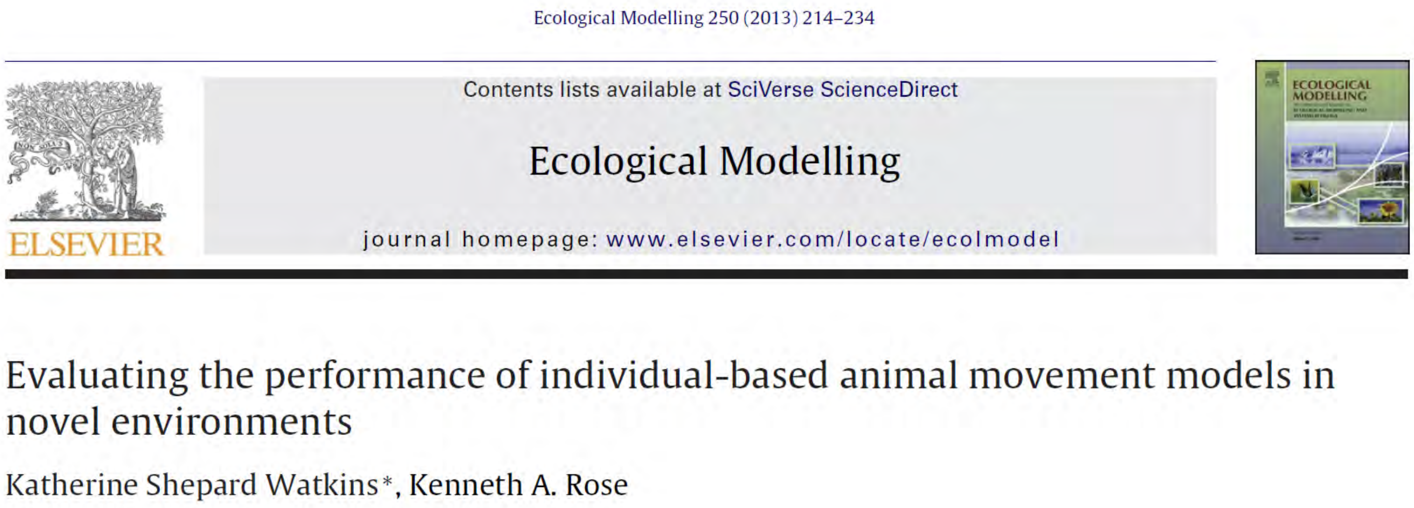
A movement ecology framework that integrates four existing paradigms for studying organismal movements.



Ran Nathan et al. J Exp Biol 2012;215:986-996

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)



Ecological Modelling 250 (2013) 214–234

Contents lists available at SciVerse ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

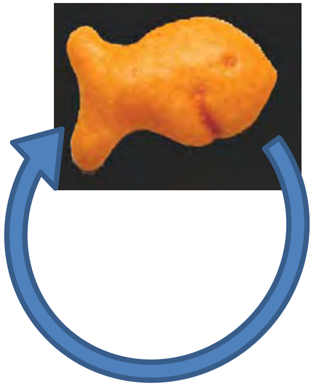
ELSEVIER

Evaluating the performance of individual-based animal movement models in novel environments

Katherine Shepard Watkins*, Kenneth A. Rose

Model Structure

Simplified Hypothetical Species



Scale

Grid: 540 x 540 cells

Cells: 5 m^2

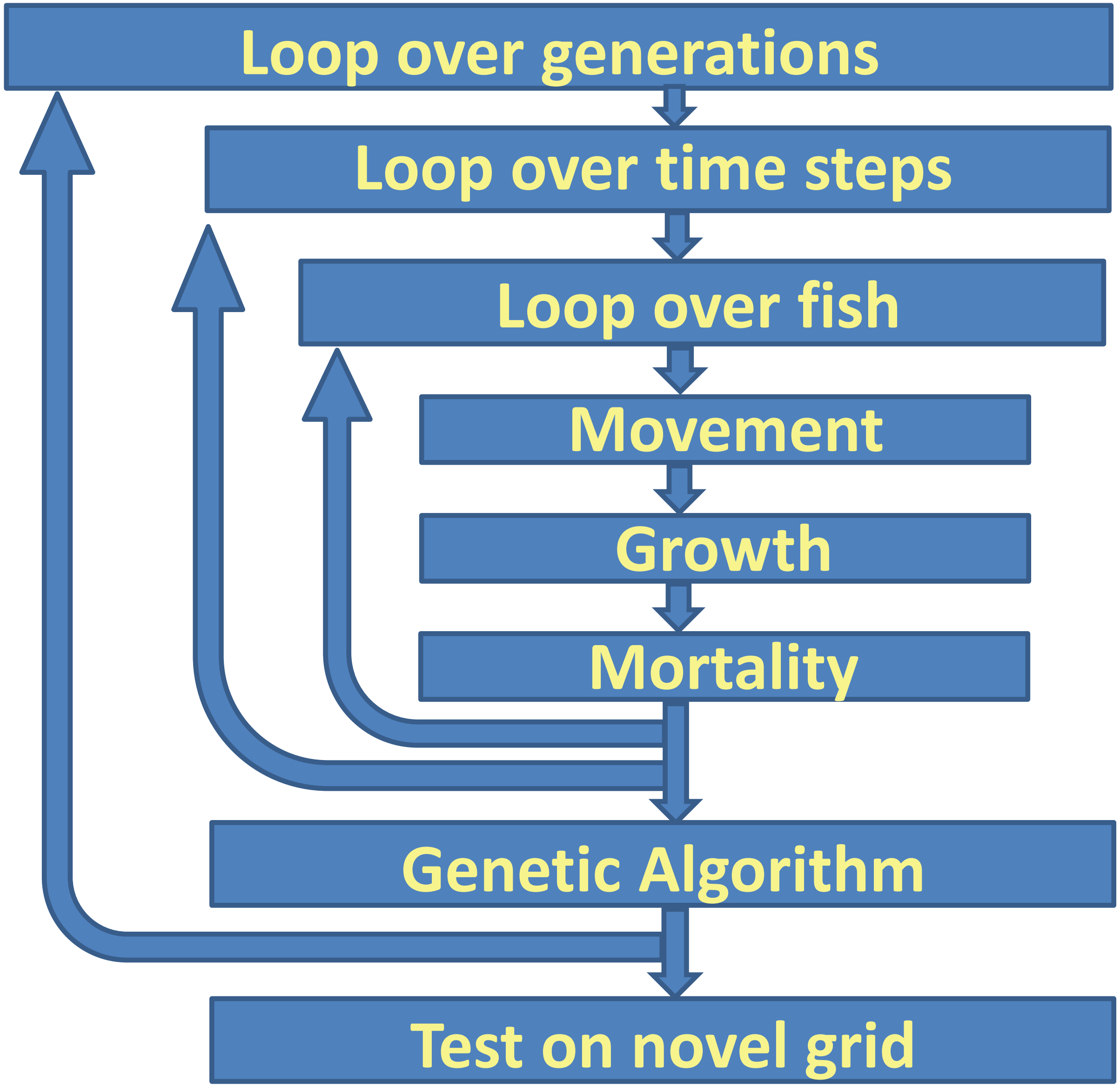
Time step: 5 minute

Generation: 30 days

Initial size = 73.3 mm

Initial worth = 100 fish

3000 super-individuals



Loop over generations

Loop over time steps

Loop over fish

Movement

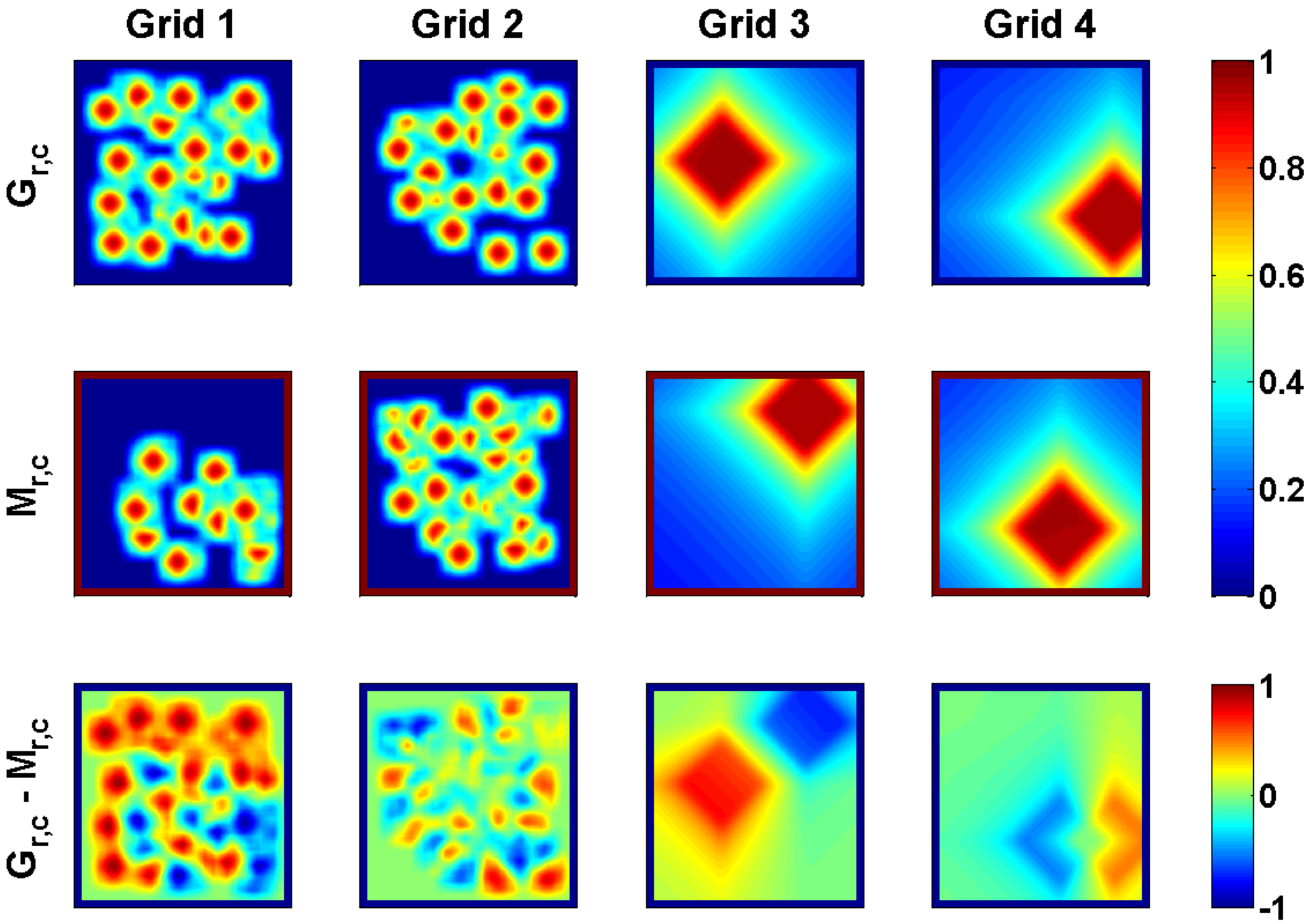
Growth

Mortality

Genetic Algorithm

Test on novel grid

Environmental Gradients



Patchy
No trade-offs

Patchy
Trade-offs

Smooth
No Trade-offs

Smooth
Trade-offs

Model Processes

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

$$G = G_{max} * G_{r,c}$$

$$L(t+1) = L(t) + G$$

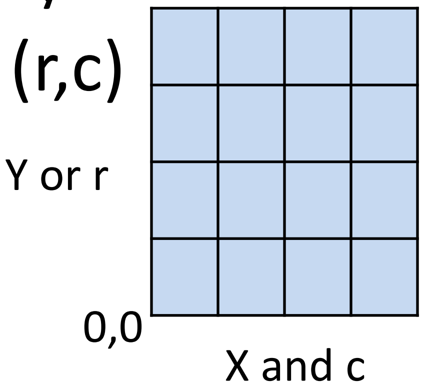
$$W(t+1) = a * L(t+1)^{b}$$

Movement

$$\mathbf{X(t+1) = X(t) + V_x(t)}$$

$$\mathbf{Y(t+1) = Y(t) + V_y(t)}$$

cell location (r,c)



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

$$M = M_{max} * M_{r,c} * M_L$$

$$S(t+1) = S(t) * e^{-M}$$

$$M_L = 1 - \frac{L_i - 73.3}{L_{max} - 73.3}$$

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(selection) = $E_i/\Sigma E$
  - 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_{hood} cell radius by habitat quality ($Q_{c,r}$)

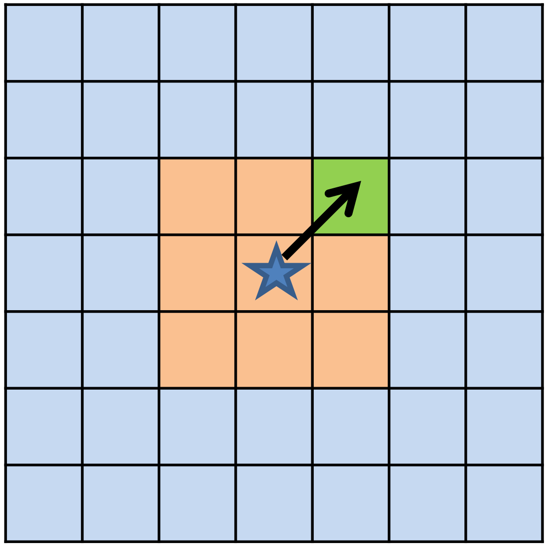
$$Q_{c,r} = (1-\delta)*(G_{c,r}+n) - \delta*(M_{c,r}*M_L + n)$$

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

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

$$\boxed{\begin{aligned} V_x(t) &= (SS + RV_1 \cdot R_{dist}) \cdot \cos(\theta + RV_2 \cdot R_\theta) \\ V_y(t) &= (SS + RV_1 \cdot R_{dist}) \cdot \sin(\theta + RV_2 \cdot R_\theta) \end{aligned}}$$

- GA evolves: δ, R_θ, R_{dist}, D_{hood}



Kinesis – Robert Humston

- Velocities are the sum of inertial (f) and random (g)
- Compute random swim speed: $\varepsilon_x = N(\sqrt{1.0/2}, 0.5)$
- Compute habitat quality: $Q_{c,r} = (1-\delta) * G_{c,r} - \delta * M_{c,r} * M_L$
- Compute f and g weighted by how close habitat quality ($Q_{c,r}$) is to the optimal habitat (Q_{opt})

$$f_x = \mathrm{Vel}_x(t-1) \cdot H_1 \cdot e^{-0.5\left(\frac{Q_{c,r}-Q_{opt}}{\sigma_Q}\right)^2}$$

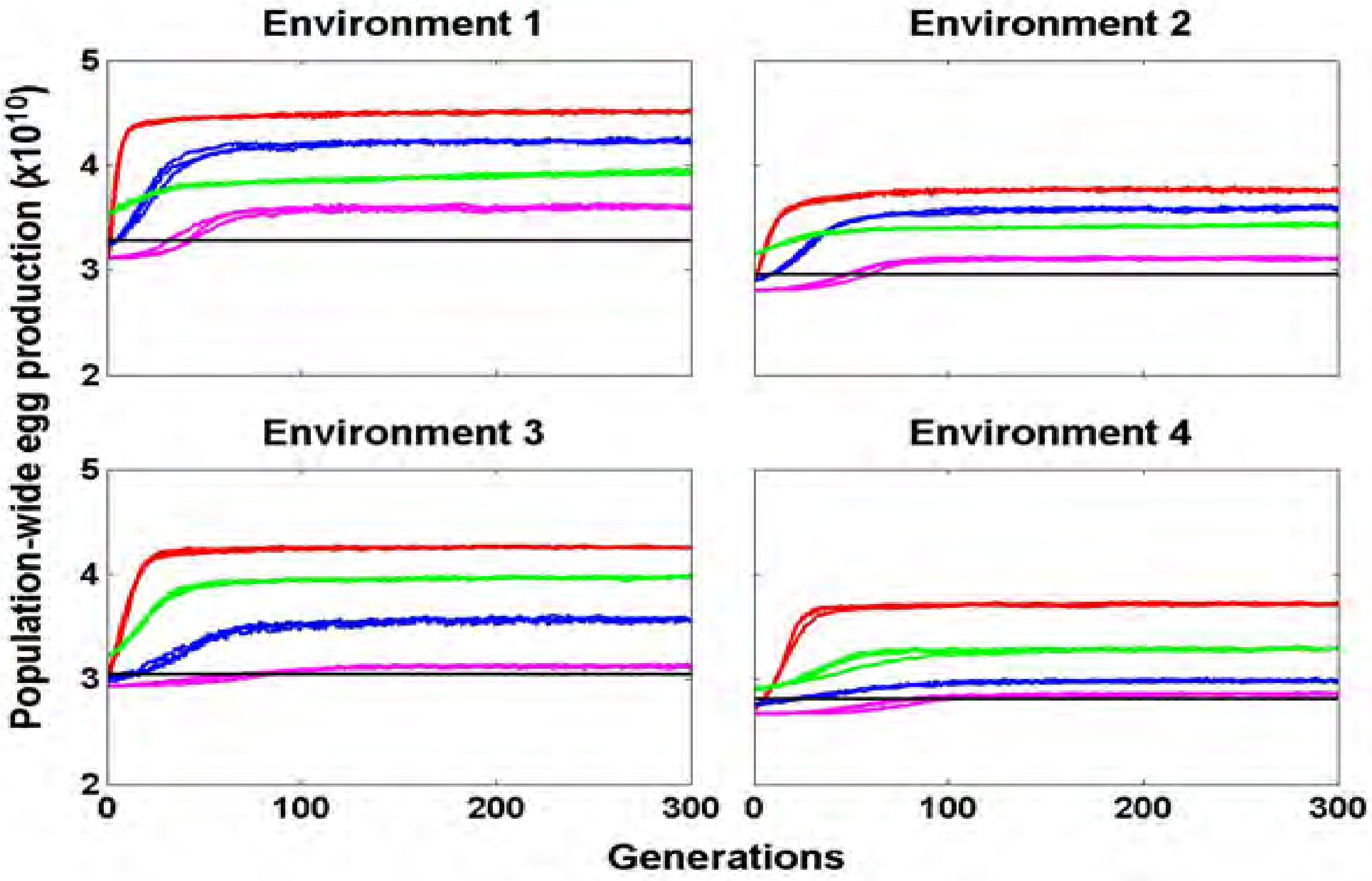
$$g_x = \varepsilon_x \cdot \left(1 - H_2 \cdot e^{-0.5\left(\frac{Q_{c,r}-Q_{opt}}{\sigma_Q}\right)^2}\right)$$

$$V_x(t) = f_x + g_x$$

$$V_y(t) = f_y + g_y$$

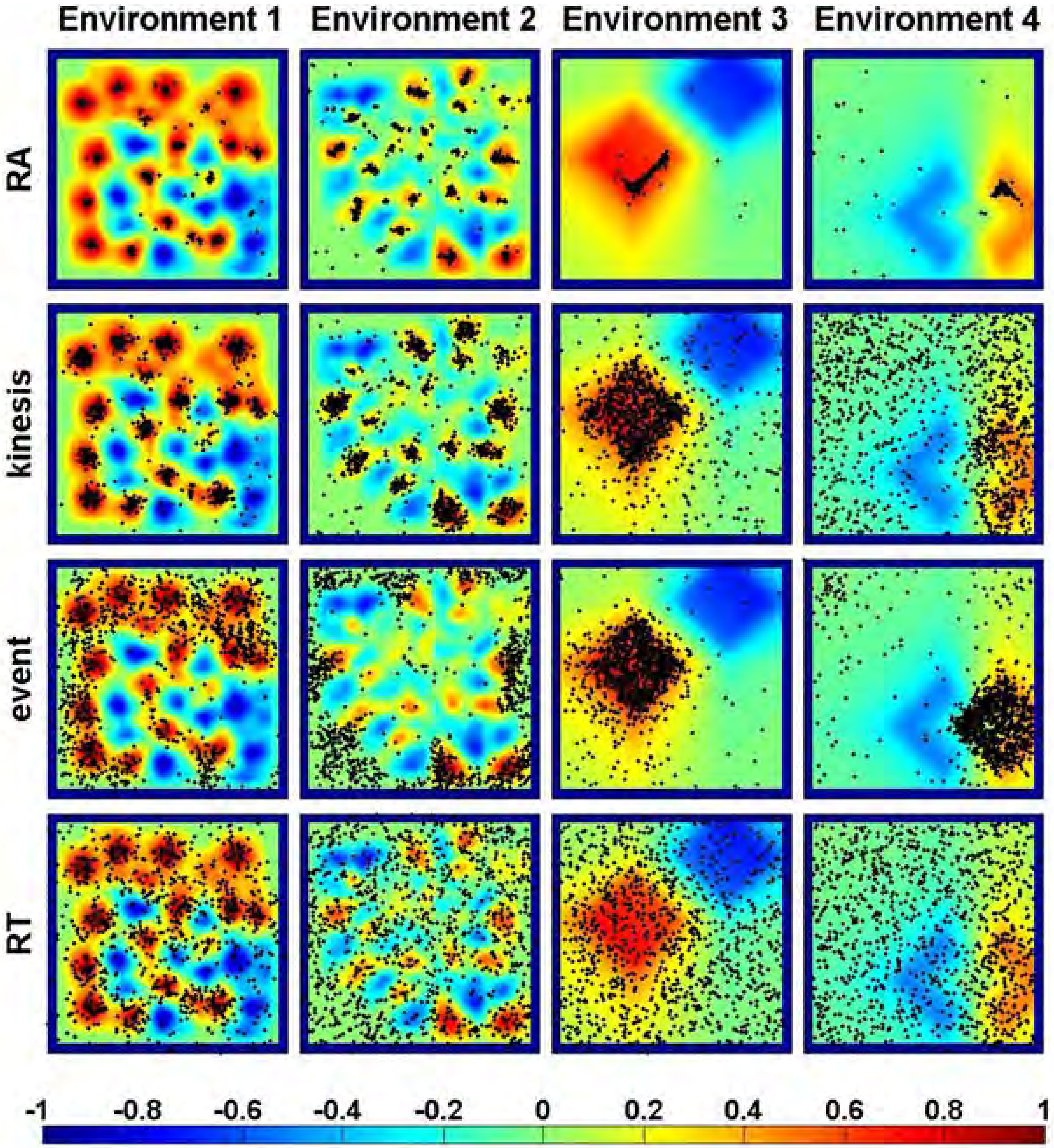
- GA evolves Q_{opt}, σ, H_1, H_2, δ

Calibration – Fitness Convergence

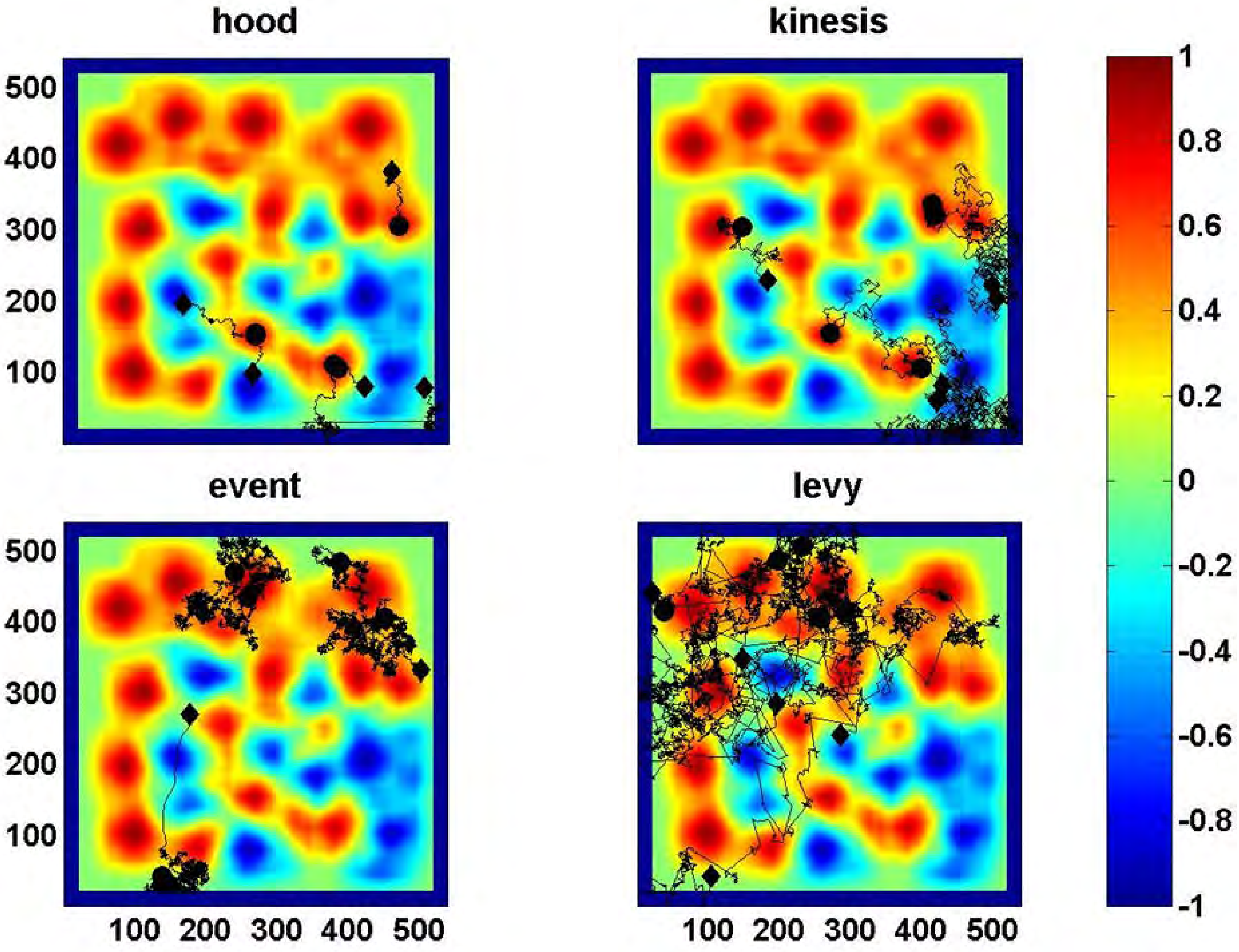


Restricted area, Kinesis , Event-based, Run-tumble

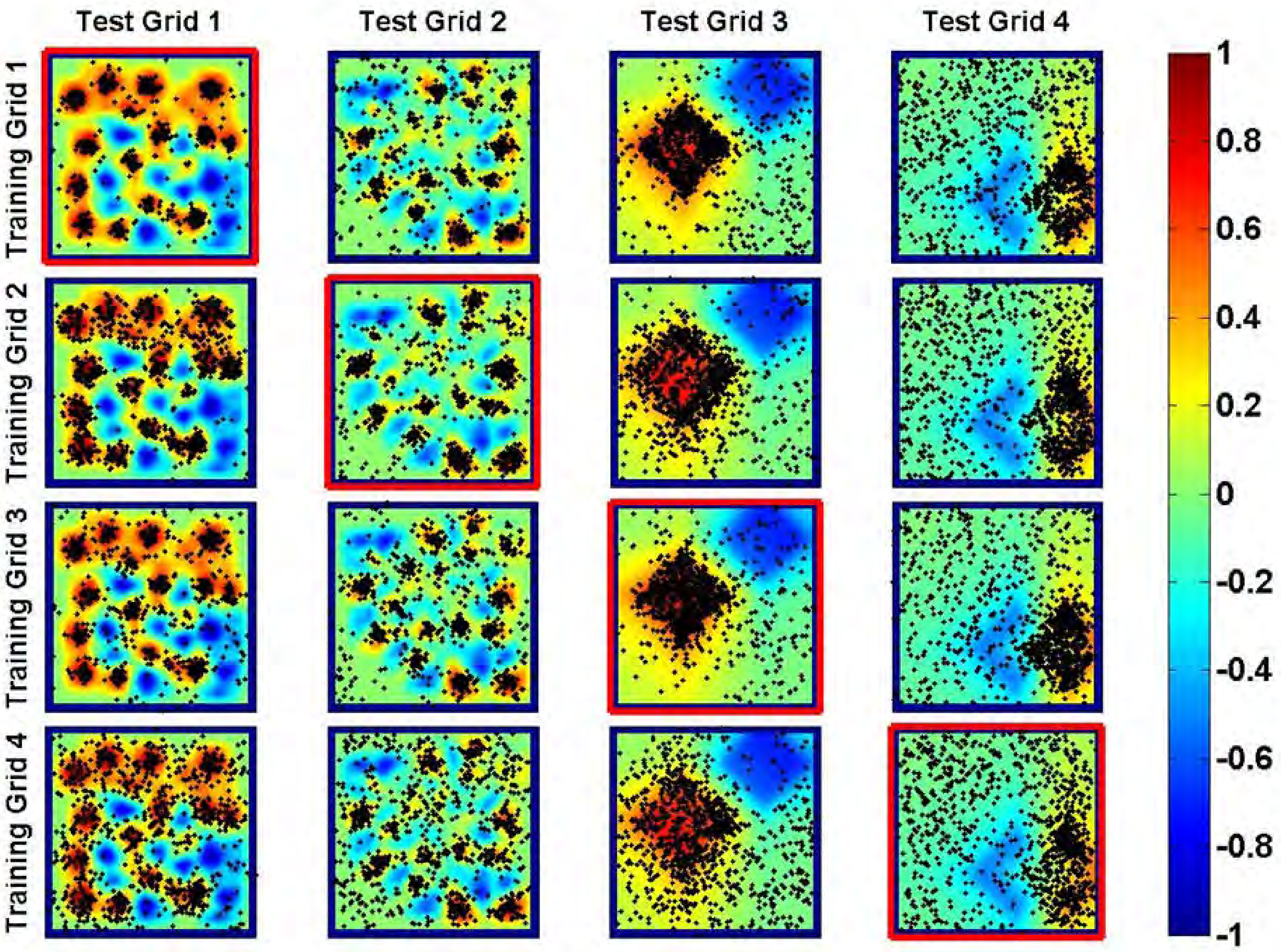
Last day of 300^{th} generation



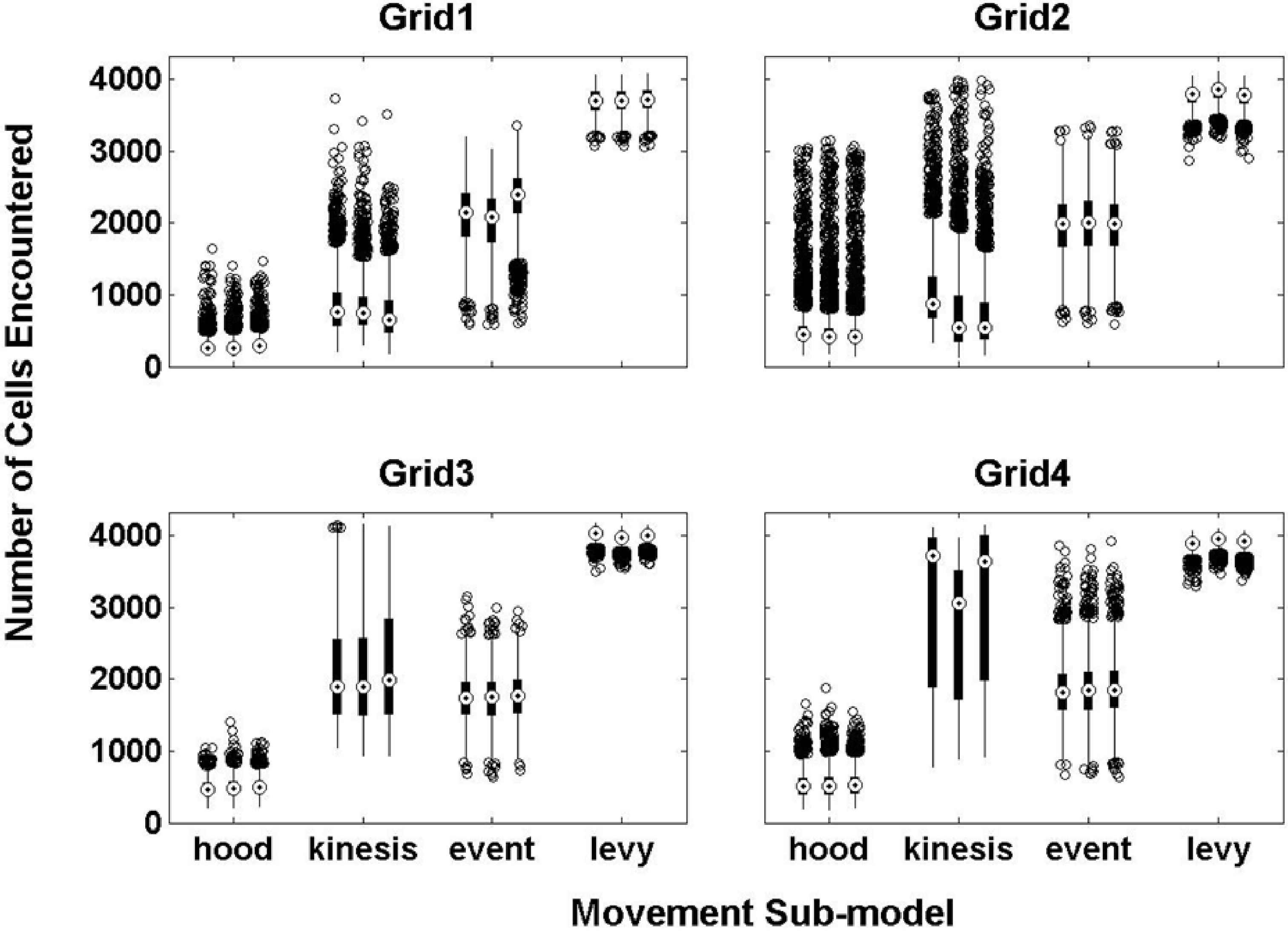
10 Individuals



Kinesis - Testing



Pathways


Grid1
Grid2
Grid3
Grid4
Number of Cells Encountered
0
1000
2000
3000
4000
hood
kinesis
event
levy
Movement Sub-model

Enrique N. Curchitser
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University of California – Santa Cruz

Kate Hedstrom
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Scripps Institute of Oceanography

Tony Koslow
Scripps Institute – CALCOFI

Sam McClatchie
Southwest Fisheries Science Center - NOAA

Francisco Werner
Southwest Fisheries Science Center - NOAA

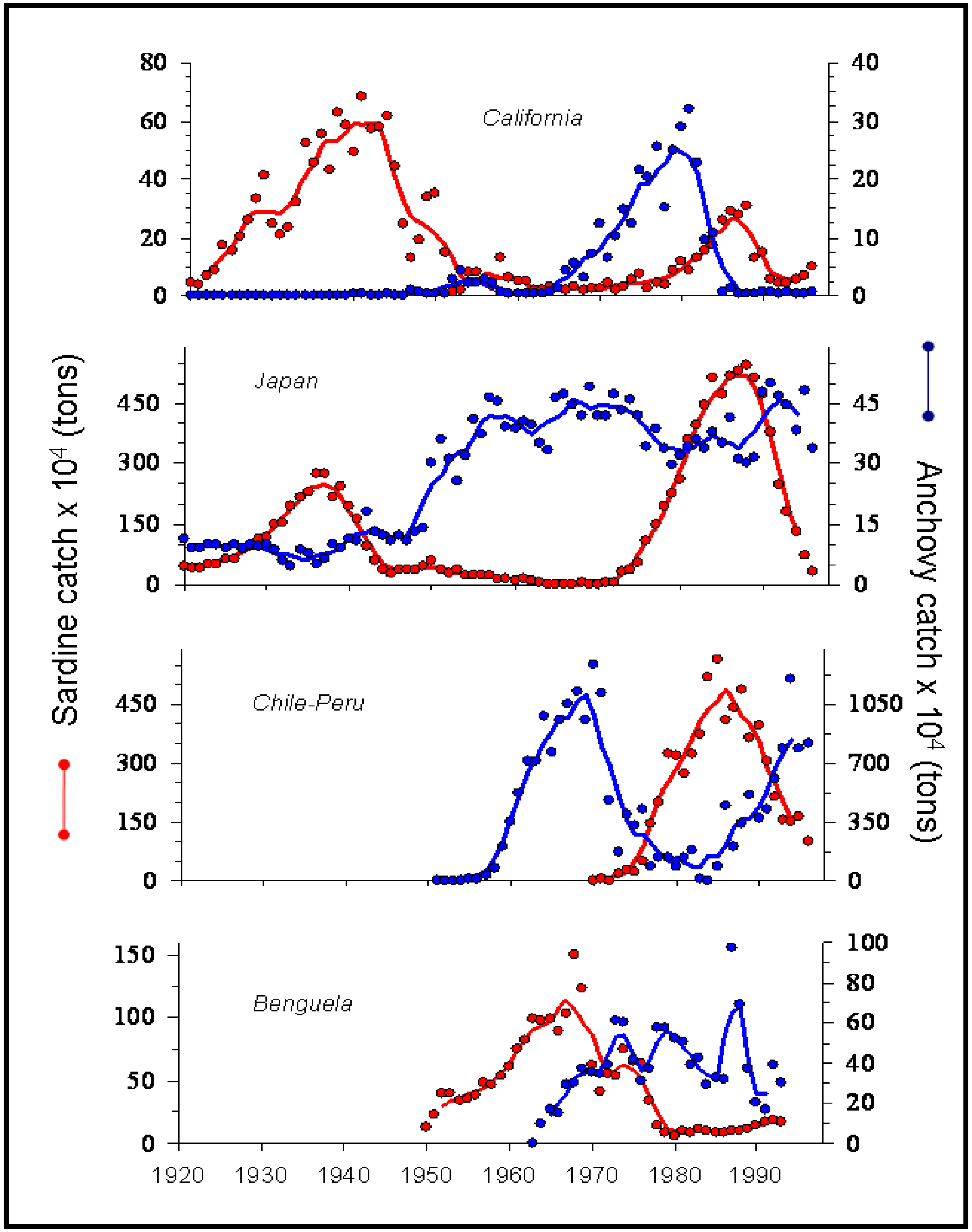
Alec MacCall
Southwest Fisheries Science Center - NOAA

Vera Agostini
Nature Conservancy

Rose et al. 2015. Demonstration of a fully-coupled end-to-end model for small pelagic fish using sardine and anchovy in the California Current. Progress in Oceanography 138: 348-380.

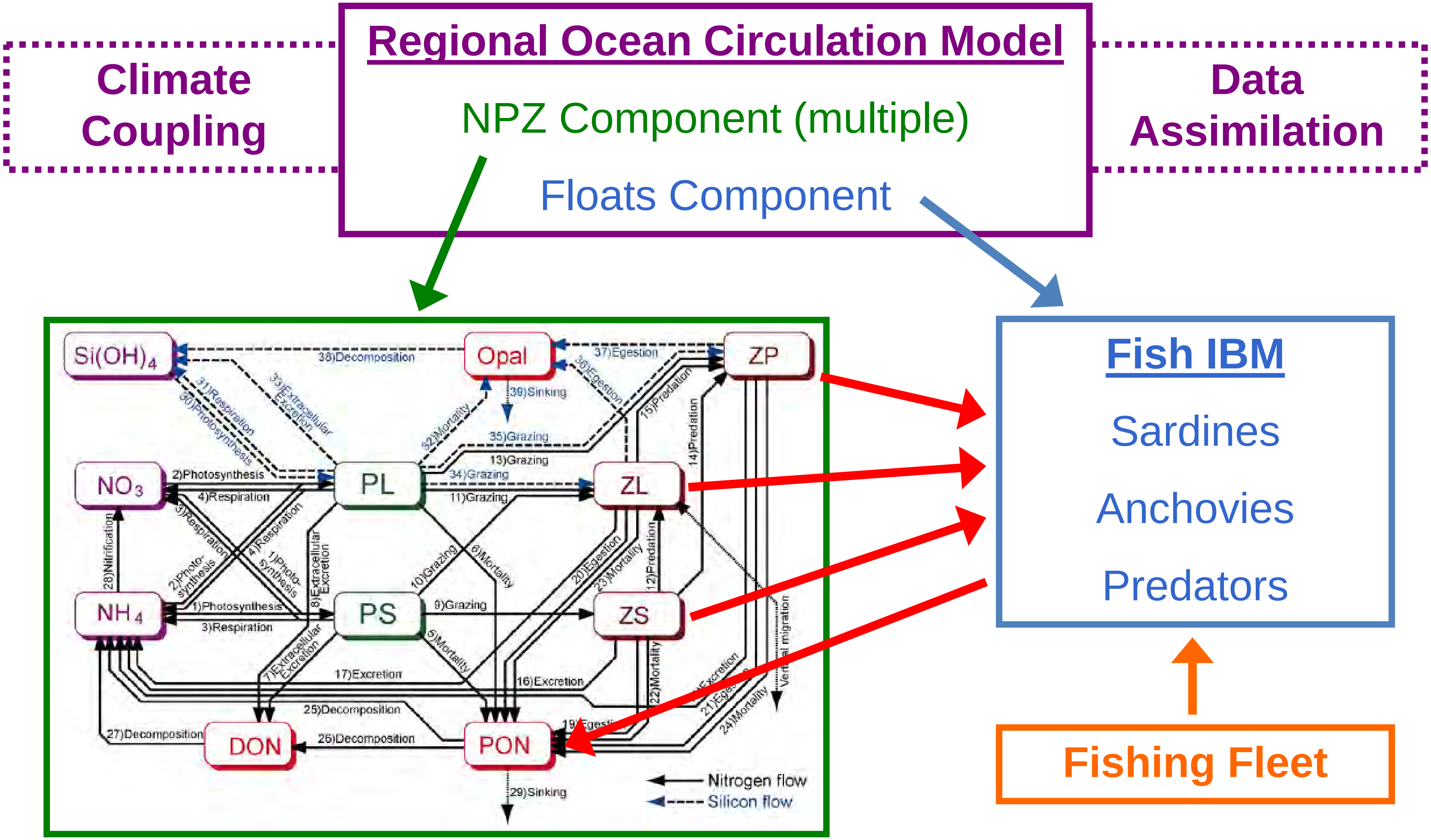
Fiechter et al. 2015. The role of environmental controls in determining sardine and anchovy population cycles in the California Current: Analysis of an end-to-end model. Progress in Oceanography 138: 381-398.


MARINE and
COASTAL SCIENCES



Provided by: Salvador E. Lluch-Cota based on Schwartzlose et al. 1999

Fully-Coupled Model Within ROMS



Climate Coupling

Regional Ocean Circulation Model

NPZ Component (multiple)

Floats Component

Data Assimilation

Fish IBM

Sardines

Anchovies

Predators

Fishing Fleet

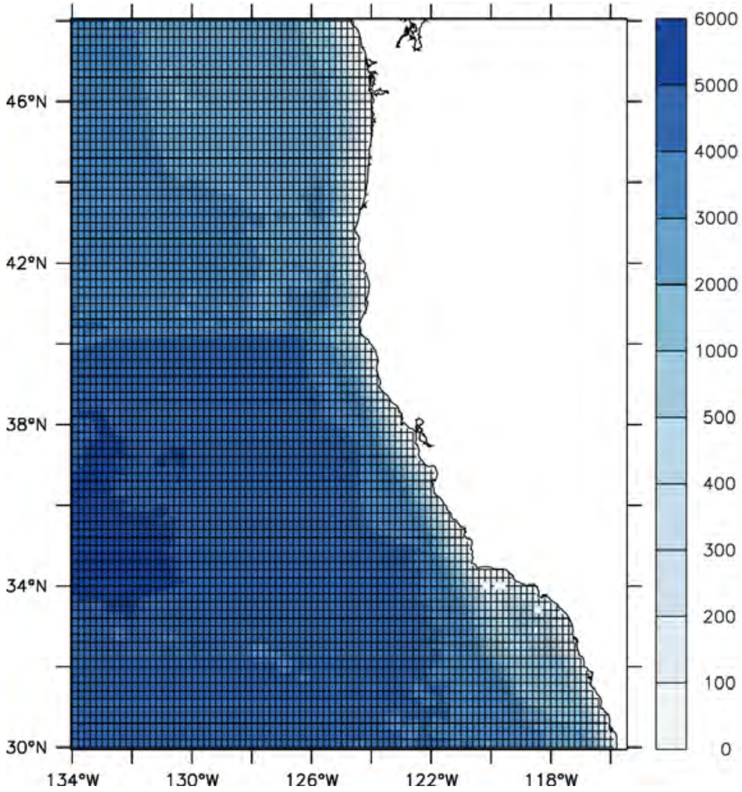
Model 1: ROMS

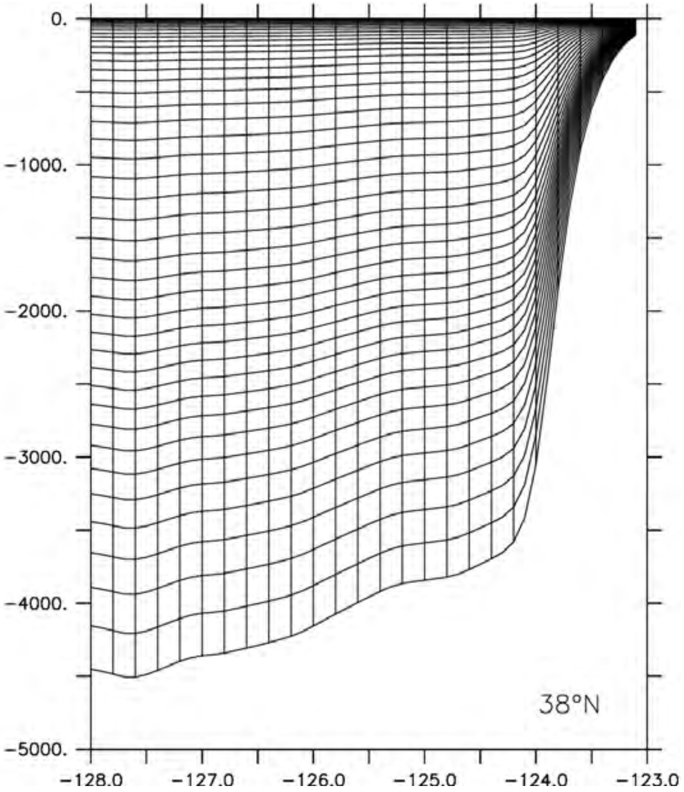
- Grid:

  10 km

  42 levels

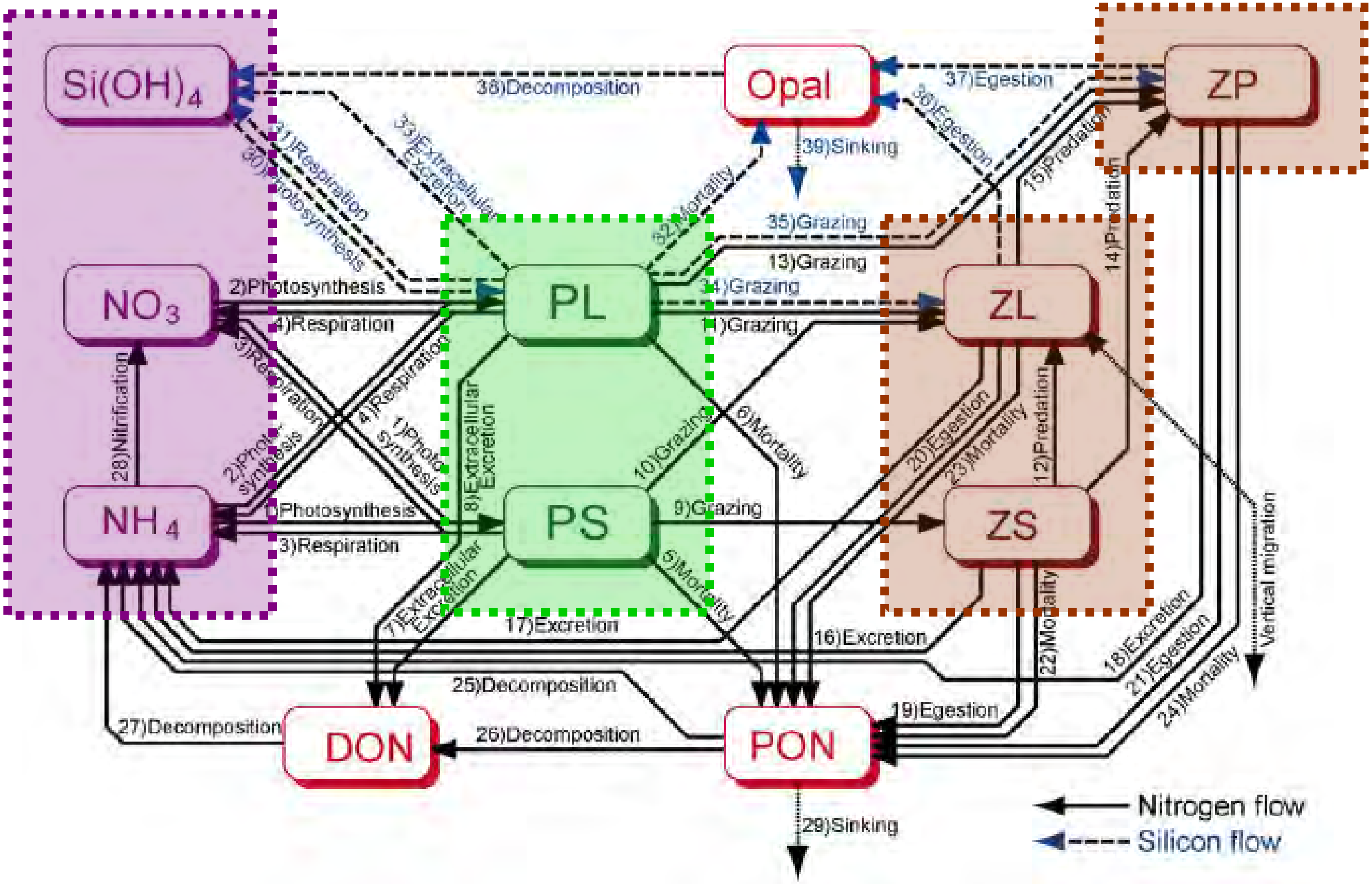
- 900 s





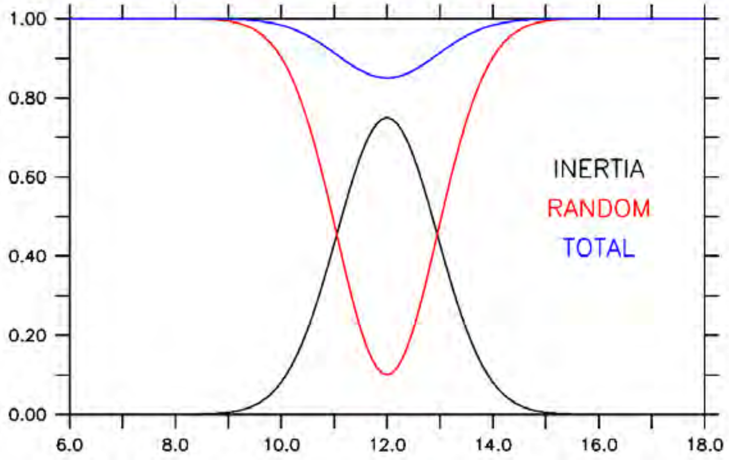
- Run duration: 50 years (1959-2009)

Model 2: NEMURO

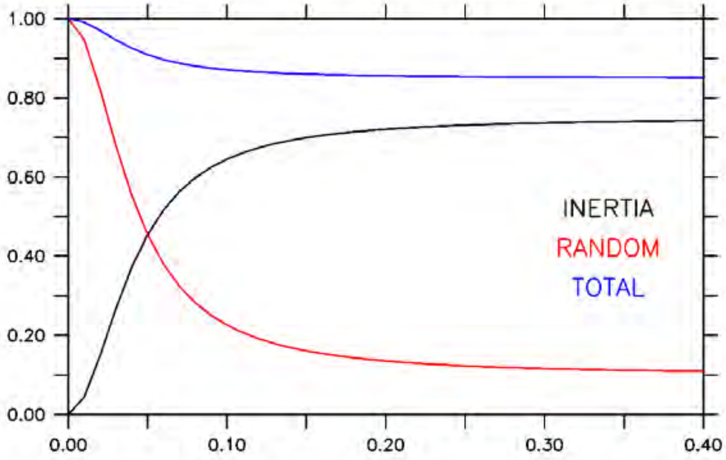


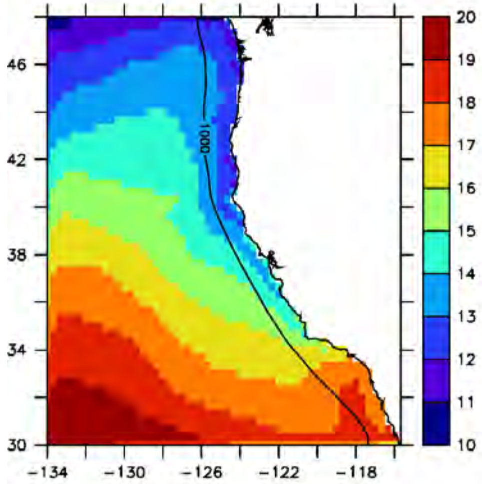
Environmental Cues for Movement (Kinesis)

Temperature (°C) - Gaussian

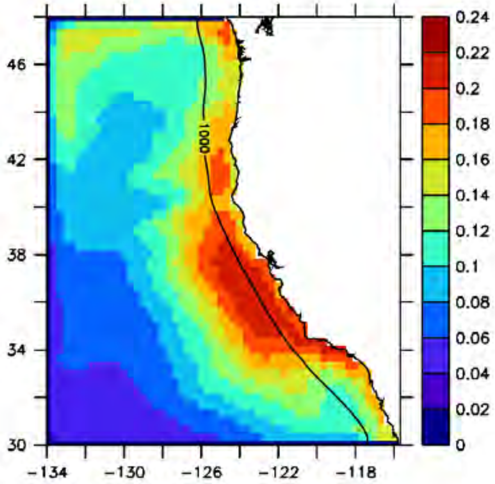


P-Value (C/C_{max}) – Holling Type III

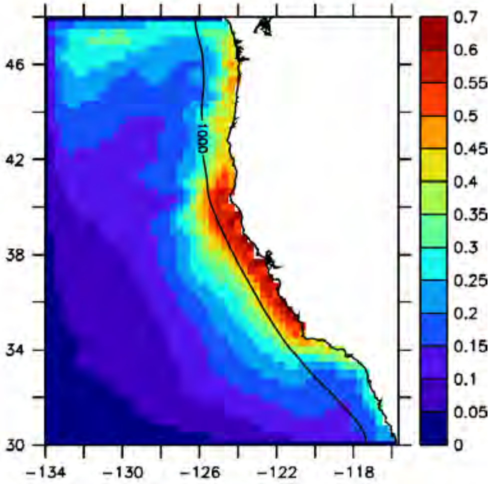




Mean SST (1985-2005)



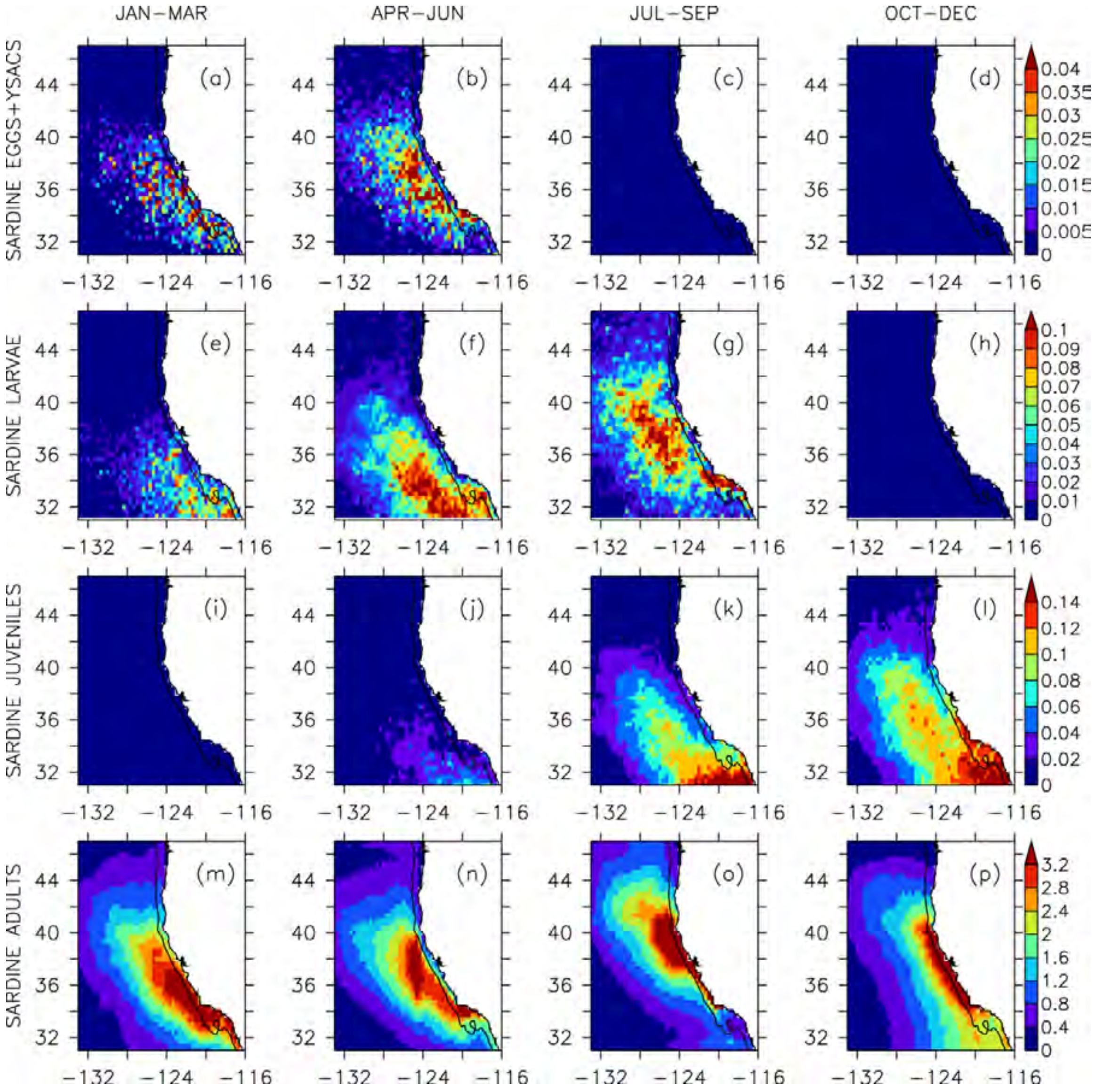
Mean ZS (1985-2005)

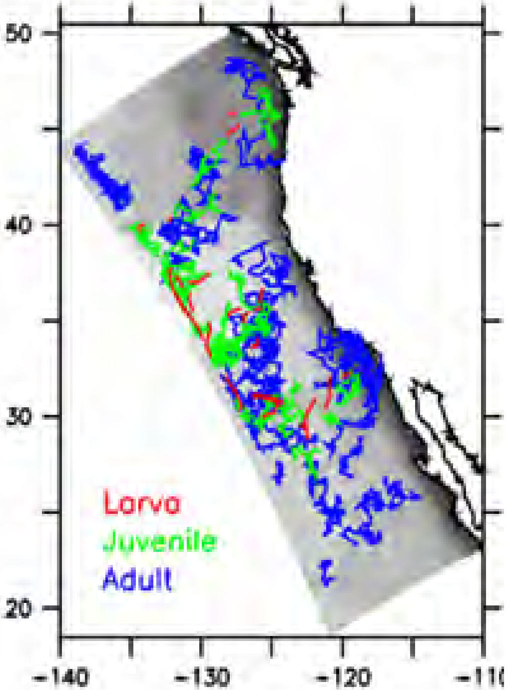


Mean ZL (1985-2005)

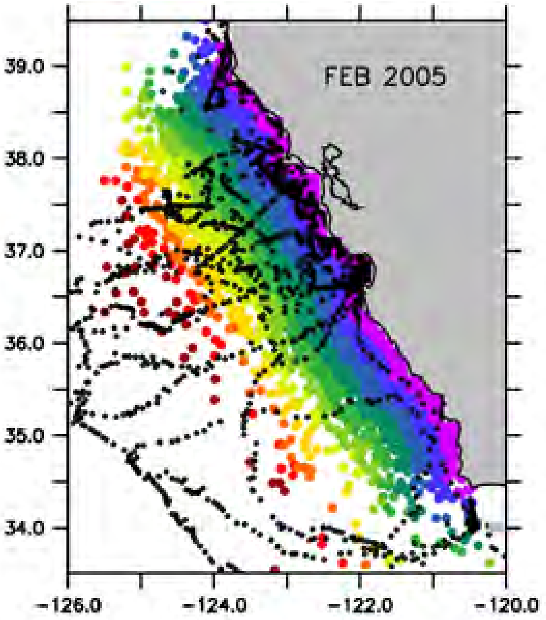
Sardine Spatial

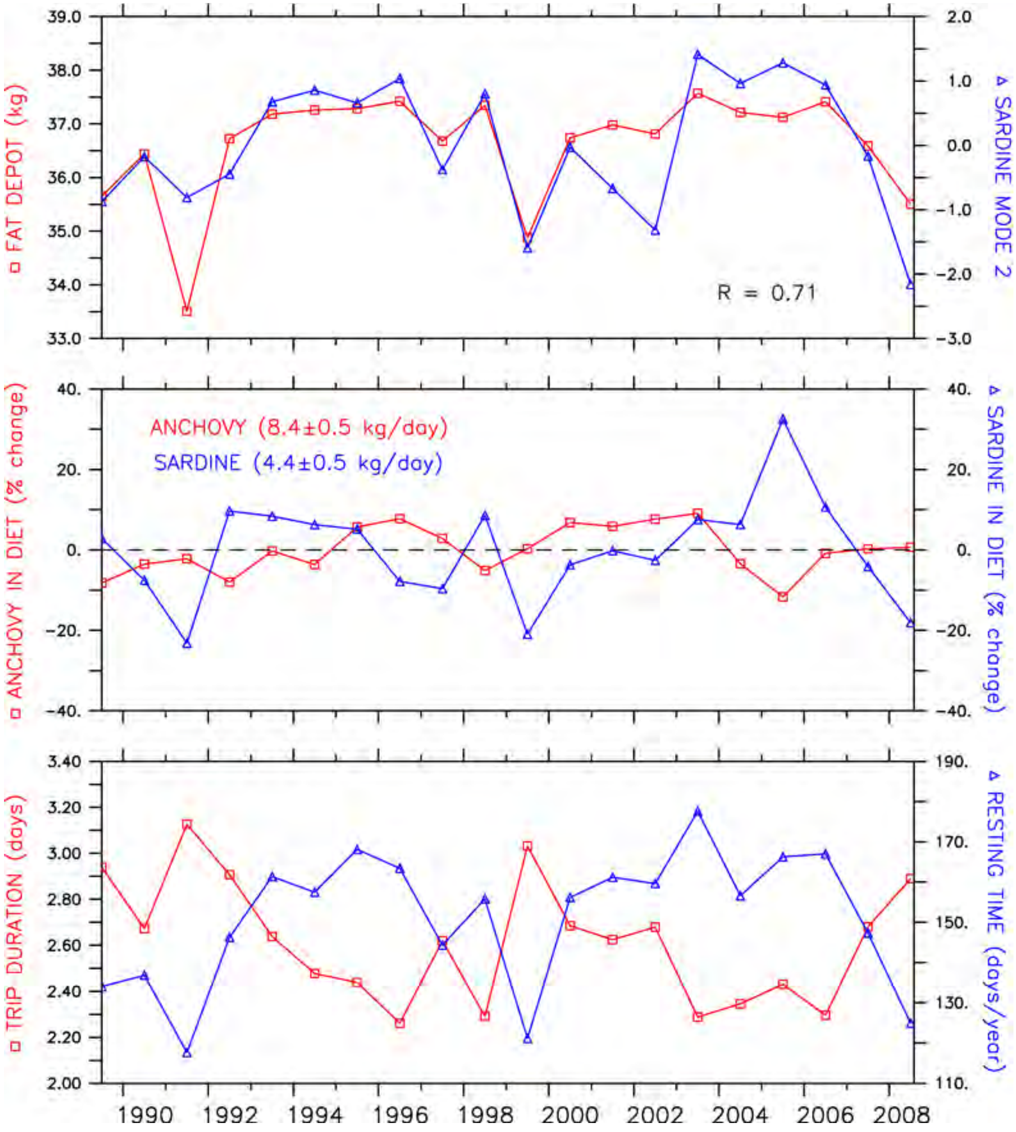
(E&YS – 10^{12}; 1000 MT)





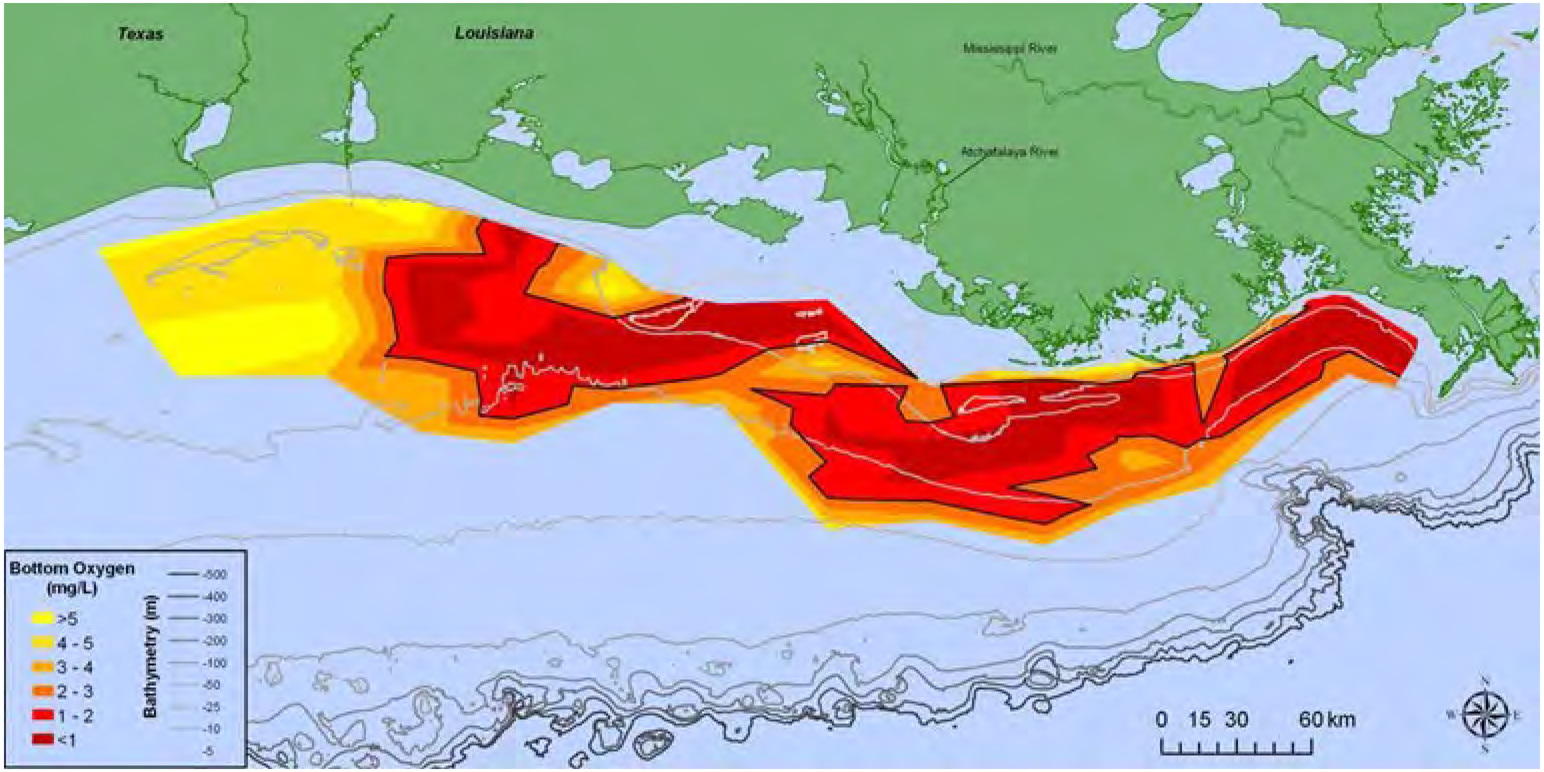
California Sea Lion





Fiechter et al. 2016. Marine Ecology Progress Series 556: 273-285.

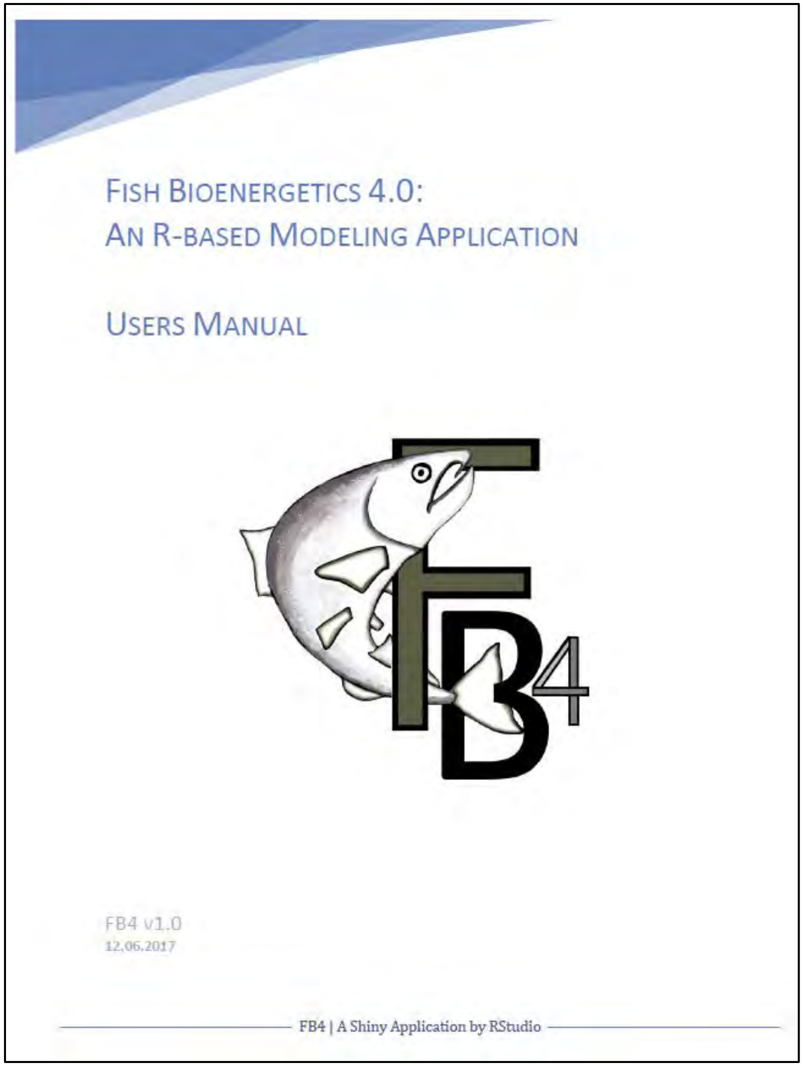
Hypoxia - Gulf of Mexico



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

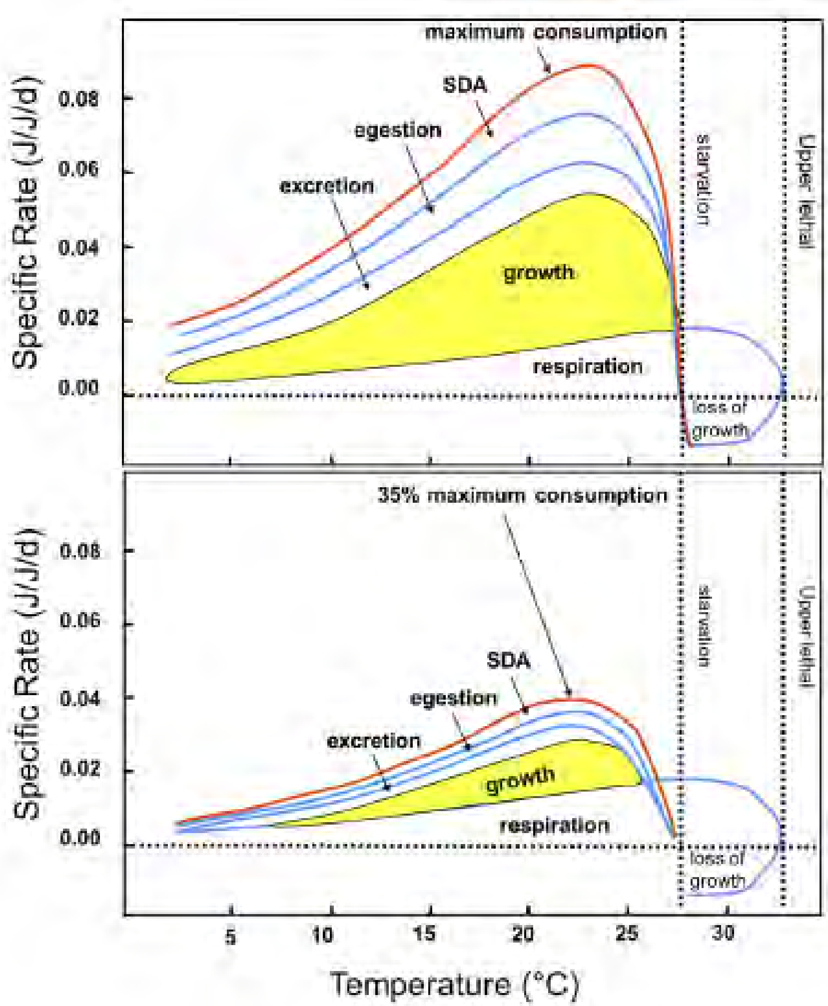


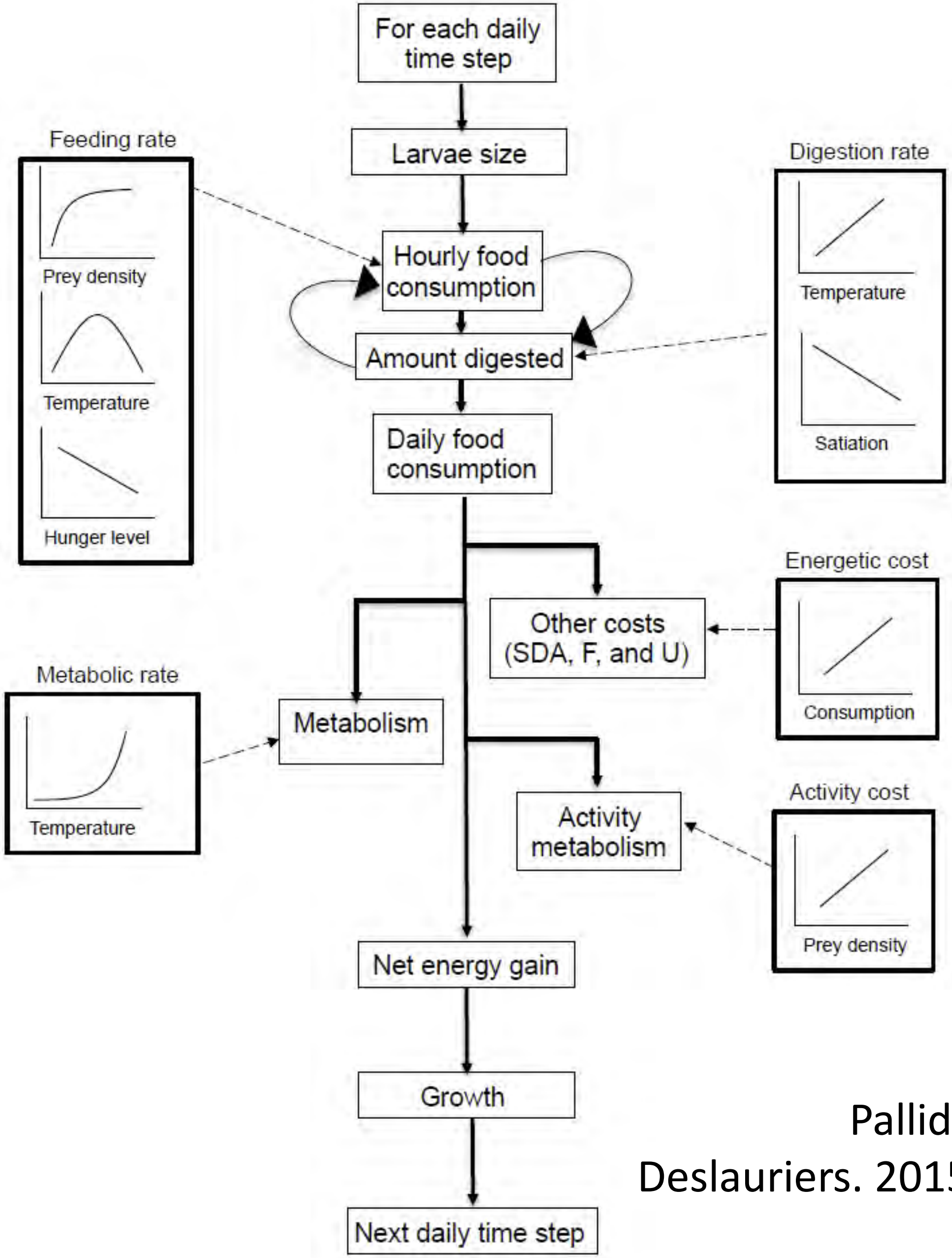
FISH BIOENERGETICS 4.0:
AN R-BASED MODELING APPLICATION

USERS MANUAL

FB4 v1.0
12.06.2017

FB4 | A Shiny Application by RStudio

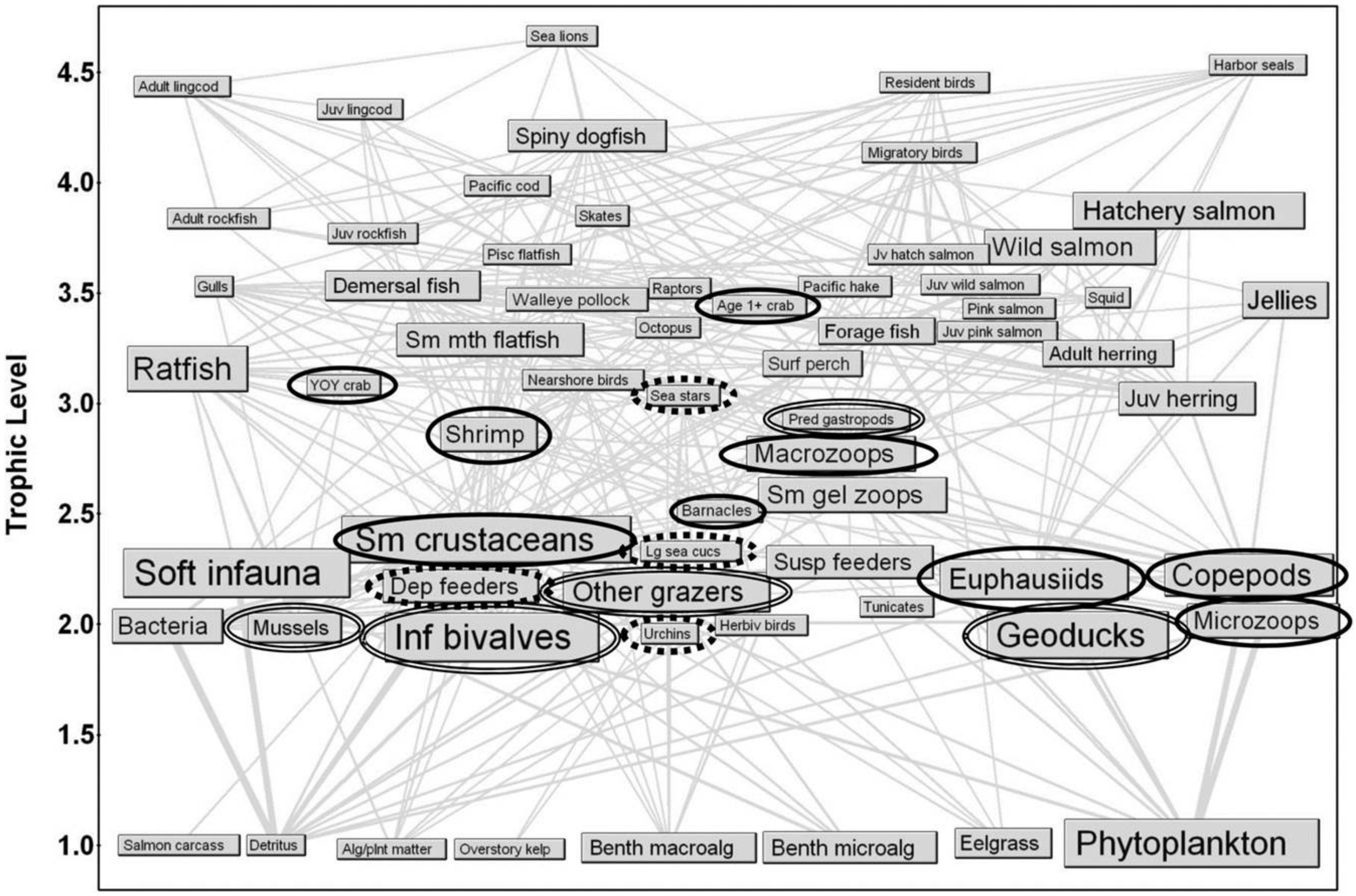


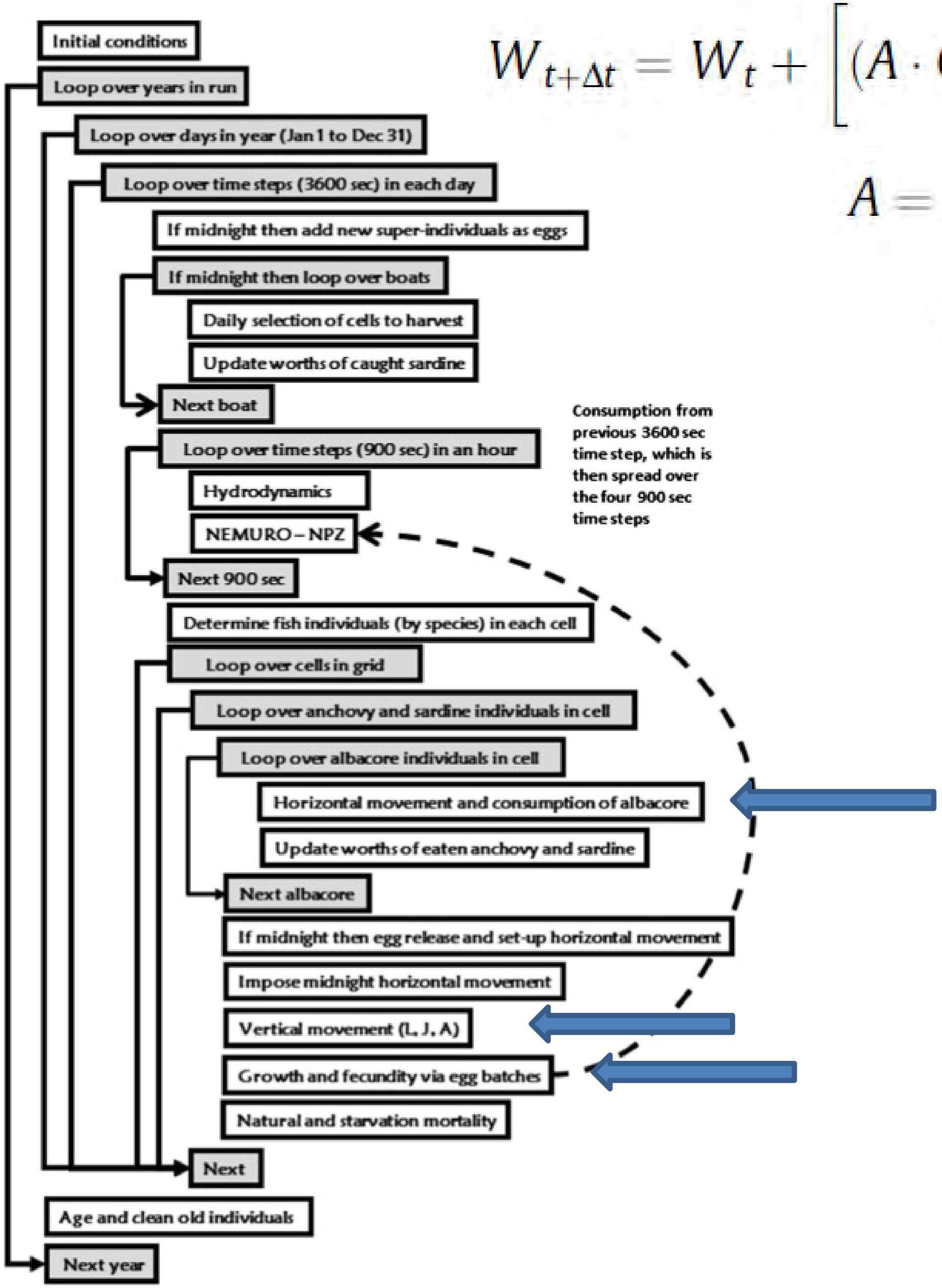


Pallid Sturgeon
Deslauriers. 2015. Dissertation, SDSU

NOAA OCEAN ACIDIFICATION PROGRAM

Busch et al. 2013. ICES Journal of Marine Science 70: 823-833.





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

Next

Age and clean old individuals

Next year

Consumption from previous 3600 sec time step, which is then spread over the four 900 sec time steps

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

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

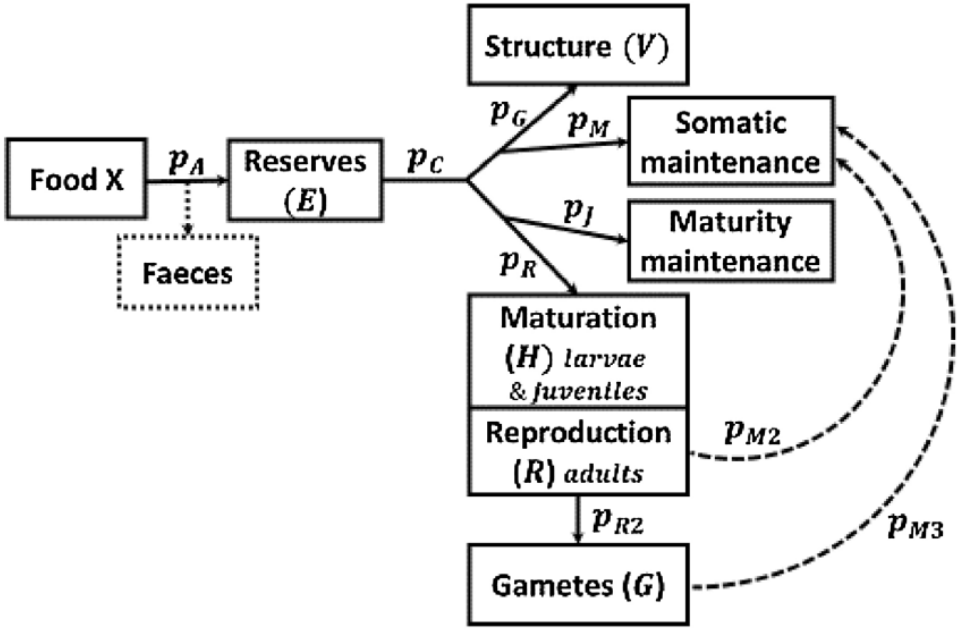
$$C_m = a_c W^{b_c} F(T)$$

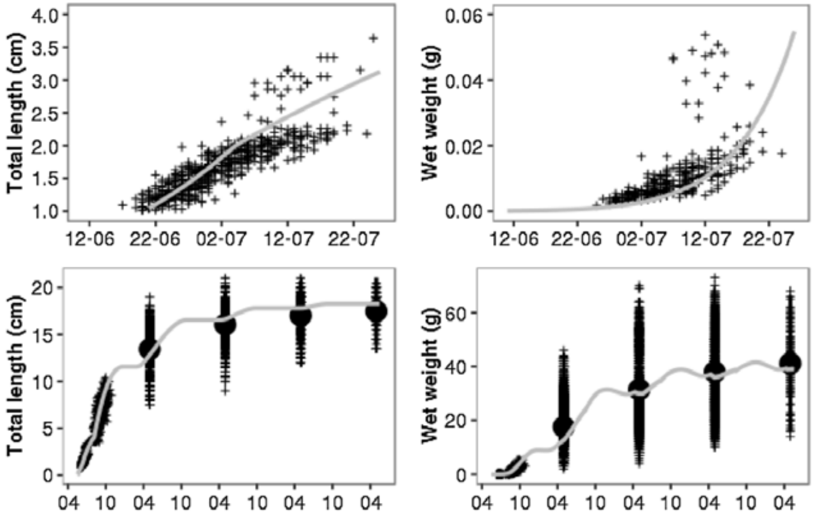
$$C_j = \frac{C_m W \left(\frac{Z_j \bullet V_{sj}}{K_{sj}}\right)}{1 + \sum_{k=1}^{3} \left(\frac{Z_k \bullet V_{sj}}{K_{sk}}\right)}$$

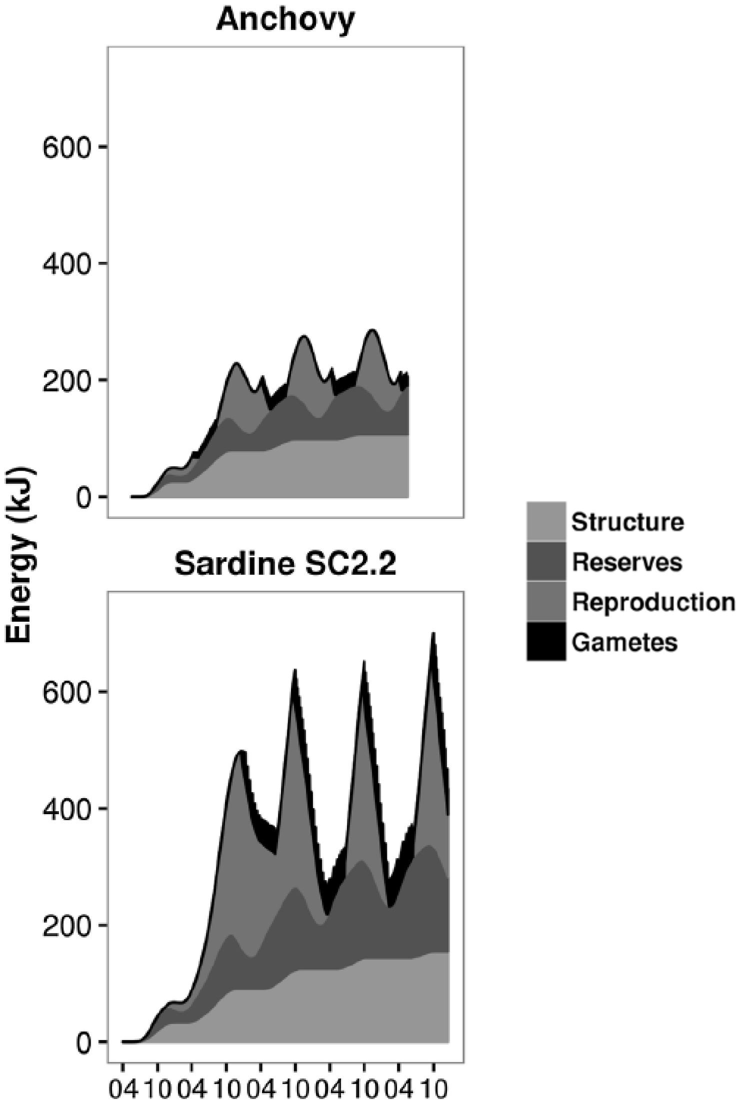
$$R = a_r W^{b_r} \cdot G(T) \cdot a_a \cdot 5.258$$

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

$$a_a = e^{d_r * U_B * L/10}$$







Gatti et al. 2017. Ecological Modelling 348: 93-109.

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

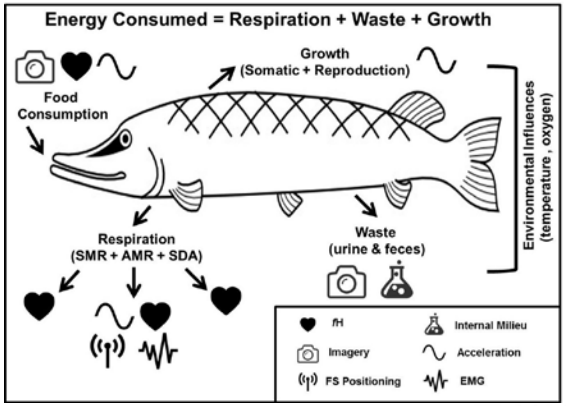
Necessity or Opportunity

- Merge movement with the bioenergetics

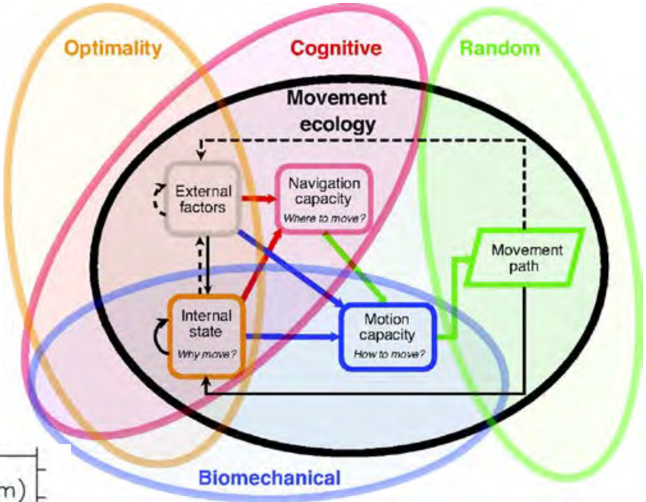
- Consistency (two-way)

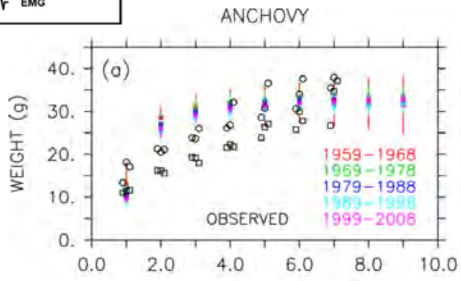
- Journey and destination affect bioenergetics the same way as used in movement

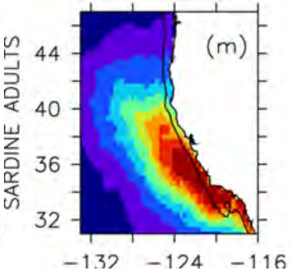
- Project responses to major changes in cues

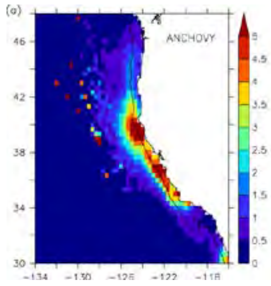


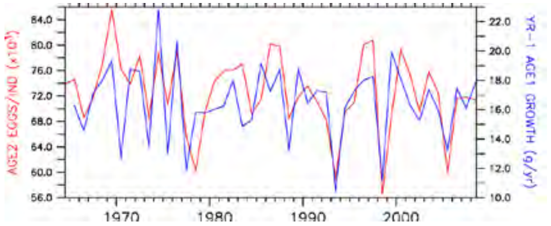
Bioenergetics











CC

Fisheries

Life stage
Recruitment
Population
Community
Food web

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