Bioenergetics modelling to advance knowledge on life history traits and population dynamics of small pelagic fish

Illustration with anchovy in the Bay of Biscay, and beyond

Ifremer

M. Huret, P. Gatti and P. Petitgas

SEAMAN

CERES

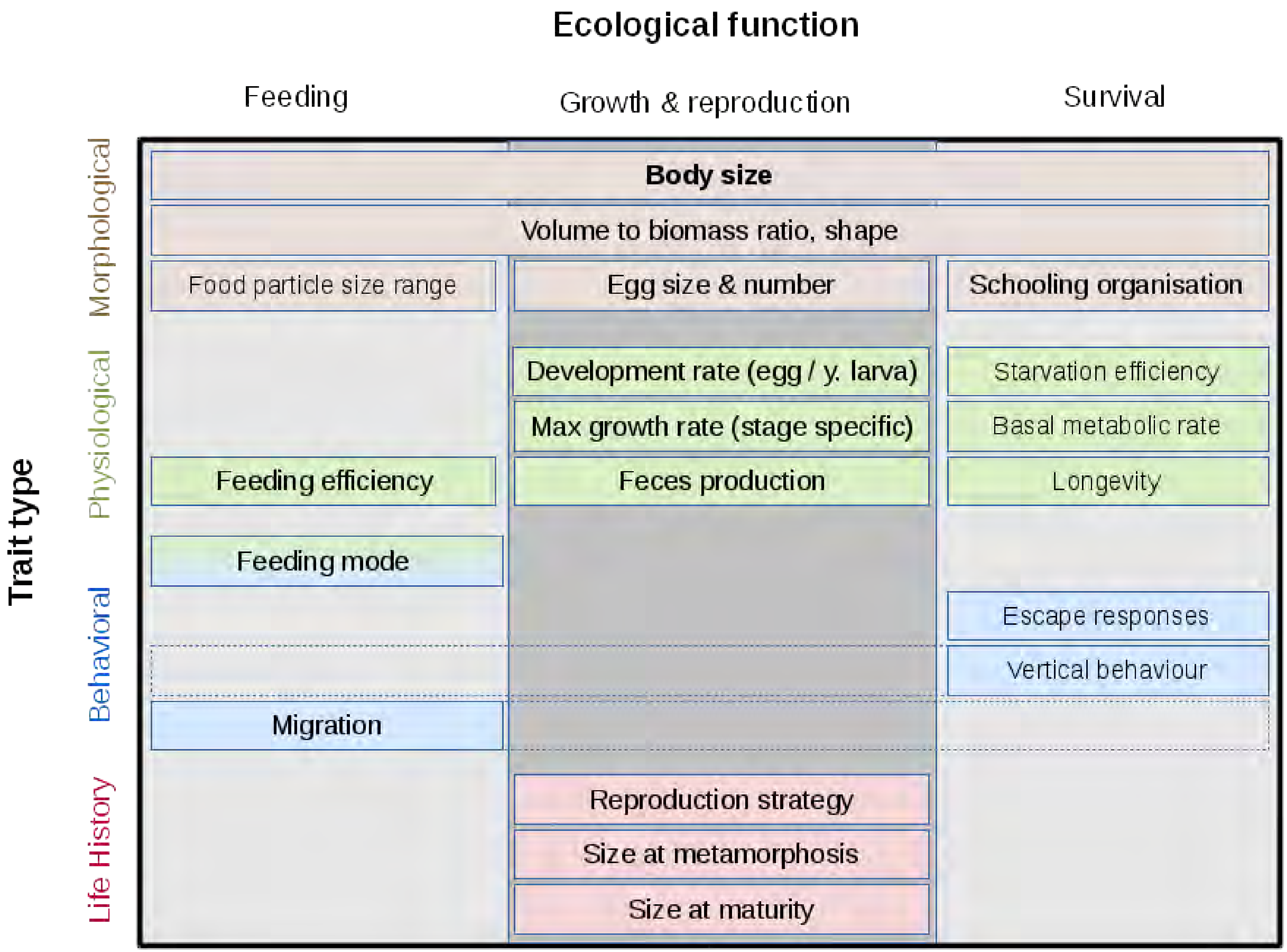
Plan

- Physiology and bioenergetics as the core of key questions in ecology
- A brief history of bioenergetics modelling
- What is important to consider dealing with bioenergetics ?
- The anchovy case study
  - Individual model calibration
  - Process understanding of seasonal migration
  - Regional inter-comparison in North-East Europe
  - Poulation dynamics

Key ecological questions

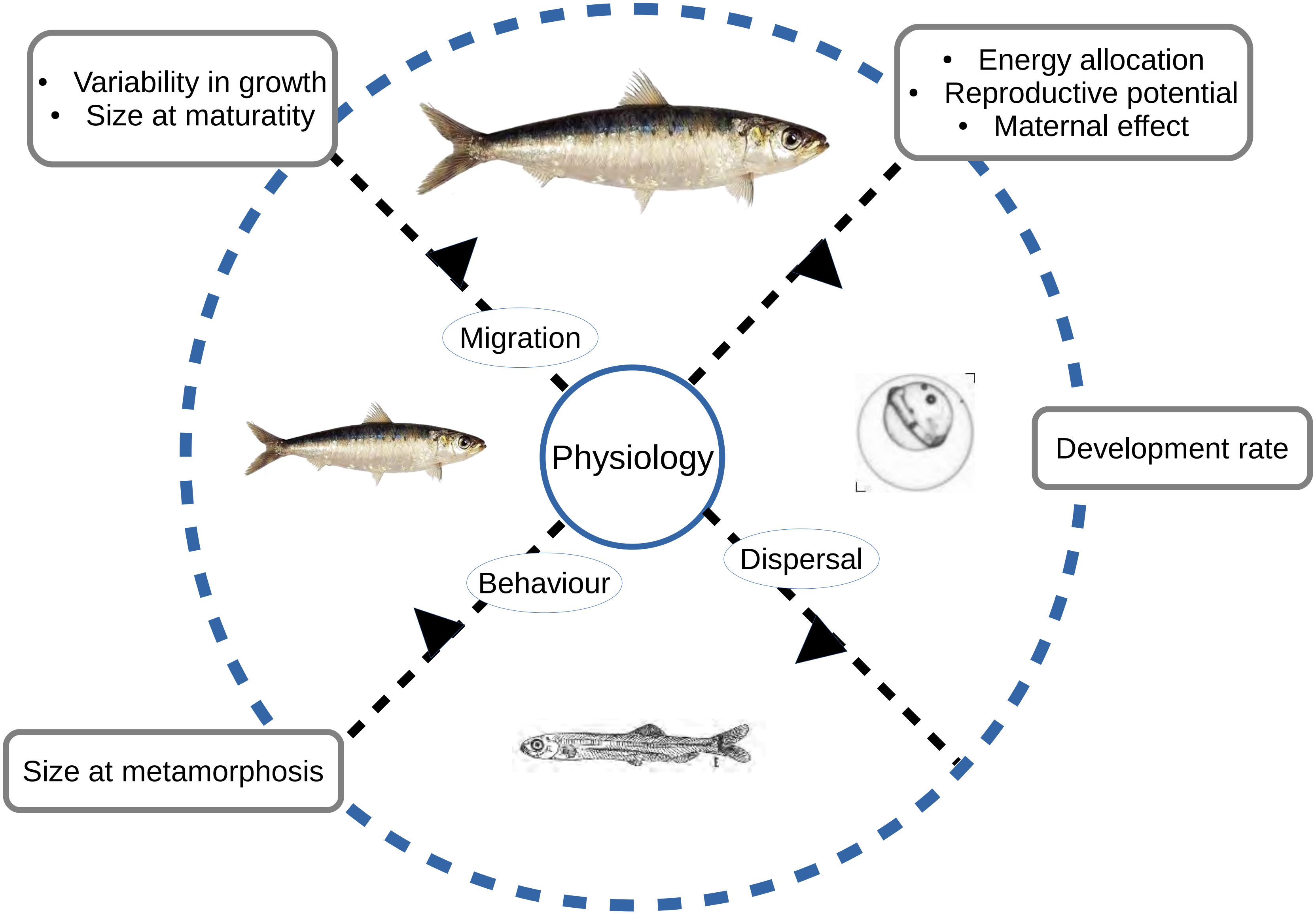
- What explains variability in species' responses to the environment ?
  - ➔ Variability in functional traits

Variability in biological traits of fish



Adapted from Litchman et al., 2013. J.Pl.Res.

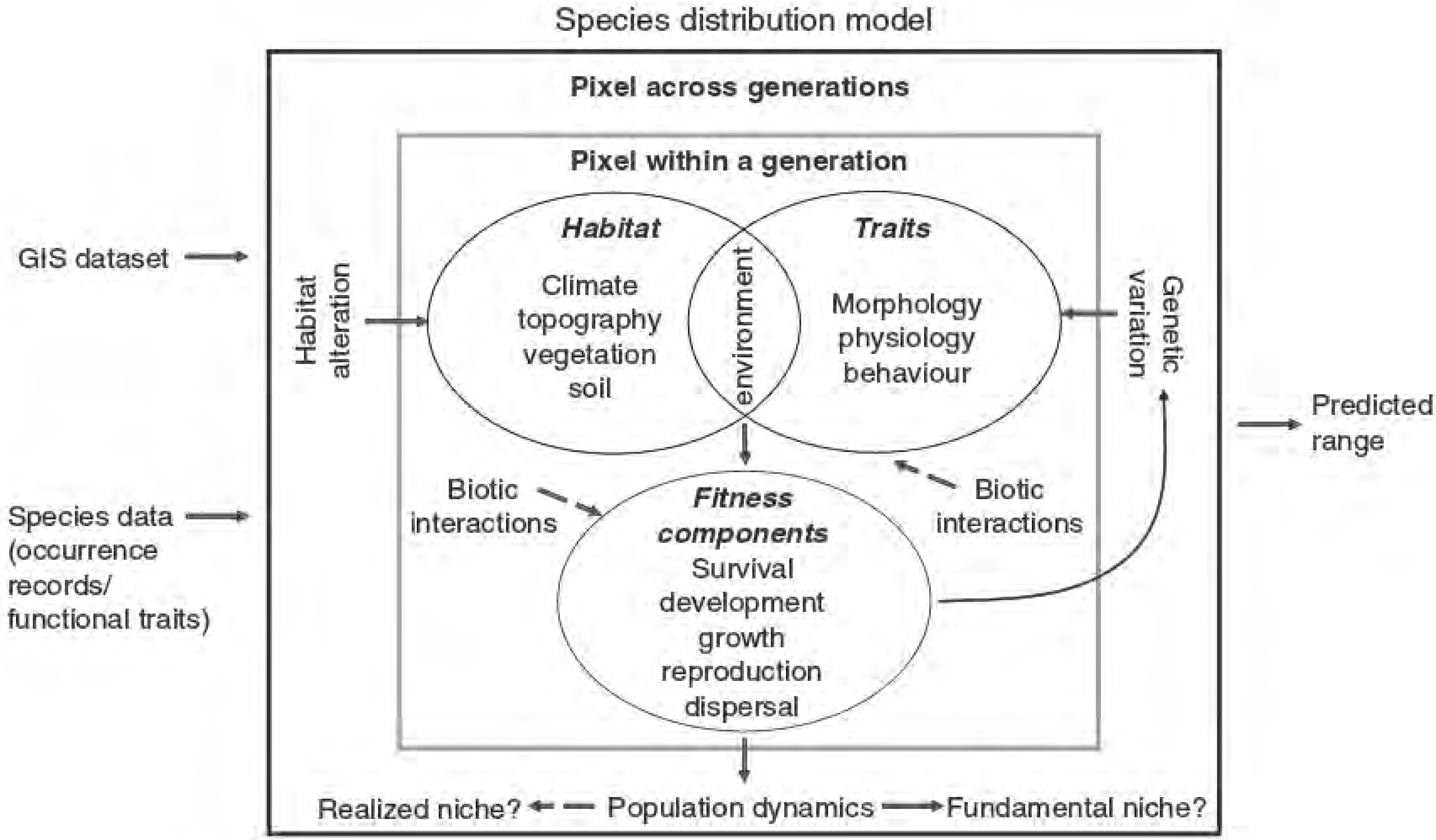
Those traits vary throughout the life cycle



Key ecological questions

- What explains variability in species responses to the environment ?
  - ➔ Variability in functional traits
- What explains species distribution and how changes are operated ?
  - ➔ Going beyond statistical habitats

Going beyond statistical habitat



Kearney et al., 2009. Ecol. Lett. Mechanistic Niche modelling.

Key ecological questions

- What explains variability in species responses to the environment ?
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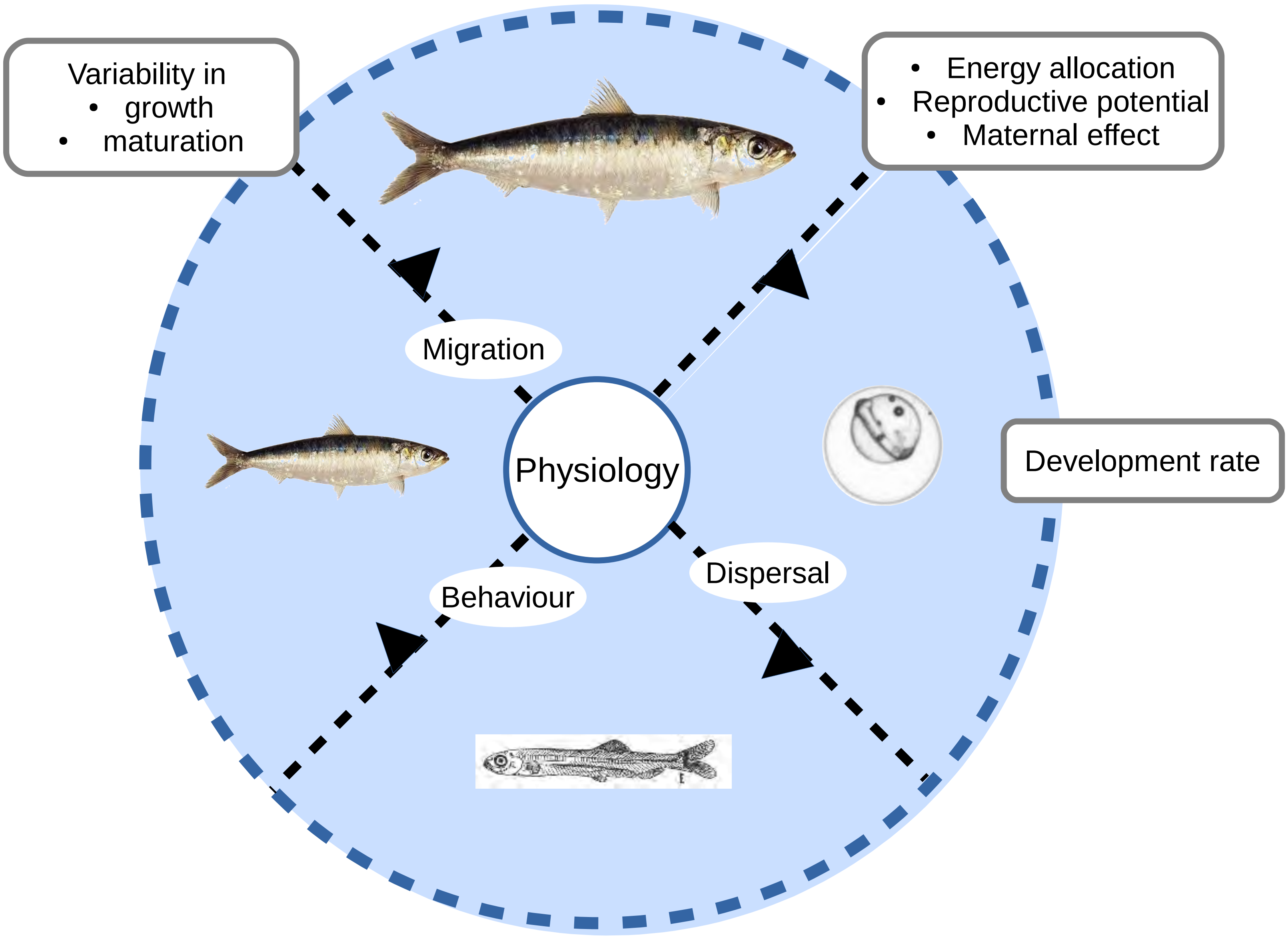
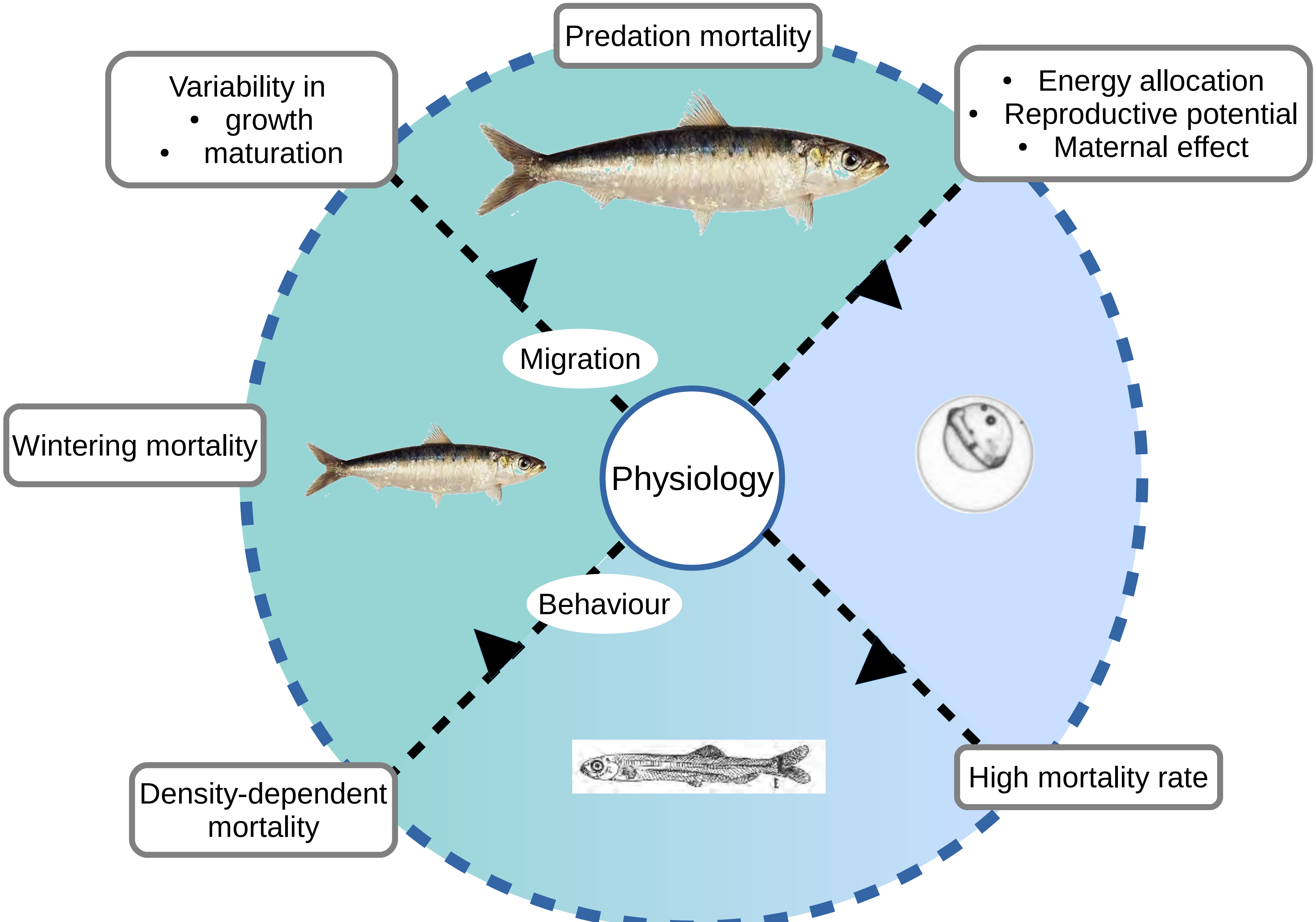
- What explains variability in small pelagics fish populations ?

Abiotic interaction with physiology throughout the life cycle



Biotic interaction with physiology throughout the life cycle



➔ Recruitment : A suite of critical periods for survival and determinant factors for reproductive potential

Key ecological questions

- What explains variability in species responses to the environment ?
  - ➔ Variability in functional traits
- What explains species distribution and how changes are operated ?
  - ➔ Going beyond statistical habitats
- What explains variability in small pelagics fish populations ?
  - ➔ External drivers' interaction with physiology at individual scale, throughout the life cycle
  - ➔ Impact on survival and reproductive potential
  - ➔ Density-dependent effects at the species and ecosystem levels

Key ecological questions

- What explains variability in species responses to environmental drivers ?
  - ➔ Variability in functional traits

- What explains species distribution and how changes are operated ?
  - ➔ Going beyond statistical habitats

- What explains variability in small pelagics fish populations ?
  - ➔ External drivers' interaction with physiology at individual scale, throughout the life cycle
  - ➔ Impact on survival and reproductive potential
  - ➔ Density-dependent effects at the species and ecosystem level

➔ Population dynamics is generated from the non-linear combination of biotic and abiotic ecosystem forcing on a variety of functional traits → emergent properties difficult to predict

➔ Mechanistic representation : only way of understanding and correctly making projections

Bioenergetics

- Bioenergetics model is a mass balance equation founded in the first law of thermodynamics regarding the conservation of mass and energy
- Links basic fish physiology and behaviour with environmental conditions
- When combined with population dynamics, it can lead to system-level estimates of fish production

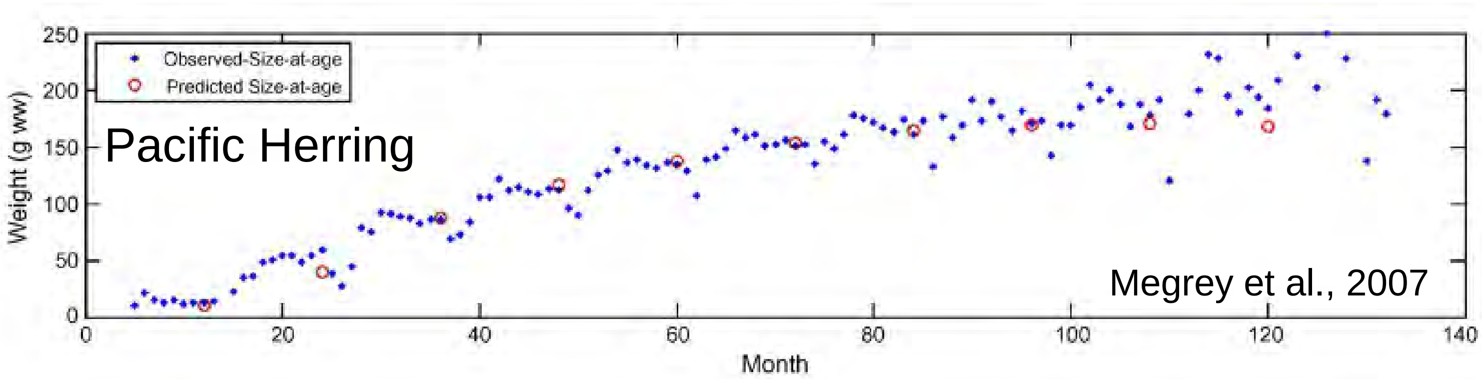
A brief history of modelling fish bioenergetics

- Early 1900's : Von Bertalanffy, first physiological model
  - $\frac{dW}{dt} = aW^{2/3} - cW$ ⟶ VB growth curve
  - Description of average growth
  - No interaction with external forcing variability

- Windberg 1956 : Consumption = Growth (soma + gonads) + Metabolic costs + Waste
- Winsconsin model (Kitchell et al., 1977) : $\frac{dW}{dt} = [C - (R + SDA + EG + EX)] \frac{CAL_z}{CAL_f} W - Egg\, W$
  - Dependency to food and temperature, estimation of consumption or growth
  - A single box

- 90' – 2000' : Dynamic allocation models (e.g. Van Winckle 1997 ; Kooijman, 2000)
  - Separate boxes : growth, reproduction, and storage/reserves
  - Rules for energy allocation

Important considerations : seasonal variability



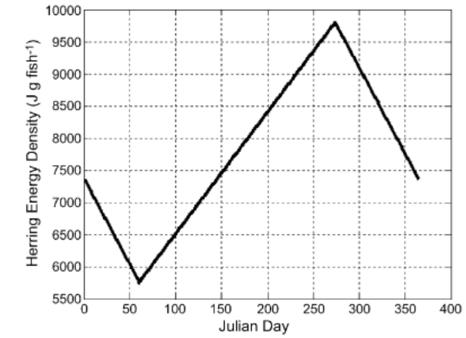
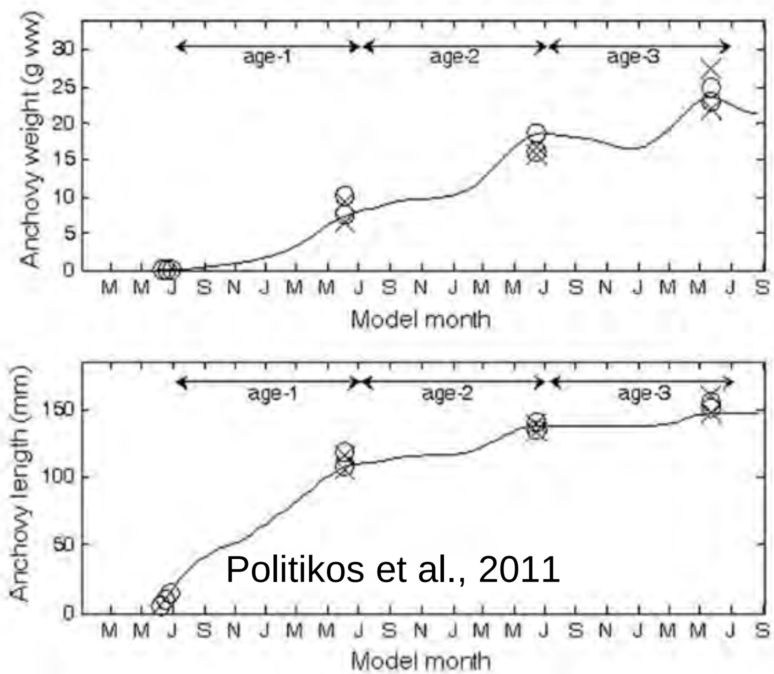


Fig. 2 – Straight line approximation to a seasonal energy density curve for Pacific herring.

Wisconsin model

$$\frac{dW}{dt}=[C-(R+SDA+EG+EX)]\frac{CAL_z}{CAL_f}W-Egg\,W$$

$$CAL_f=\begin{cases}3120, & \text{if length} < 40 \text{ mm}\\ 3520, & \text{if } 40 \le \text{length} < 60 \text{ mm}\\ 4048, & \text{if } 60 \le \text{length} < 90 \text{ mm}\\ 5150, & \text{if length} \ge 90 \text{ mm}\end{cases}$$



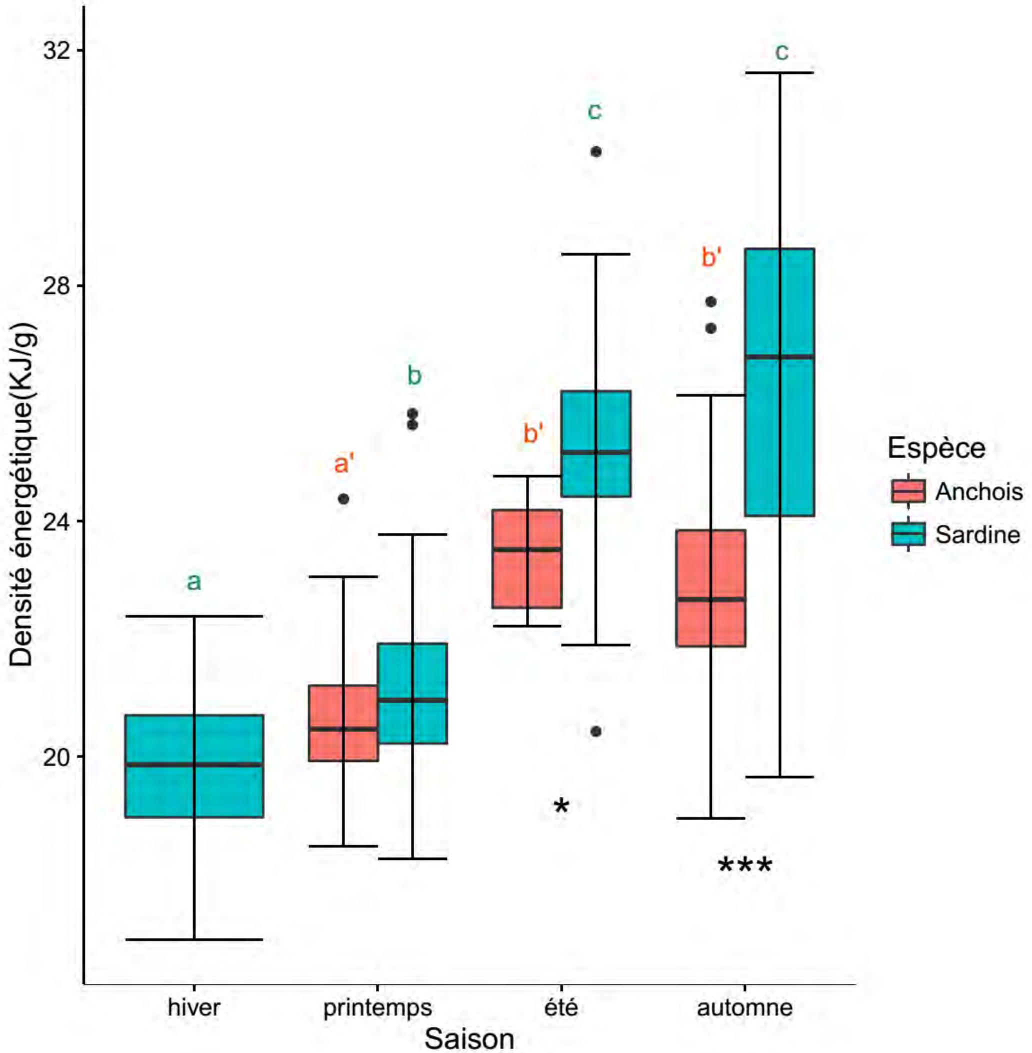
- Energy density of fish is constrained, not dynamic !
- Not conservative !
- No explicit energy density seasonal variability !

- Validation of seasonal variability rare (1 point per year/age) !
- Validation of energy even more rare, though mass/energy conversion is not straight-forward

➔ Need # compartment for correct representation of energy density variability

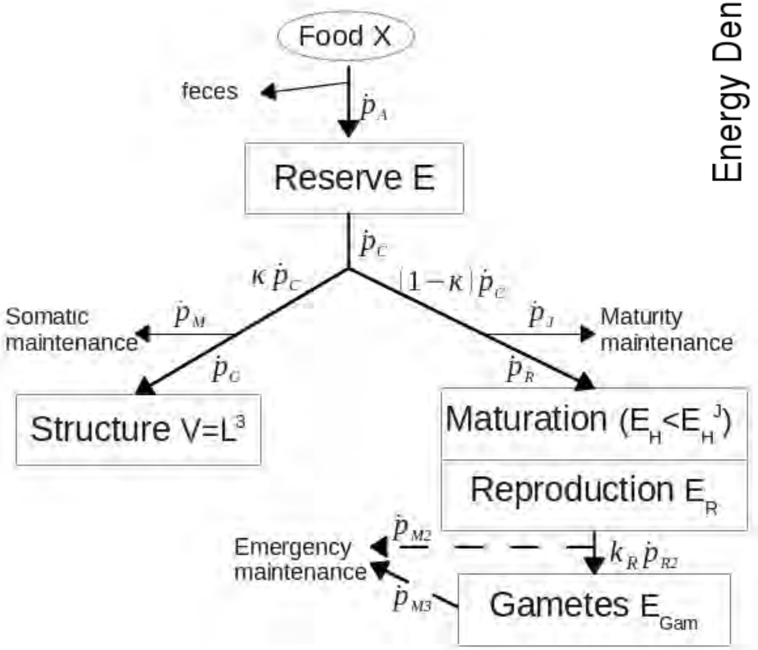
Seasonal variability in energy density

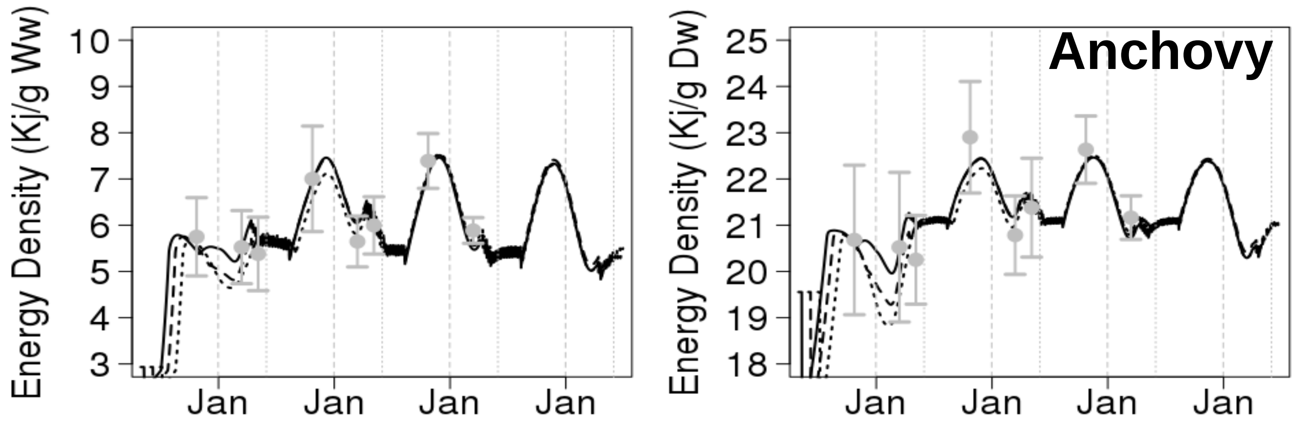
- Strong seasonality in energy density (
- Higher than seasonality in weight, since ED of lipids very high

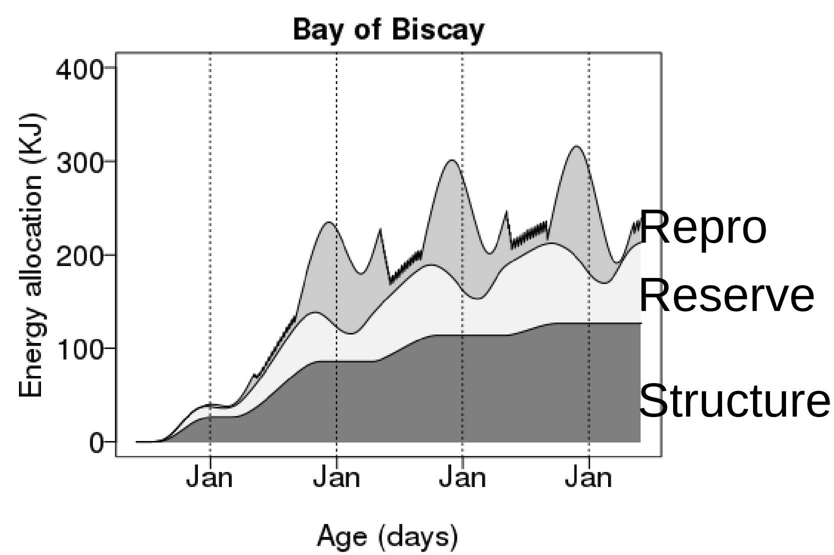


Seasonal variability of the energy density (DW) in the Bay of Biscay in 2014

The DEB allows variation in energy density

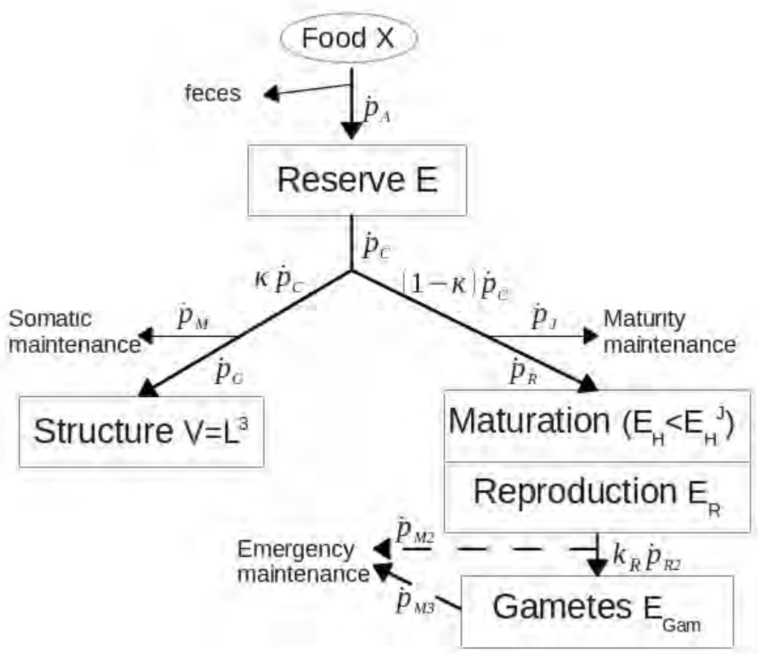






- In winter fish lose reserves (lipids) and %Water increases proportionally
- Weight loss is limited because lipids has high energy density
- Energy adds further challenges for bioenergetics modelling than only weight

Important considerations : proximal composition



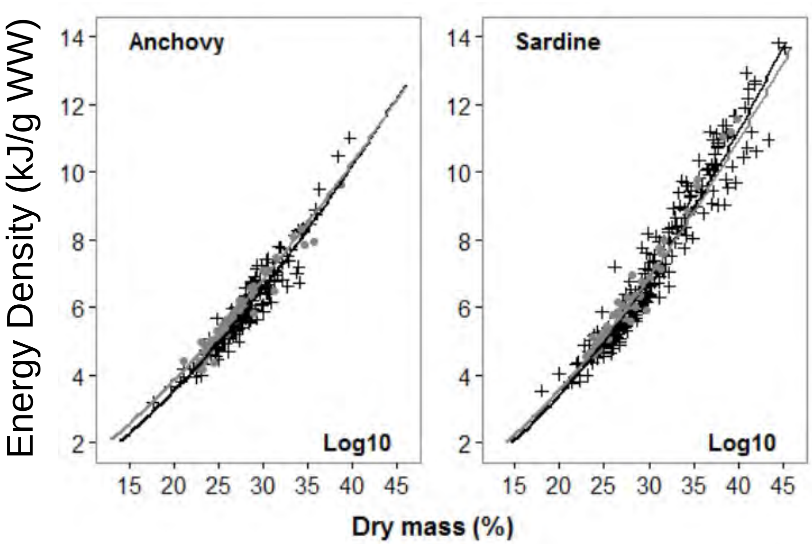
Ash-free Dry Weight

Water

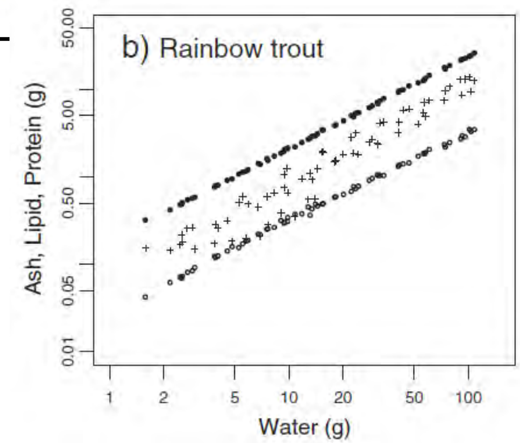
Ash

Wet Weight

Proximal composition and size



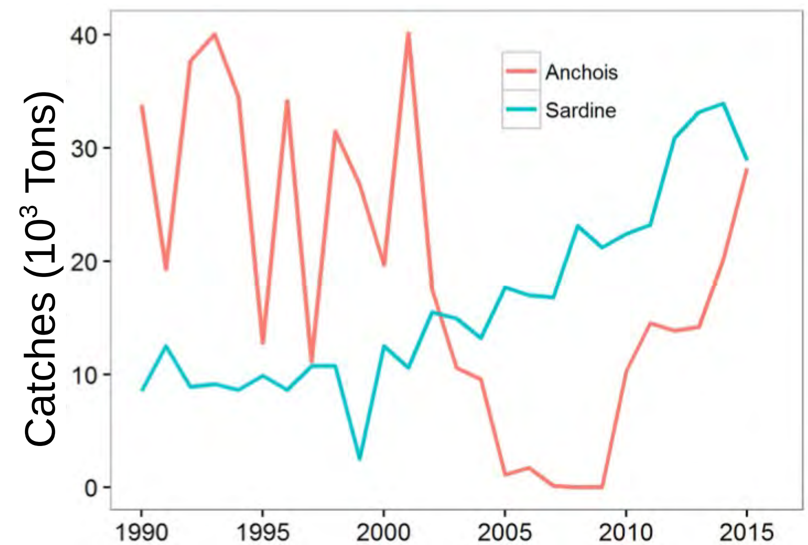

Aquaculture 433 (2014) 40–49
Contents lists available at ScienceDirect
Aquaculture
journal homepage: www.elsevier.com/locate/aqua-online
ELSEVIER
Review
Body composition in fishes: body size matters
James E. Breck *

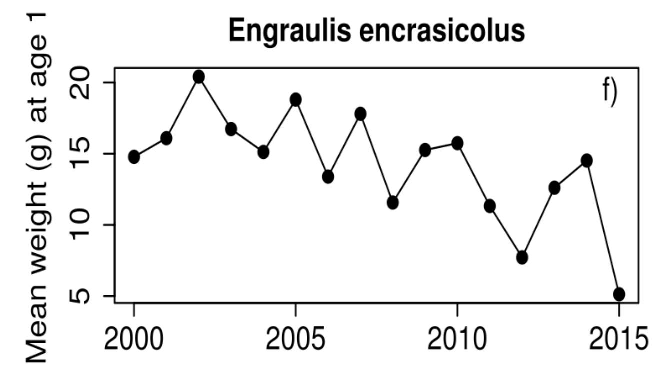


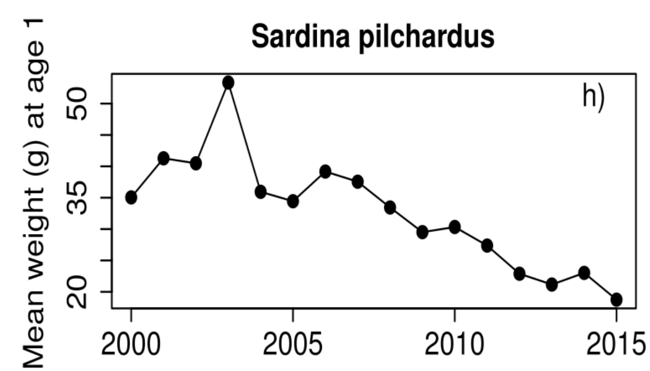
- Large variability of the water content
  ➔ conversion from dry to wet is not constant

- Very strong relationship between protein and water mass, as well as ash and water mass, with ratios varying with fish size
  ➔ The models should be validated on those biochemical patterns

Bay of Biscay CS

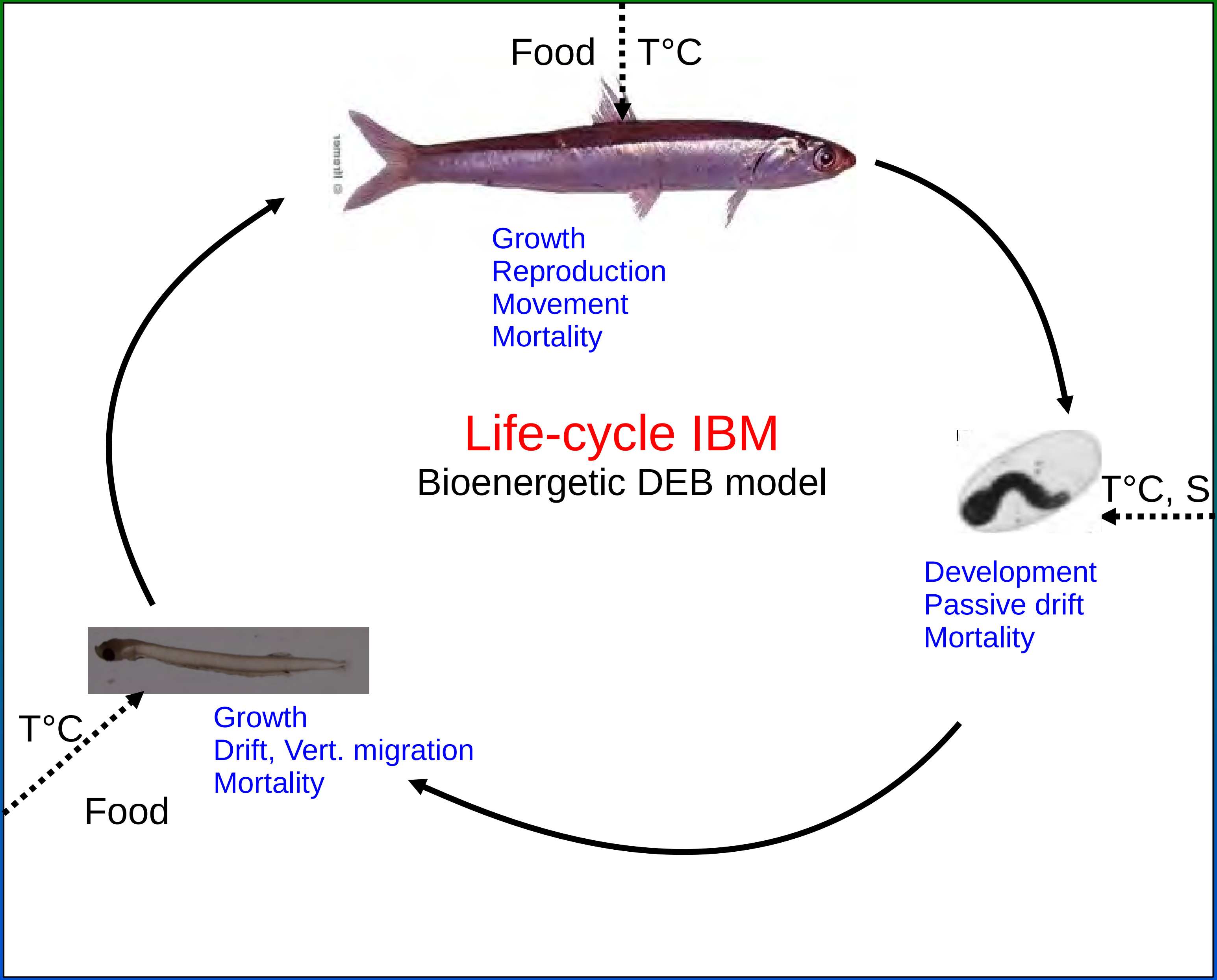






Doray et al., submitted

ECO-MARS



MARS-3D

Depending on the question, the model can be run

- in 0D, 1D-V, or 3D
- Single life stage or full life cycle
- Individual or population scale (IBM)

Improved knowledge on anchovy and sardine biological traits from a comparative analysis (0-D life cycle)

Contents lists available at ScienceDirect

Ecological Modelling

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

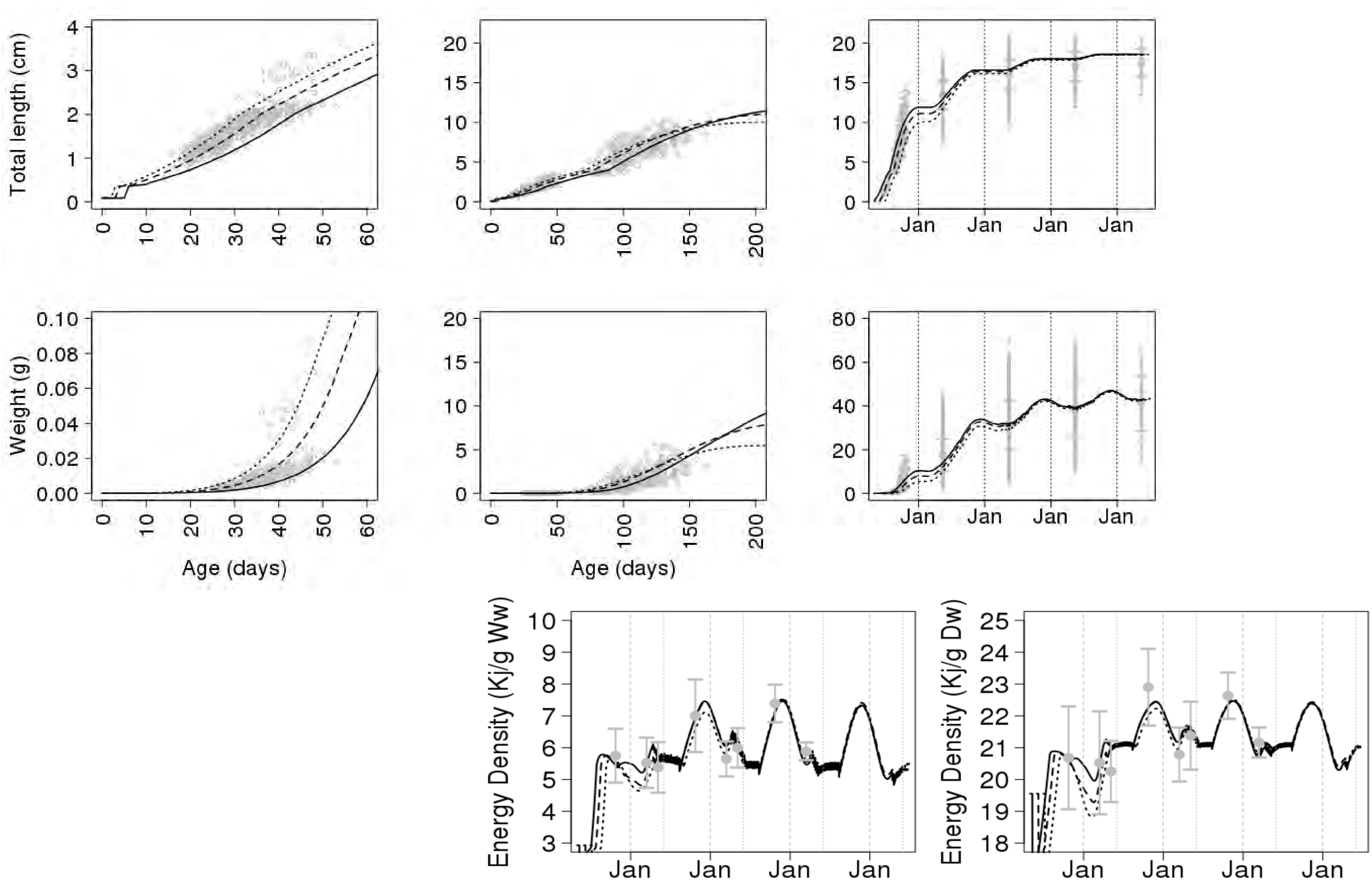
Comparing biological traits of anchovy and sardine in the Bay of Biscay: A modelling approach with the Dynamic Energy Budget

Paul Gatti [a,*], Pierre Petitgas [b], Martin Huret [a]

- See also presentation by P. Gatti in Session 2 (Monday)
- And follow-on presentation :

'Calibration of the DEB model for small pelagics. What data is needed and at which timescale' ?

Validation on field 'population data' with seasonal information on energy density



Determinism of fish migration : example of anchovy spawning migration (3-D adult stage)

Contents lists available at ScienceDirect

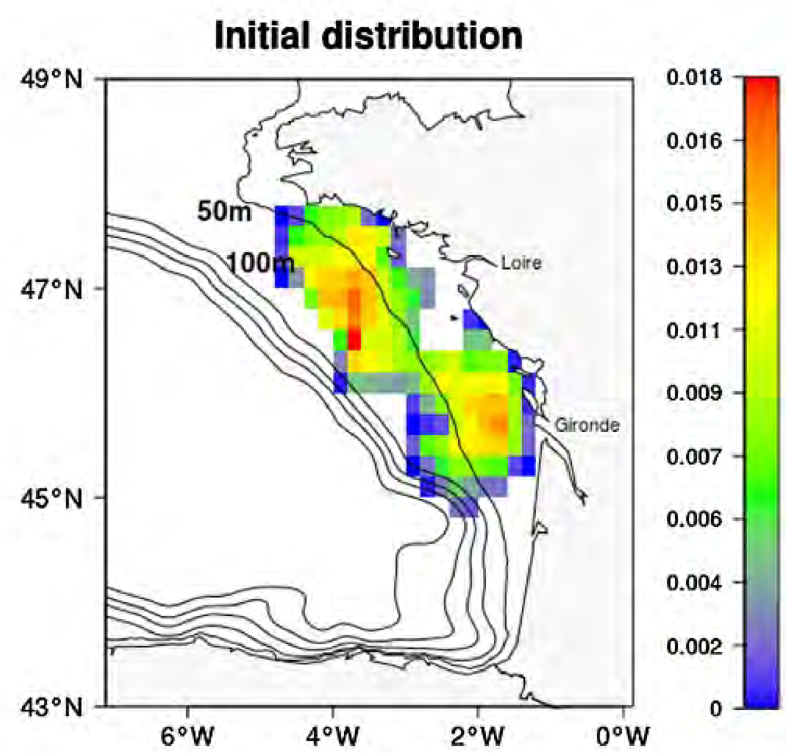
Ecological Modelling

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

A coupled movement and bioenergetics model to explore the spawning migration of anchovy in the Bay of Biscay

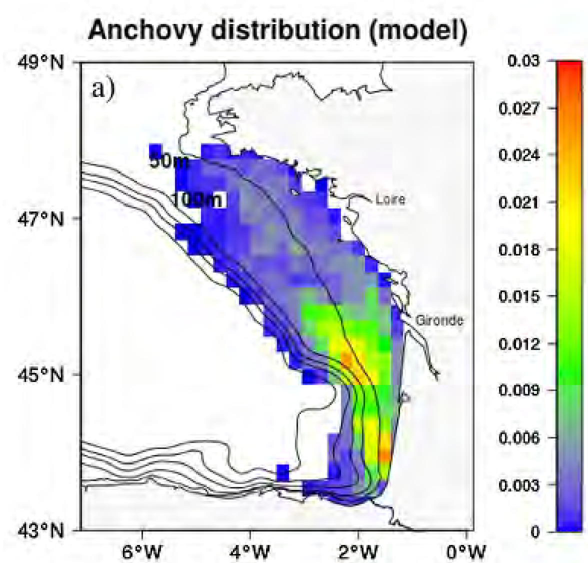
Dimitrios V. Politikos[a], Martin Huret[a,*], Pierre Petitgas[b]

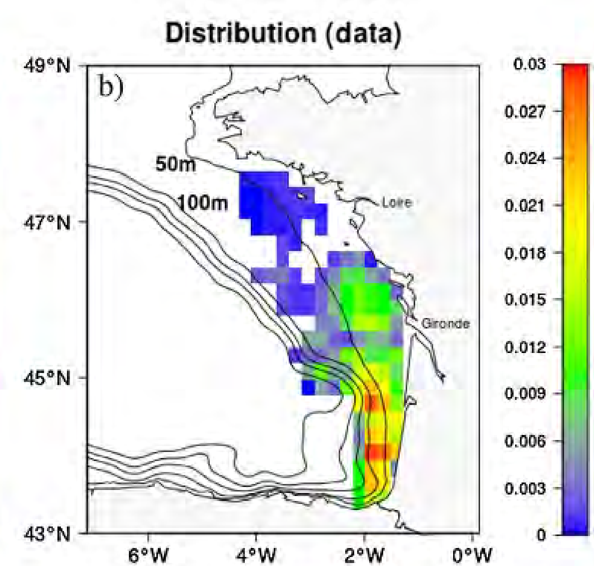
Movement and bioenergetics



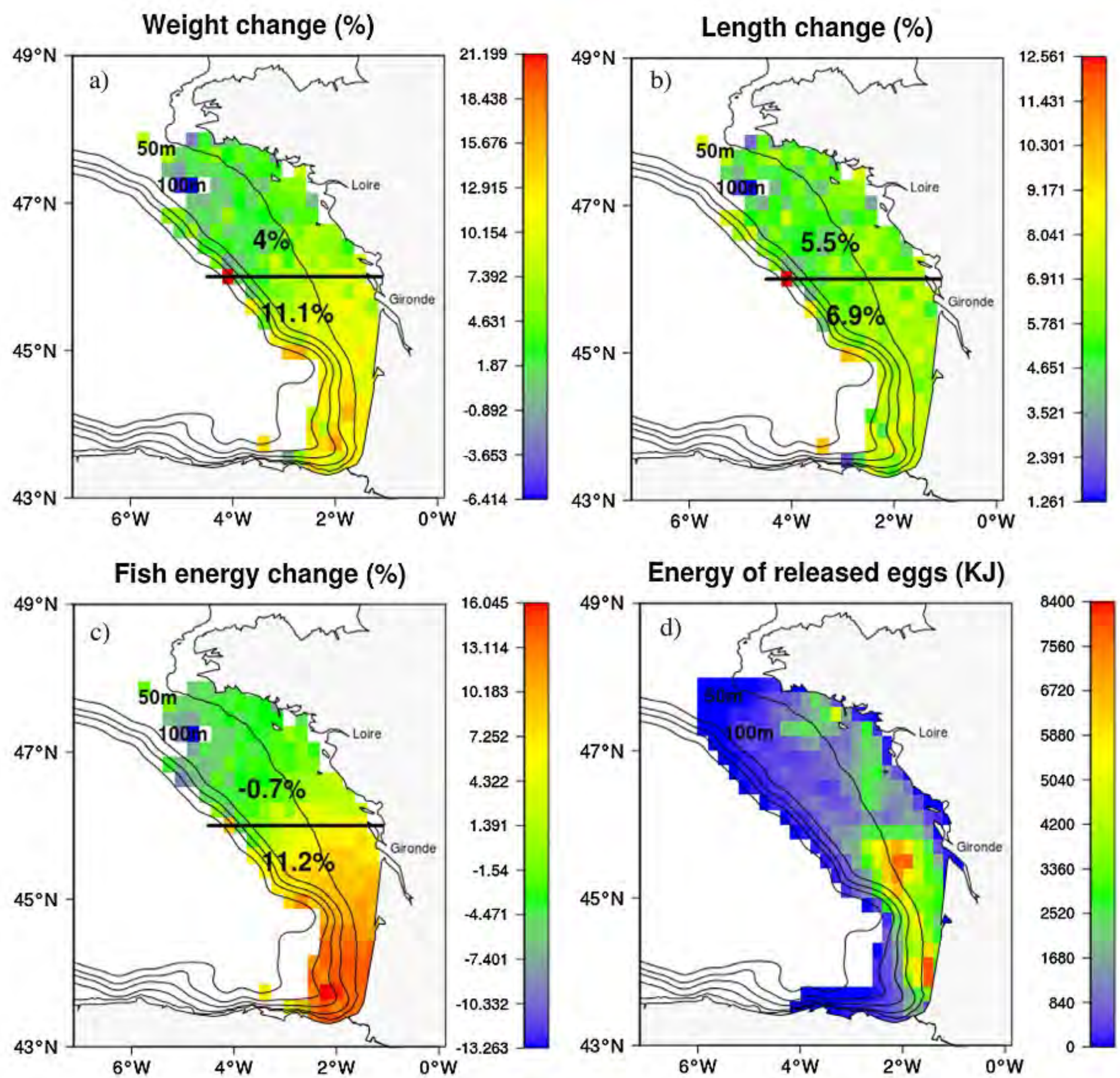
Winter

Spring





Movement and bioenergetics



- Anchovy movement to the south is profitable for fish condition and reproductive potential

Anchovy in NE Atlantic : explaining variability in regional traits from bioenergetics

EUROPE

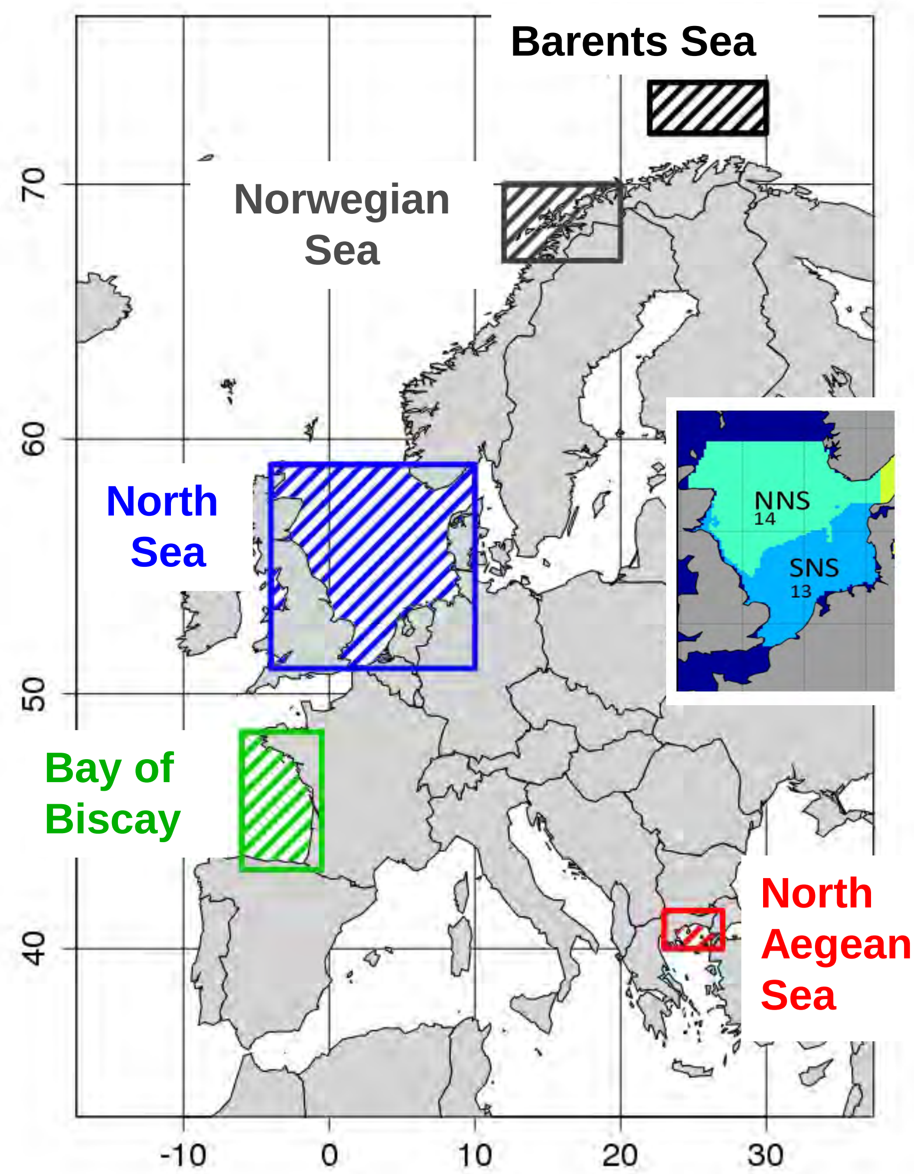
- Subtropicalisation of pelagic species (Montero-Serra et al., 2015)

North Sea

- Northern limit for anchovy
- Increase of abundance since mid-90's (Beare et al. 2004)
- Local expansion (Petitgas et al., 2012)
- Link with climate variability (Alheit et al., 2012)

MEDITERRANEAN Sea

- Low fish condition since 2007 in the Gulf of Lyon (Van Beveren et al., 2014)

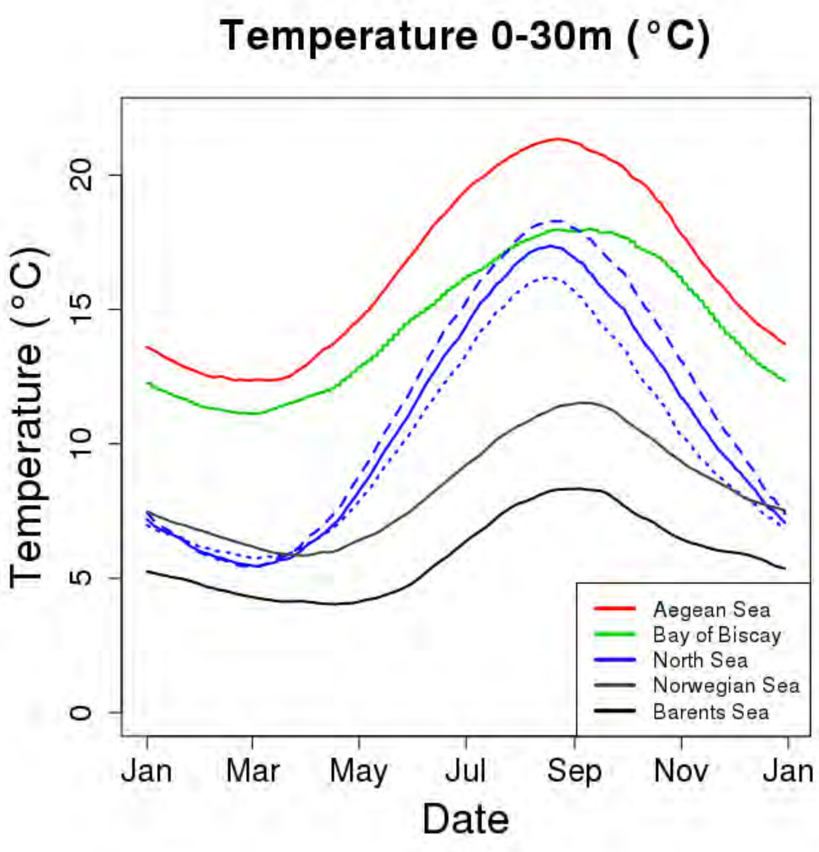


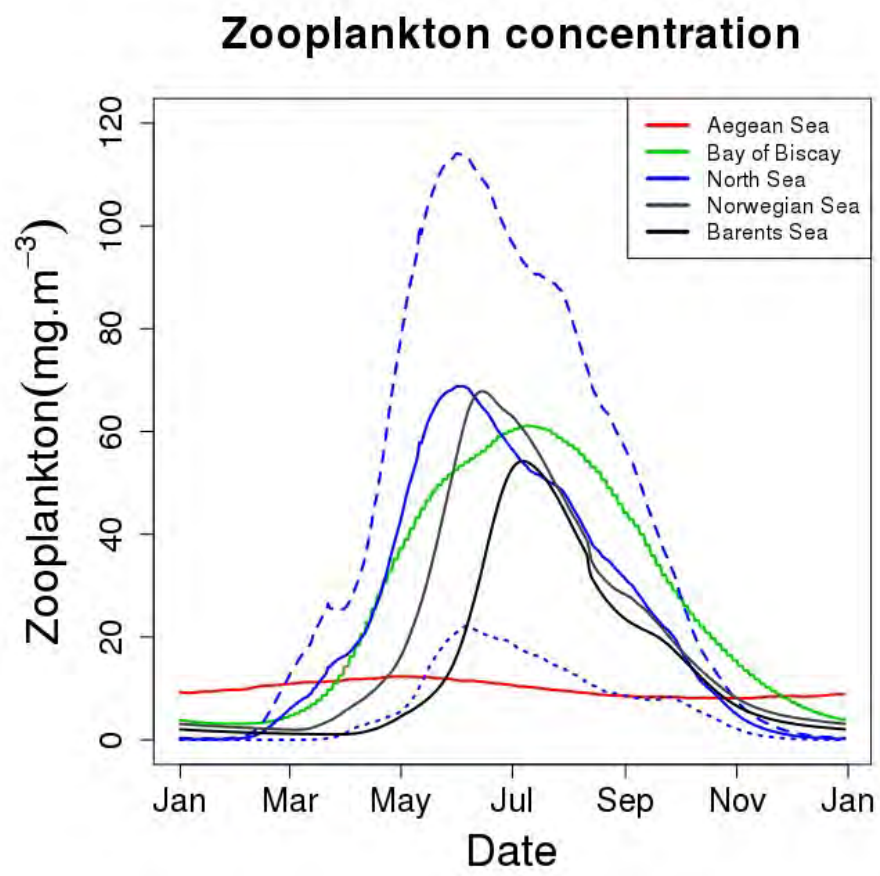
EUFP7ERA-NET

Variability in regional environment forcing

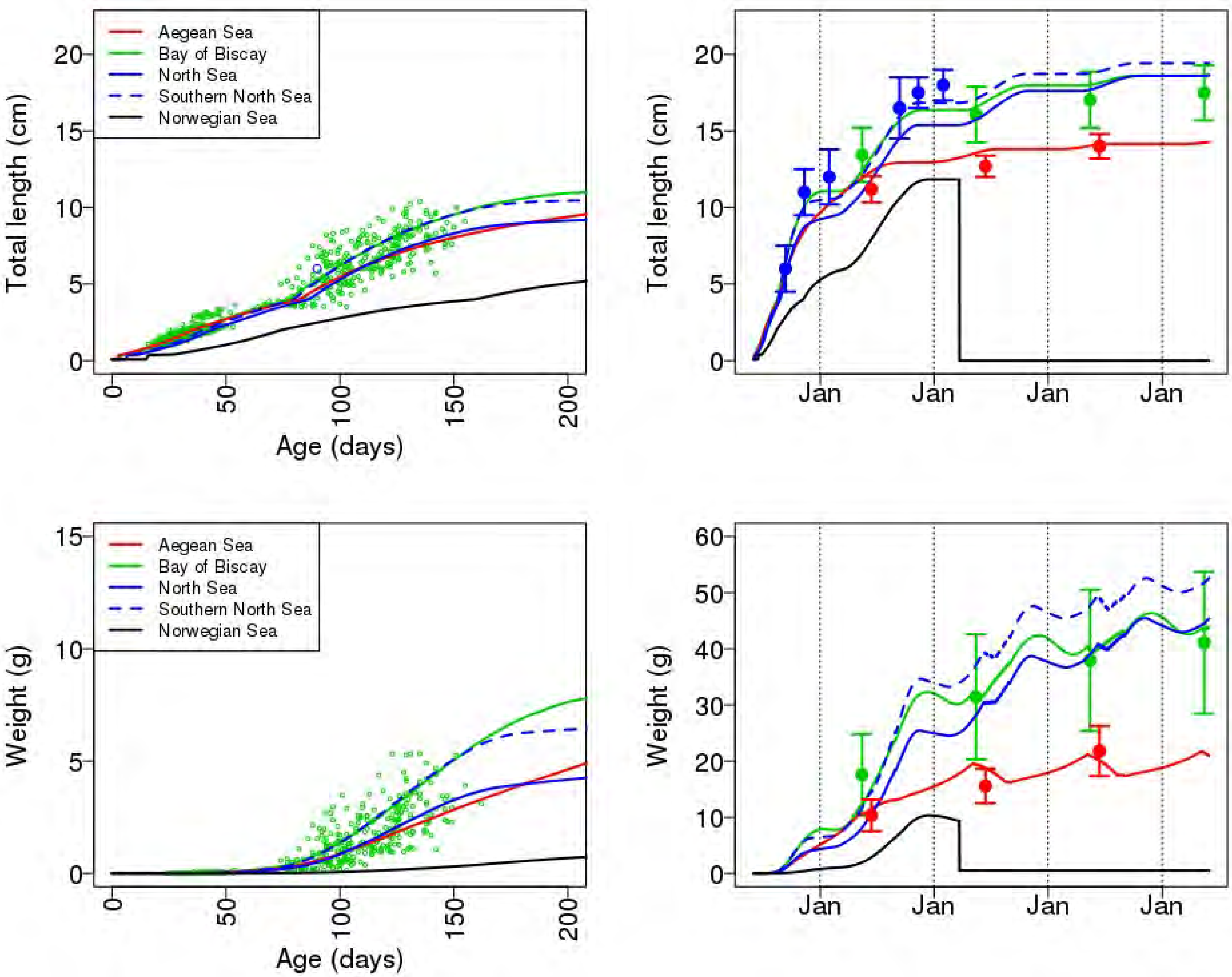
- Daily climatologies (temperature / Zoo) as forcing

POM-ERSEM
ECO-MARS3D
ECOSMO
NORWECOM





Regional growth from June spawning



- Good fitting when data available

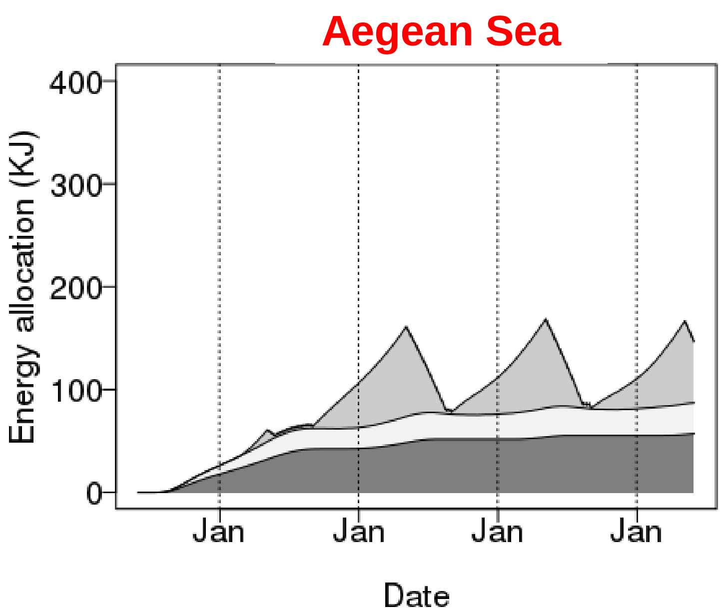
Aegean Sea

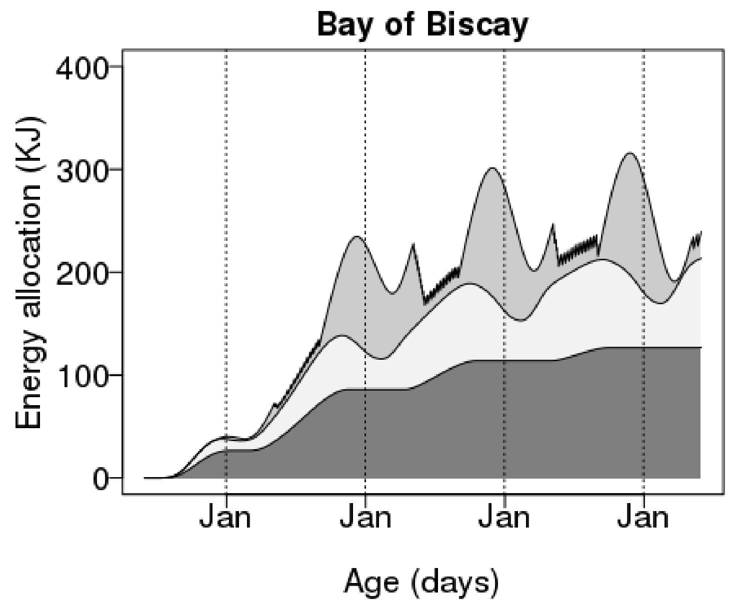
- Small max sizes
- Food limitation but no real starvation
- Weight loss mostly due to reproduction (summer)

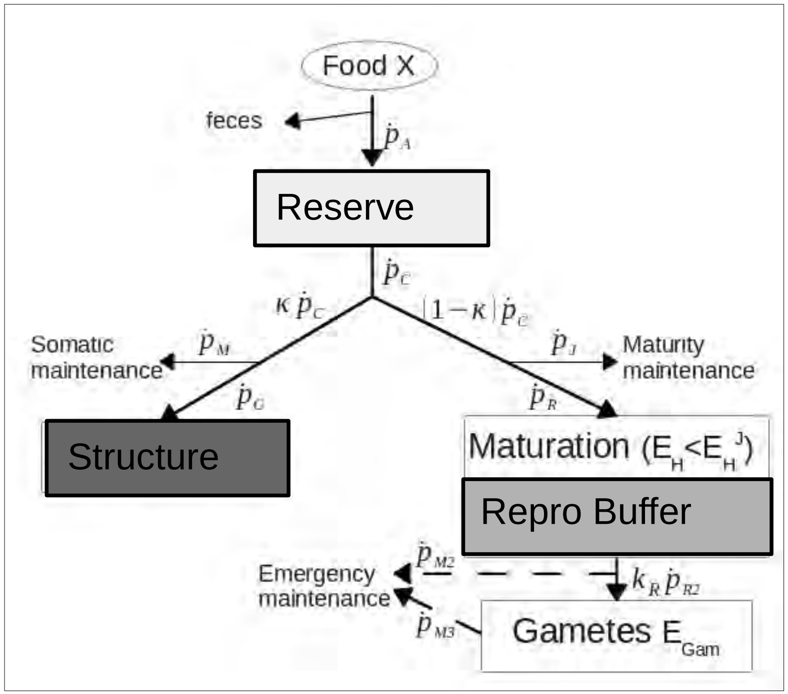
North Sea

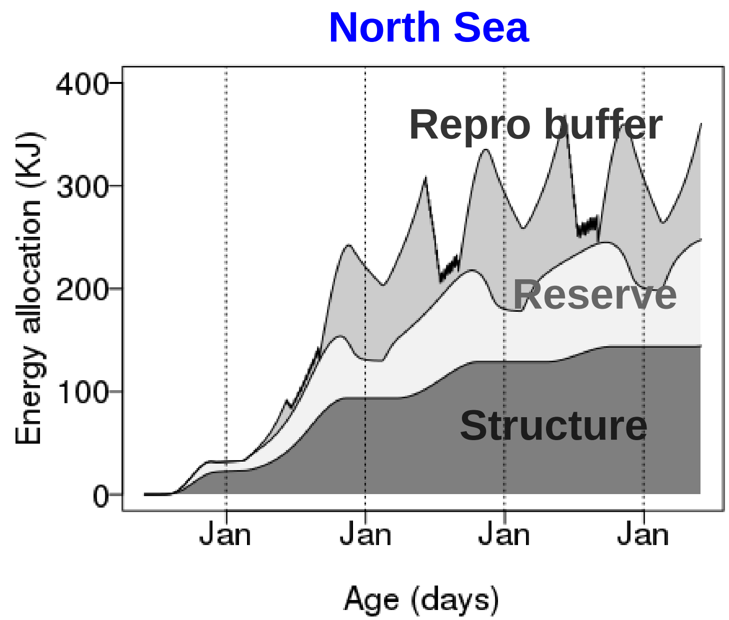
- Big max sizes
- Strong food limitation in winter
- Best fit with southern North Sea forcing

Seasonal energy allocation





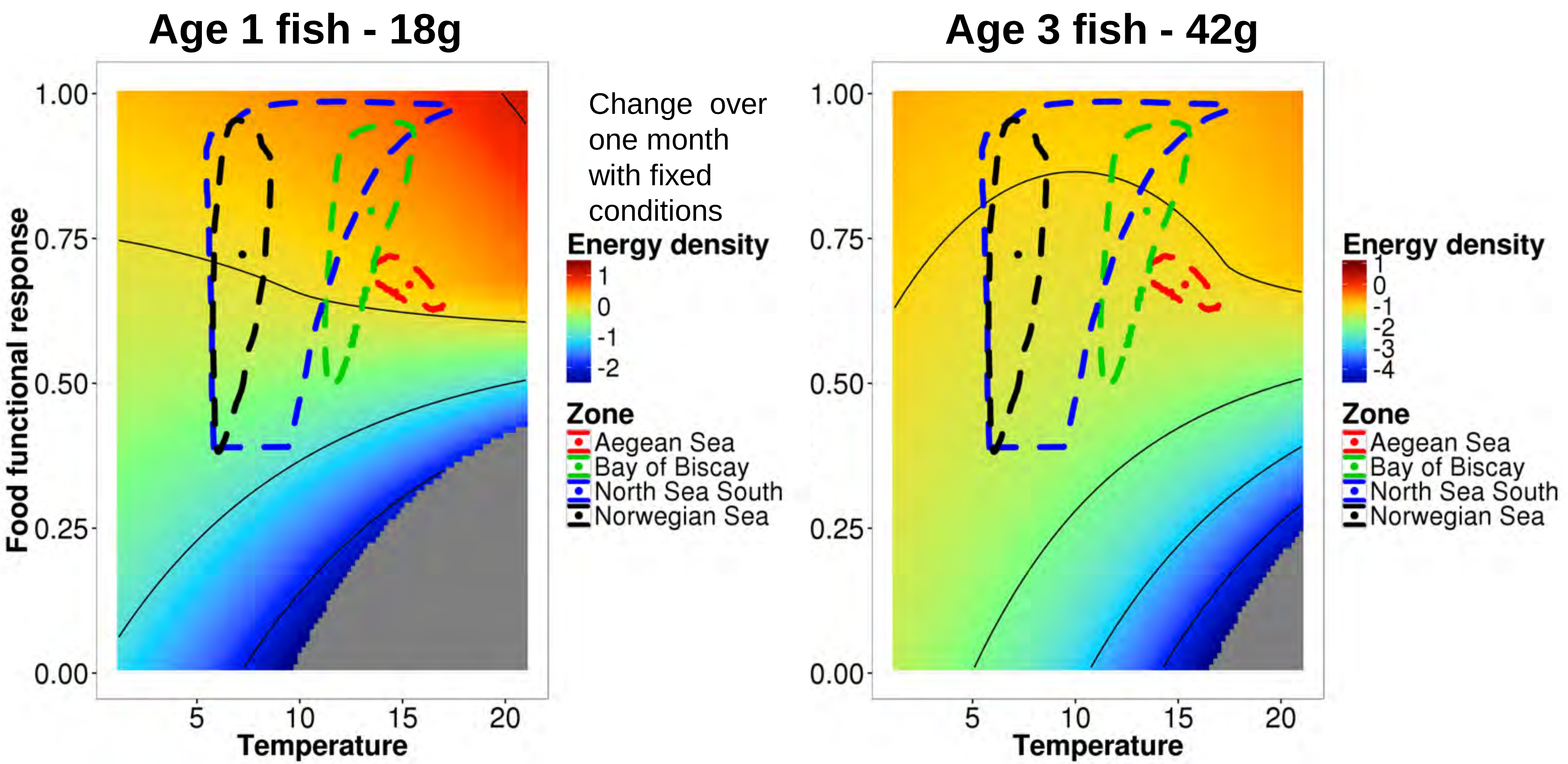




Aegean Sea
- Low seasonal variation of reserves
- Variation in weight/Energy related to reproduction

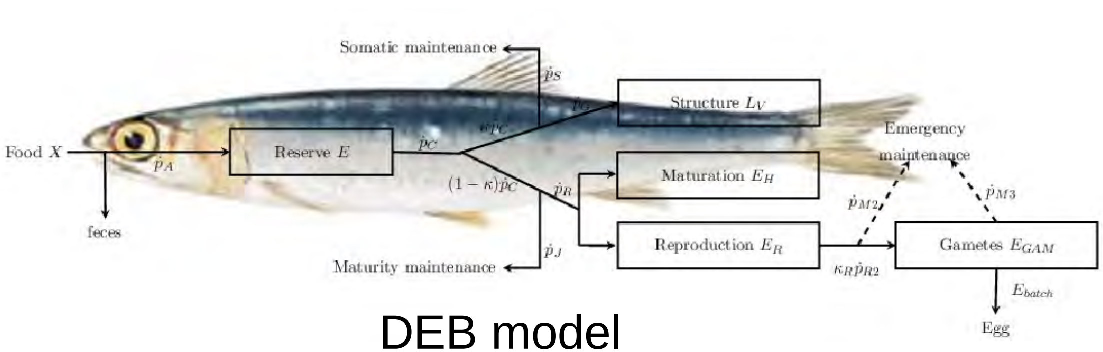
North Sea
- Large amount of reserves and high variability
- Variation in weight/Energy related to winter starvation

An annual trajectory in the temperature-food space

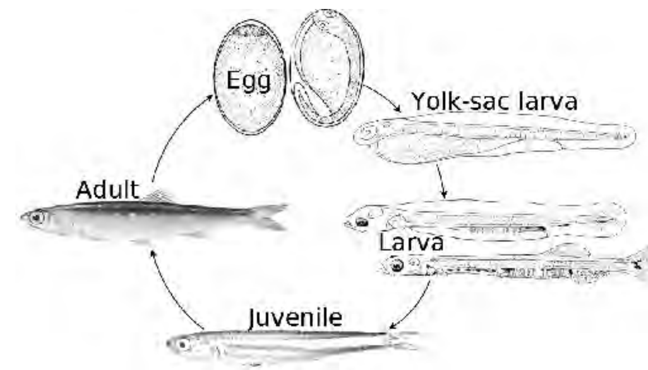


- Better be small in warm regions
- Harsh winter conditions in northern latitudes have to be compensated by good enough conditions the rest of the year

Simulation at population scale (0-D life cycle population)



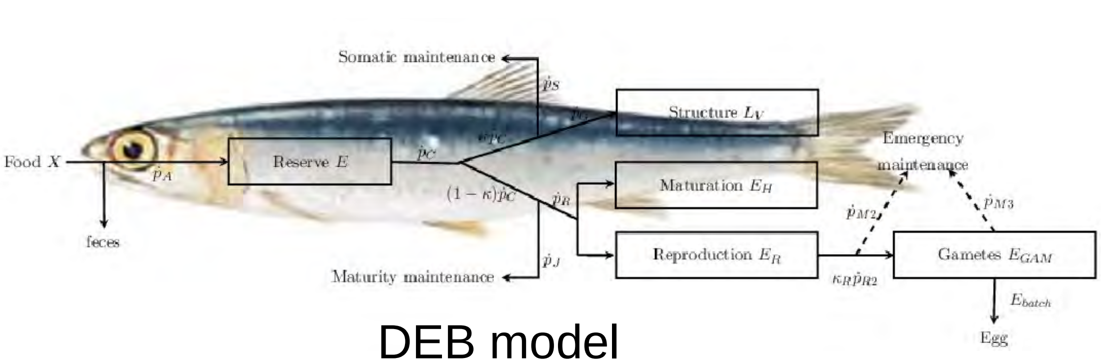
DEB model



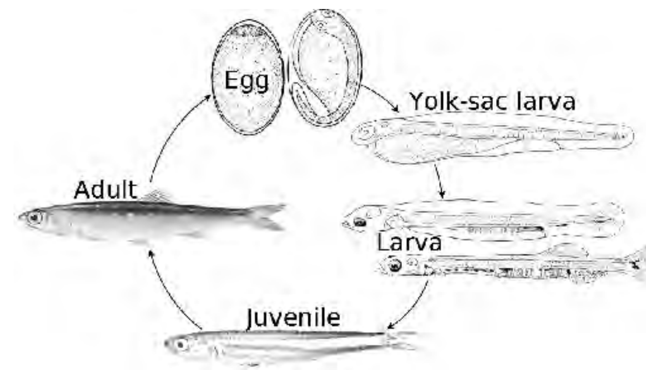
Mortality :

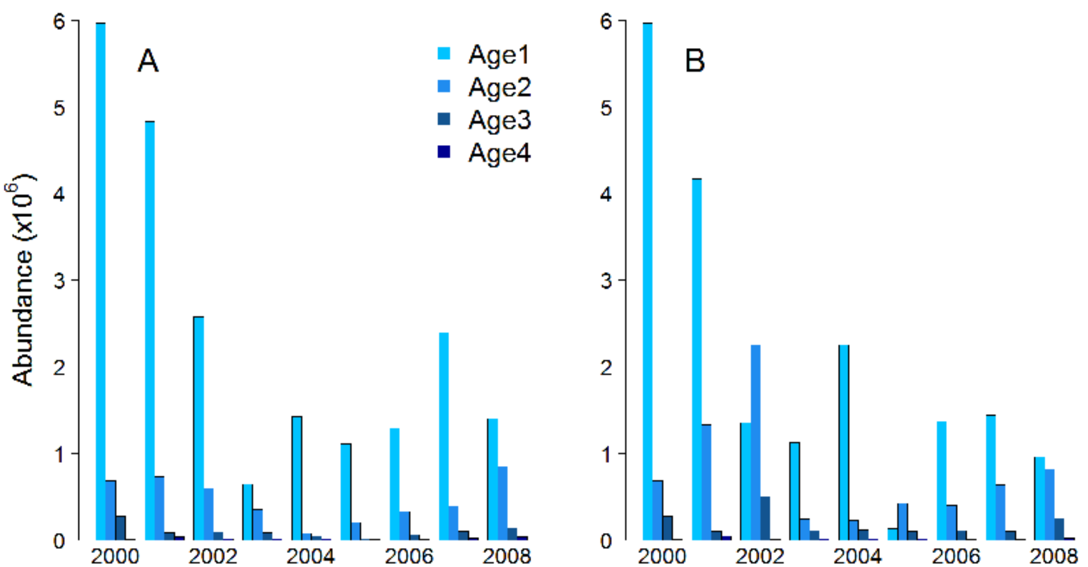
- Natural mortality =f(size) + starvation (DEB explicit, mostly juveniles in winter)
- Fishing mortality constrained from yearly catches

Simulation at population scale (0-D -life cycle population)



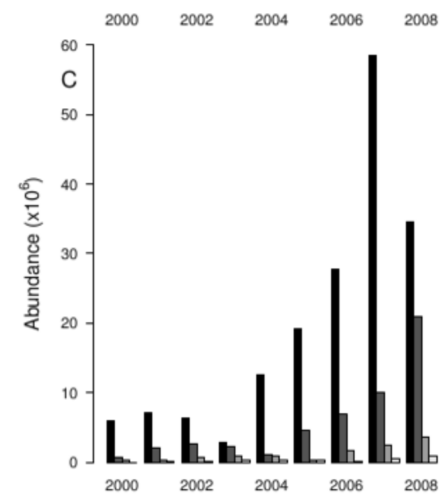
DEB model





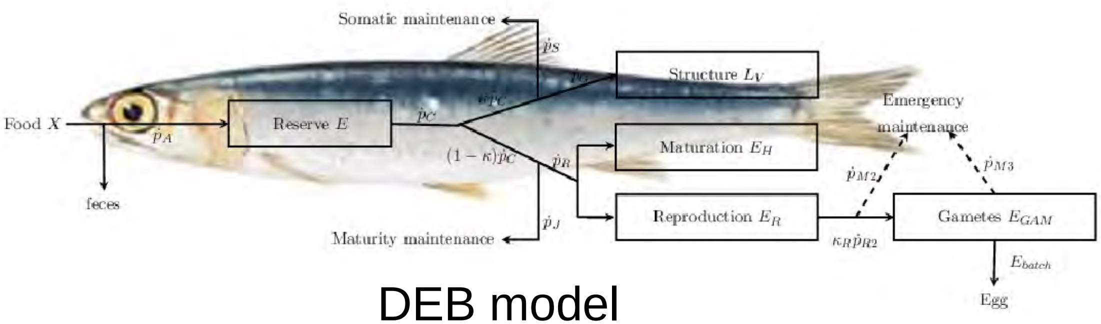
Model based abundance Survey based abundance

Scenario without fishing

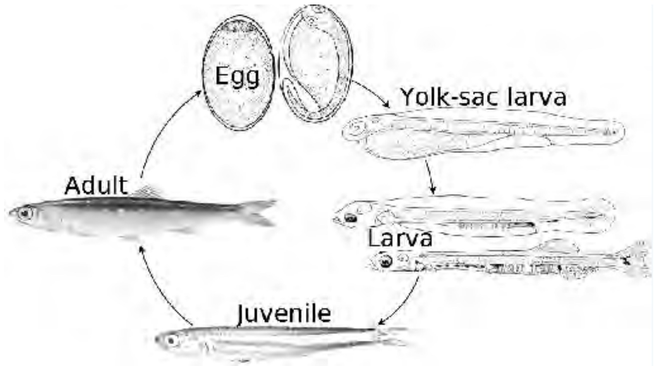


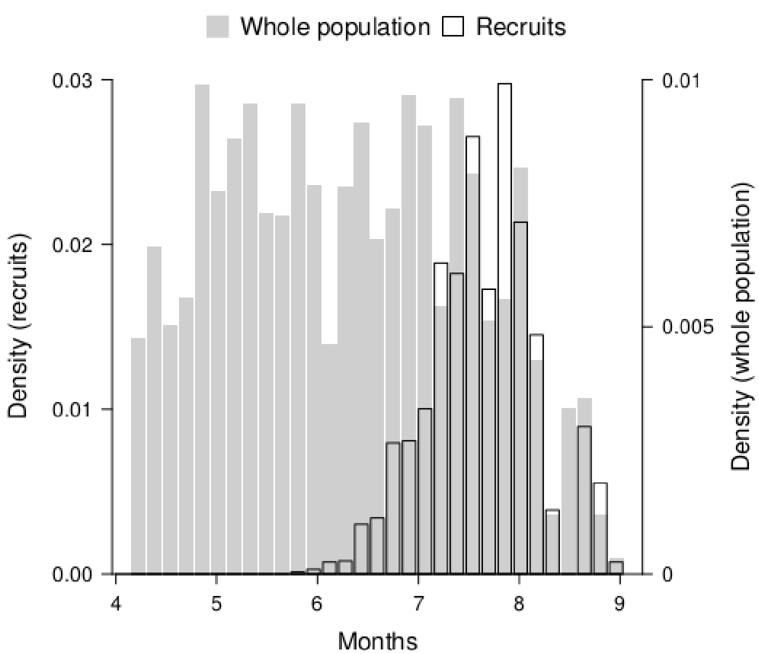
Model based abundance

Simulation at population scale (0-D -life cycle population)



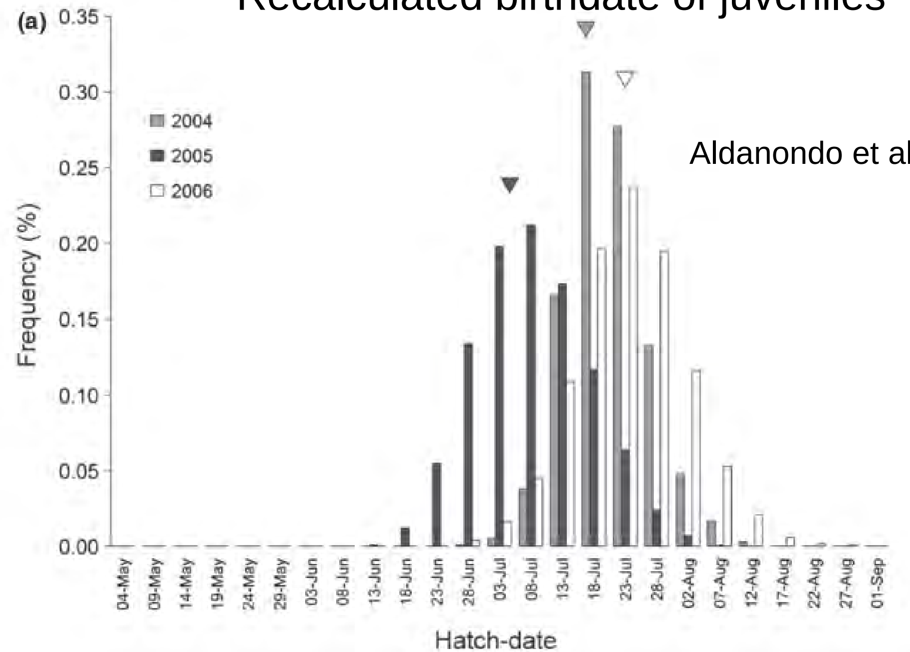
DEB model





Selective survival to recruitment from birthdate

Recalculated birthdate of juveniles



Aldanondo et al., 2016

Now time to apply the physiological - life history nexus to fisheries management and forecast

Towards use in management (WS in 1990)

Transactions of the American Fisheries Society 122:731–735, 1993

Innovative Approaches with Bioenergetics Models: Future Applications to Fish Ecology and Management

STEPHEN B. BRANDT AND KYLE J. HARTMAN
*University of Maryland System, Chesapeake Biological Laboratory
Post Office Box 38, Solomons, Maryland 20688, USA*

FISH and FISHERIES, 2006, **7**, 262–283

Integrating physiology and life history to improve fisheries management and conservation

Jeffery L. Young[1], Zosia B. Bornik[2], Michelle L. Marcotte[3], Kim N. Charlie[2], Glenn N. Wagner[1,4], Scott G. Hinch[1,2] & Steven J. Cooke[1,5]*

Integration in E2E models

Contents lists available at ScienceDirect
ELSEVIER
Progress in Oceanography
journal homepage: www.elsevier.com/locate/pocean

Demonstration of a fully-coupled end-to-end model for small pelagic fish using sardine and anchovy in the California Current

Kenneth A. Rose[a,*], Jerome Fiechter[b], Enrique N. Curchitser[c], Kate Hedstrom[d], Miguel Bernal[e], Sean Creekmore[a], Alan Haynie[f], Shin-ichi Ito[g], Salvador Lluch-Cota[h], Bernard A. Megrey[f,1], Chris A. Edwards[i], Dave Checkley[j], Tony Koslow[k], Sam McClatchie[l], Francisco Werner[l], Alec MacCall[m], Vera Agostini[n]

Conclusion

- Recent developments in dynamic energy models founded on theories and first principles
  - Optimal strategy of energy allocation (Clarck and Mengel, 2000)
  - DEB theory (Kooijman, 2000;2010)
  - Their generalisation is a proof of interest and utility, the field will improve from comparative studies (species, regions, etc.)
  - Has permitted a closer look at the link between fish physiological state (condition) and allocation of energy

- More energy data and proximal composition analysis is necessary, with seasonal resolution
  - ➔ See next presentation of Paul Gatti

- Bioenergetics implies
  - modelling the full life cycle
  - coupling with other models (physical, biogeochemical, ecosystem for bottom-up and top-down effects)
  - Platforms to extrapolate at the population level (ex : IBMs)

Further research priorities

- Computing power has contributed a lot, but can not do all :
  - predictive capacity in bioenergetics and population dynamics will always rely on the skills of ecosystem models (bottom-up and top-down control)
  - Choose the right level of complexity, parcimony, in both the physiological processes and the end-to-end integration
- Trophodynamics : energy # mass → assessment of energy density of both fish and their prey, at the seasonal scale
- Experimentation has to continue developing, for accuracy of measurements of vital rates (growth, allocation to reproduction under controlled conditions)
- Energy cost of movement/migration : measurements (lab, telemetry) and implementation in models
- Studies on allocation rules to reproduction
  - Environment trigger for maturation ?
  - Interaction between physiology and the environment
- Comparative studies for intra-population variability, acclimation, adaptation

Thank you and have nice discussions during the Workshop

No baby yet !
I should have come.