DEB
2023

DEB modules and applications

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΡΗΤΗΣ

UNIVERSITY OF CRETE

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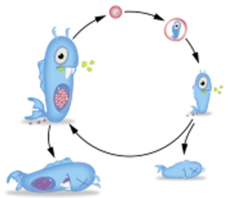
deb2023.sciencesconf.org



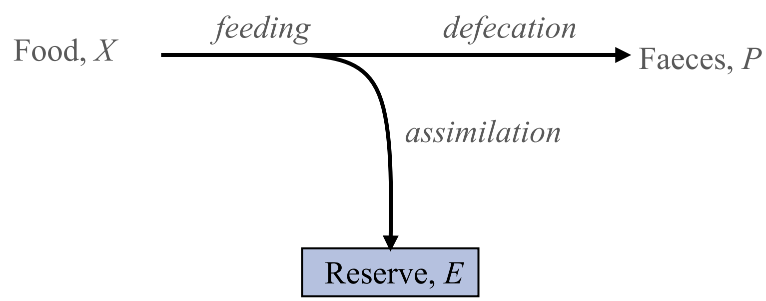
Outline

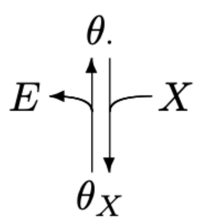
- Feeding-digestion modules
- Starvation modules
- Reproduction modules

Feeding/Digestion - iso 111

Standard module of food uptake

- make product E from a single substrate X
- food searching and food handling





Dynamics of the fractions θ of the SUs at different states:

$$\frac{d\theta_{.}}{dt} = -y_{EX}\dot{J}_X\theta_{.} + \dot{k}\theta_X$$

$$\frac{d\theta_X}{dt} = y_{EX}\dot{J}_X\theta_{.} - \dot{k}\theta_X$$

$$\theta_{.} + \theta_X = 1$$

$$\dot{J}_{EA} = \dot{k}\ \theta_X^* = \frac{1}{\dot{k}^{-1} + \left(y_{EX}\dot{J}_X\right)^{-1}}$$

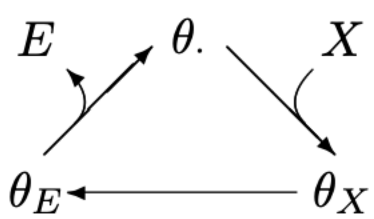
$$\dot{J}_{EA} = \dot{k}\ \frac{X}{X+\dot{k}\left(y_{EX}\dot{b}_X\right)^{-1}}$$

$\dot{J}_*$	Flux of the substrate
y_{EX}	Yield coefficient
$\dot{k}$	metabolic/handling processing

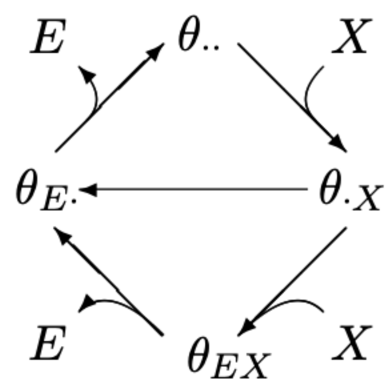
Extensions DEB3 Chapter 7.2.2

Food handling is partitioned in mechanical and metabolic handling

- metabolic handling follows mechanical handling (**sequential**)



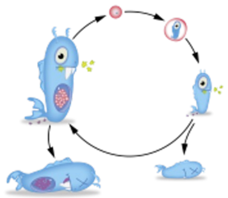
- food searching can be **parallel** to metabolic handling

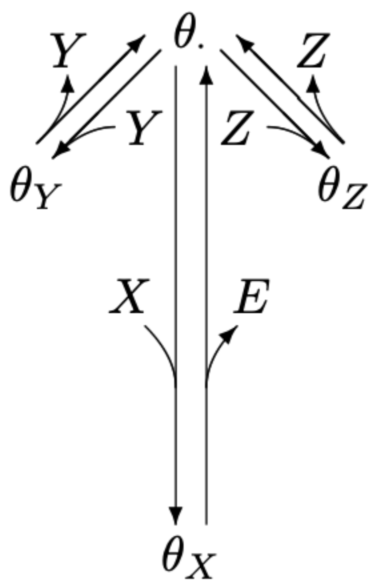


Applied to feeding data for sea bream *Sparus aurata* larvae

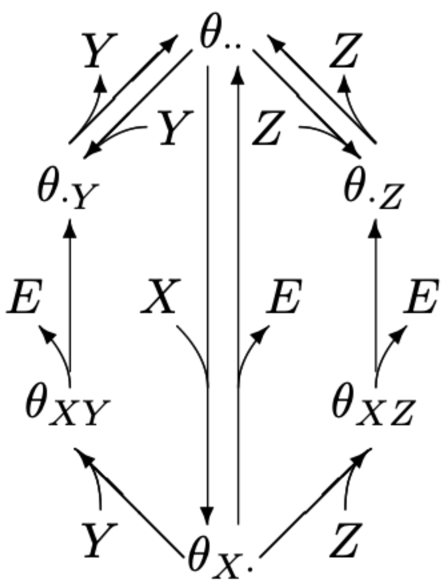
Lika & Papandroulakis (2005) Can. J. Fish. Aquat. Sci. 62: 425–435

Social interaction DEB3 7.2.4



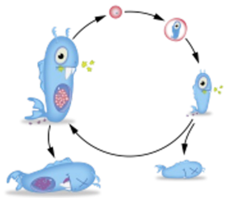


Food processing sequential to socialisation

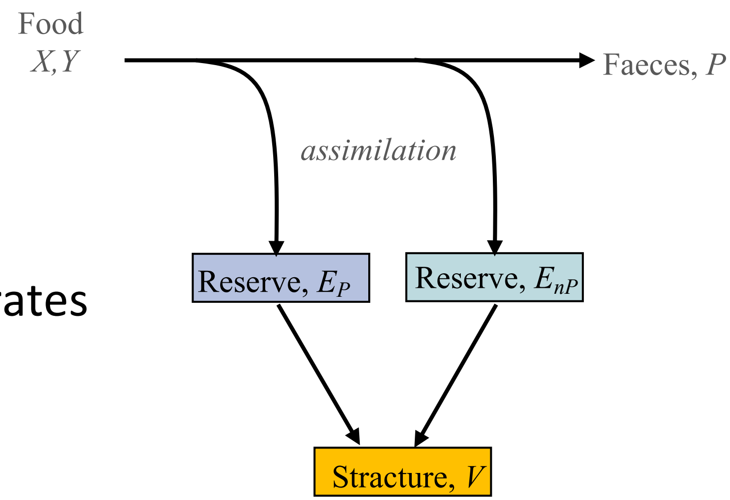


Food processing parallel to socialisation

iso 221 DEB3 comments 5.2.7



Extension of the standard DEB model for



2 types of food X and Y of constant composition

sequential processing of substitutable substrates

2 reserves

protein standing for ‘building block’ reserve

non-protein for energy reserve

each food type contributes to both reserves

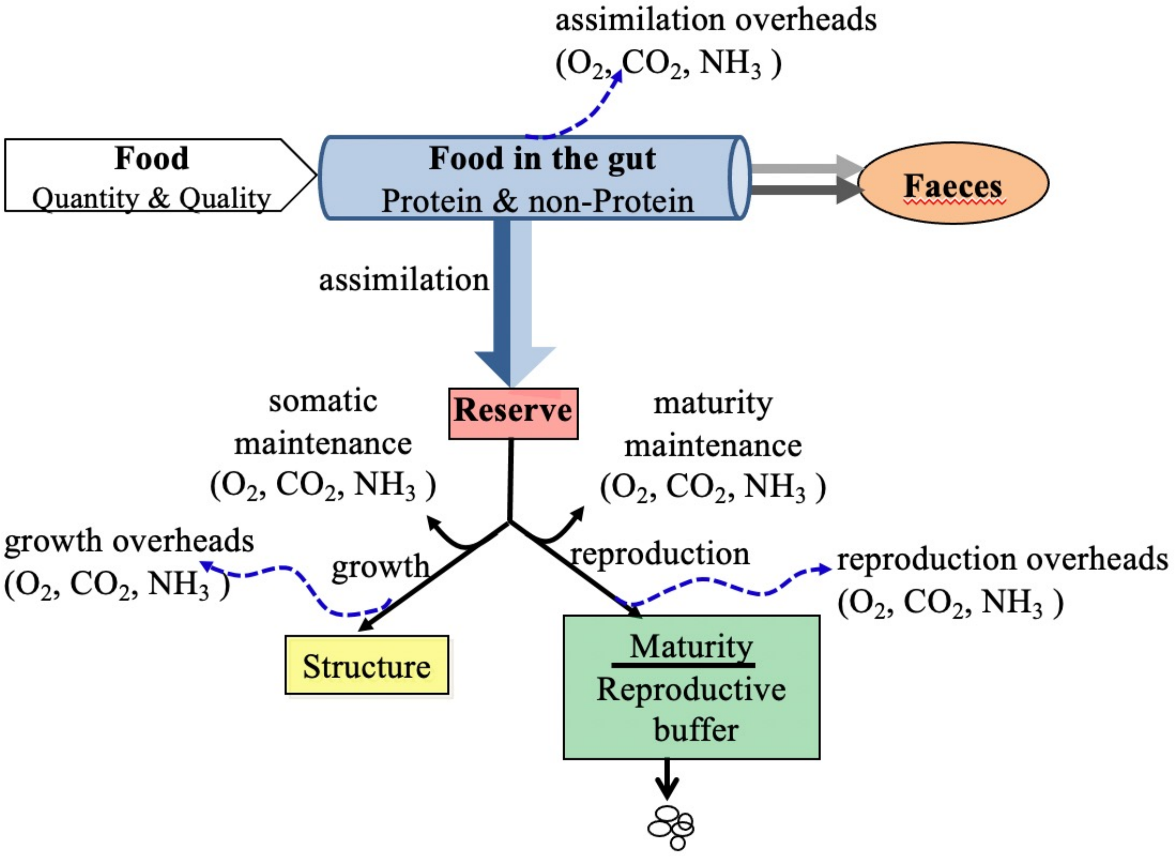
1 structure

Somatic maintenance is paid from protein and non-protein reserves (substitutable), with a strong preference for non-proteins, and the binding is parallel.

Nutrional bioenergetics model

State variables

- Food in the gut (M_X)
- Reserve energy (E)
- Structural body volume (V)
- Energy investment into maturation (embryos, juveniles) (E_H)
- Energy allocated to reproduction (adults) (E_R)



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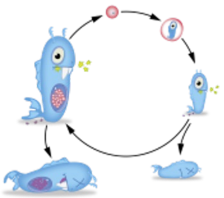
Food, faeces, and biomass composition



“generalized compound” with fixed stoichiometry

1 molecule of compound Υ has the formula $CH_{n_{H\Upsilon}}\ O_{n_{O\Upsilon}}\ N_{n_{N\Upsilon}}$

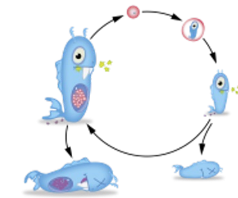
Matrix of chemical indices n_{**} : relate the frequency of the chemical elements H, O and N to C

	Organic compounds				
	Food (X_P)	Food (X_{nP})	Reserve (E)	Structure (V)	Faeces (P)
C	1	1	1	1	1
H	n_{HXP}	n_{HXnP}	n_{HE}	n_{HV}	n_{HP}
O	n_{OXP}	n_{OXnP}	n_{OE}	n_{OV}	n_{OP}
N	n_{NXP}	n_{NXnP}	n_{NE}	n_{NV}	n_{NP}

Chemical potentials μ_* : converts mass to energy (J/mol)

Organic compounds				
Food (X_P)	Food X_{nP})	Reserve (E)	Structure (V)	Faeces (P)
μ_{XP}	μ_{XnP}	μ_E	μ_V	μ_P

Metabolic transformation



$\blacksquare$ Yield coefficients

Assimilation (food → reserve)

$$\blacksquare\, CH_{n_{HX_P}} O_{n_{OX_P}} N_{n_{NX_P}} + \blacksquare\, CH_{n_{HX_{nP}}} O_{n_{OX_{nP}}} + \blacksquare\, \mathrm{O} \rightarrow CH_{n_{HE}} O_{n_{OE}} N_{n_{NE}} + \blacksquare\, CH_{n_{HP}} O_{n_{OP}} N_{n_{NP}} + \text{mineral products } (\mathrm{C}, \mathrm{H}, \mathrm{N})$$

Growth (reserve → structure)

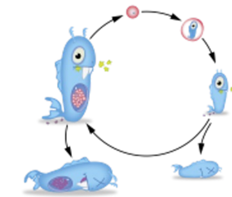
$$\blacksquare\, CH_{n_{HE}} O_{n_{OE}} N_{n_{NE}} + \blacksquare\, \mathrm{O} \rightarrow \blacksquare\, CH_{n_{HV}} O_{n_{OV}} N_{n_{NV}} + \text{mineral products } (\mathrm{C}, \mathrm{H}, \mathrm{N})$$

Dissipation (metabolic work that does not lead to the production of new biological material: maintenance, maturation, reproduction overheads)

$$\blacksquare\, CH_{n_{HE}} O_{n_{OE}} N_{n_{NE}} + \blacksquare\, \mathrm{O} \rightarrow \text{mineral products } (\mathrm{C}, \mathrm{H}, \mathrm{N})$$

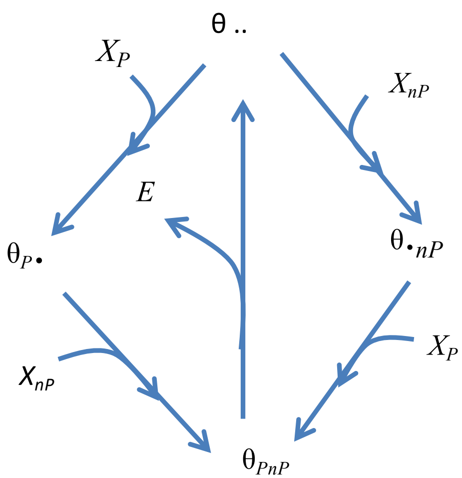
C: carbon dioxide
H: water
O: dioxygen
N: nitrogen waste

iso-211



Making product E from two **supplementary** substrates: protein, X_P, and non-protein, X_{nP}, components of food

$$y_{EX_P}\, CH_{n_{HX_P}} O_{n_{OX_P}} N_{n_{NX_P}} + y_{EX_{nP}}\, CH_{n_{HX_{nP}}} O_{n_{OX_{nP}}} + O \rightarrow CH_{n_{HE}} O_{n_{OE}} N_{n_{NE}} + faeces + \text{ mineral products } (\mathrm{H_2O}, \mathrm{CO_2}, \mathrm{N-wastes})$$



Dynamics of the fractions θ of the SUs at different states.

$$\frac{d\theta_{..}}{dt} = -(y_{EX_P}\dot{J}_{X_P} + y_{EX_{nP}}\dot{J}_{X_{nP}})\theta_{..} + \dot{k}\theta_{PnP}$$

$$\frac{d\theta_{P.}}{dt} = y_{EX_P}\dot{J}_{X_P}\theta_{..} - y_{EX_{nP}}\dot{J}_{X_{nP}}\theta_{P.}$$

$$\frac{d\theta_{.nP}}{dt} = y_{EX_{nP}}\dot{J}_{X_{nP}}\theta_{..} - y_{EX_P}\dot{J}_{X_P}\theta_{.nP}$$

$$\frac{d\theta_{PnP}}{dt} = y_{EX_{nP}}\dot{J}_{X_{nP}}\theta_{P.} + y_{EX_P}\dot{J}_{X_P}\theta_{.nP} - \dot{k}\theta_{PnP}$$

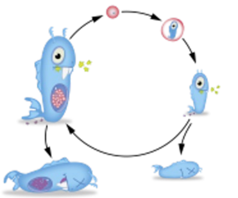
$$\theta_{..} + \theta_{P.} + \theta_{.nP} + \theta_{PnP} = 1$$

$\dot{J}_*$	fluxes of the substrates
y_{EX_*}	yield coefficients
$\dot{k}$	metabolic/handling processing

Equilibrium fraction of SUs in the processing state:

$$\theta^*_{PnP} = \left(\dot{k}^{-1} + (y_{EX_P}\dot{J}_{X_P})^{-1} + (y_{EX_{nP}}\dot{J}_{X_{nP}})^{-1} - (y_{EX_P}\dot{J}_{X_P} + y_{EX_{nP}}\dot{J}_{X_{nP}})^{-1}\right)^{-1}$$

Assimilation module



Assimilation rate

Depends on the mass of food in the stomach-gut

Proportional to the surface of the gut wall

Depends on the fraction of protein and lipid in the food

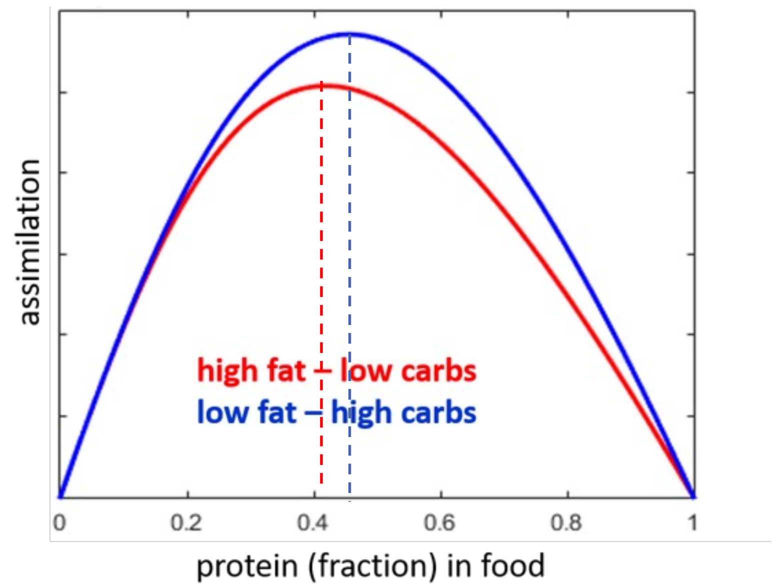
$$\dot{J}_{EA} = \{\dot{J}_{EA_m}\} f L^2$$

$$f = \frac{M_X}{M_X + M_K^X}$$

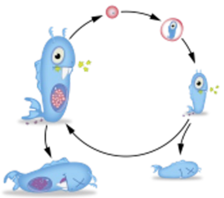
$$M_K^X = \frac{\{\dot{J}_{EA_m}\}}{\{\dot{J}_{Xg_m}\}} \left(\left(y_{EX_P} a_P\right)^{-1} + \left(y_{EX_{nP}} (1 - a_P)\right)^{-1} - \left(y_{EX_P} a_P + y_{EX_{nP}} (1 - a_P)\right)^{-1} \right)$$

Effects of food composition on assimilation

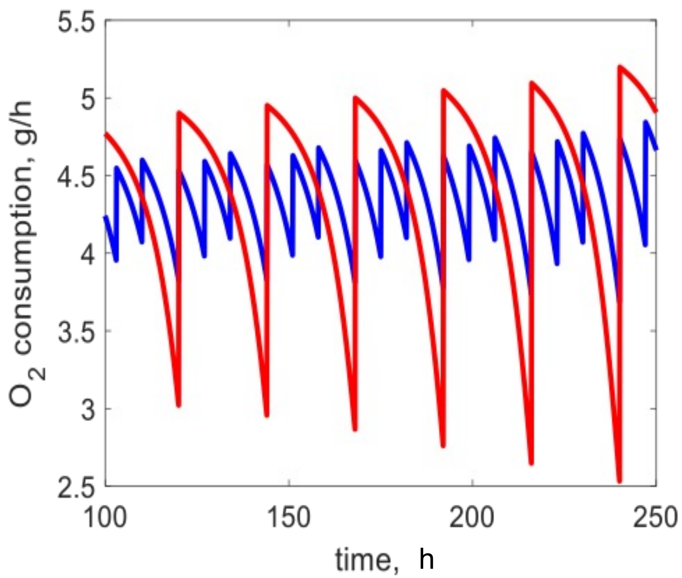
Effects of protein-energy (PE) ratio in the diet



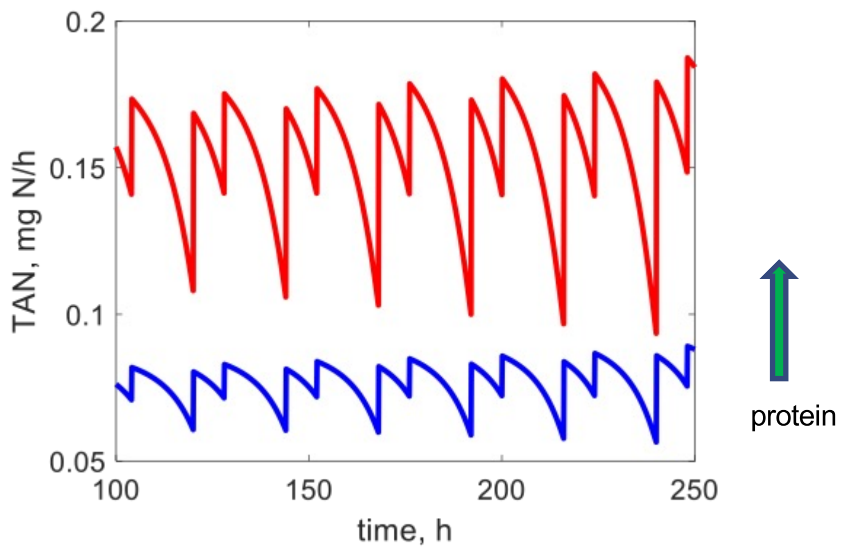
Model outputs - effects of rearing conditions



Effects feeding frequency



Effects of feed composition



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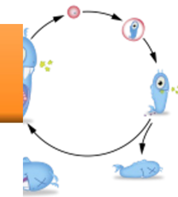

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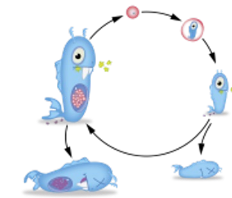
A **VL** system to test in silico different experimental protocols, before the real implementation in the research facility.

Models for **growth**, **nutrition** and **waste production**, **hydrodynamic flow fields** in tanks and cages, and **water quality** and **water treatment** have been wrapped in **Functional Mock-up Units** (FMUs).

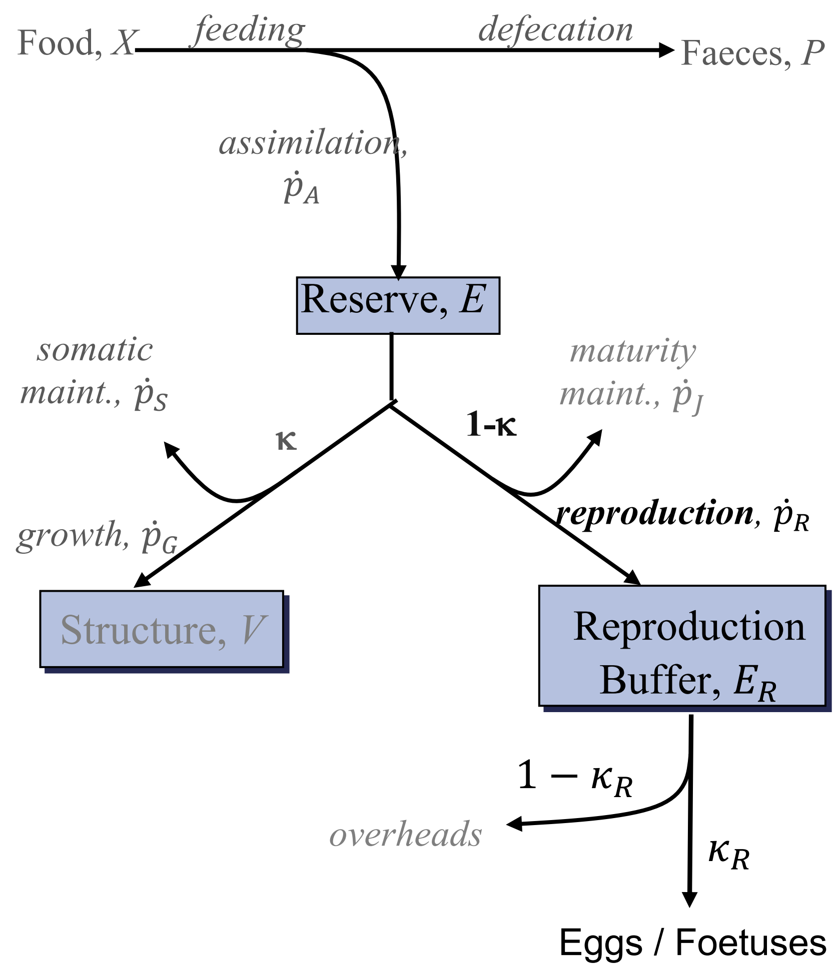
FMUs provide a standardized interface that allows different simulation tools to communicate and interact with each other.



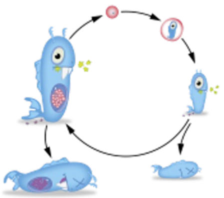
Reproduction

Reserve allocated to reproduction is collected in a **reproduction buffer**

Species-specific buffer handling rules for the conversion to eggs or foetuses



Reproduction module



Handling rules of the reproduction buffer for multiple-batch spawners

Reproduction rate

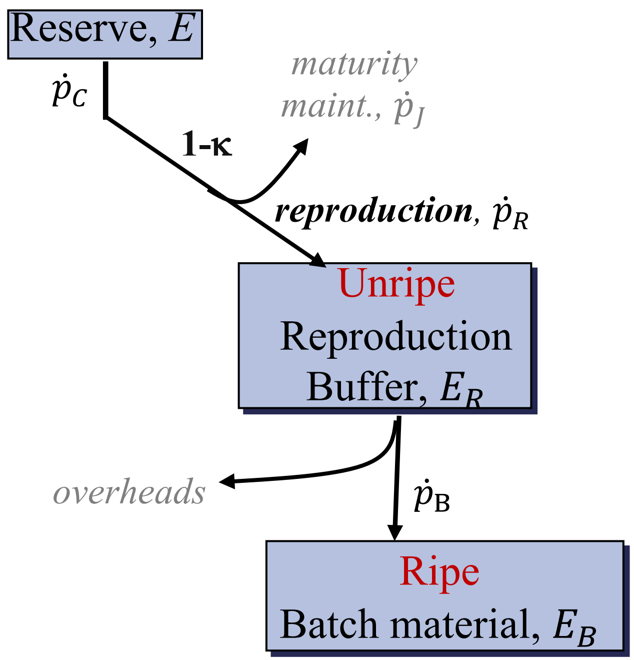
$$\dot{p}_R = (1-\kappa)\dot{p}_C - \dot{p}_J$$

Rate of batch preparation

$$\dot{p}_B = \kappa_R((1-\kappa)\dot{p}_{Cm} - \dot{p}_J)$$

Batch initiation: e.g. $T > T_{threshold}$

Batch size $E_B^* = \min(E_R, [E_B]L^3)$



At spawning t_B

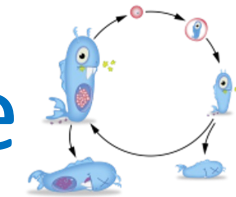
$$E_R(t_B + dt) = E_R(t_B) - E_B^*$$

$$E_B(t_B + dt) = 0$$

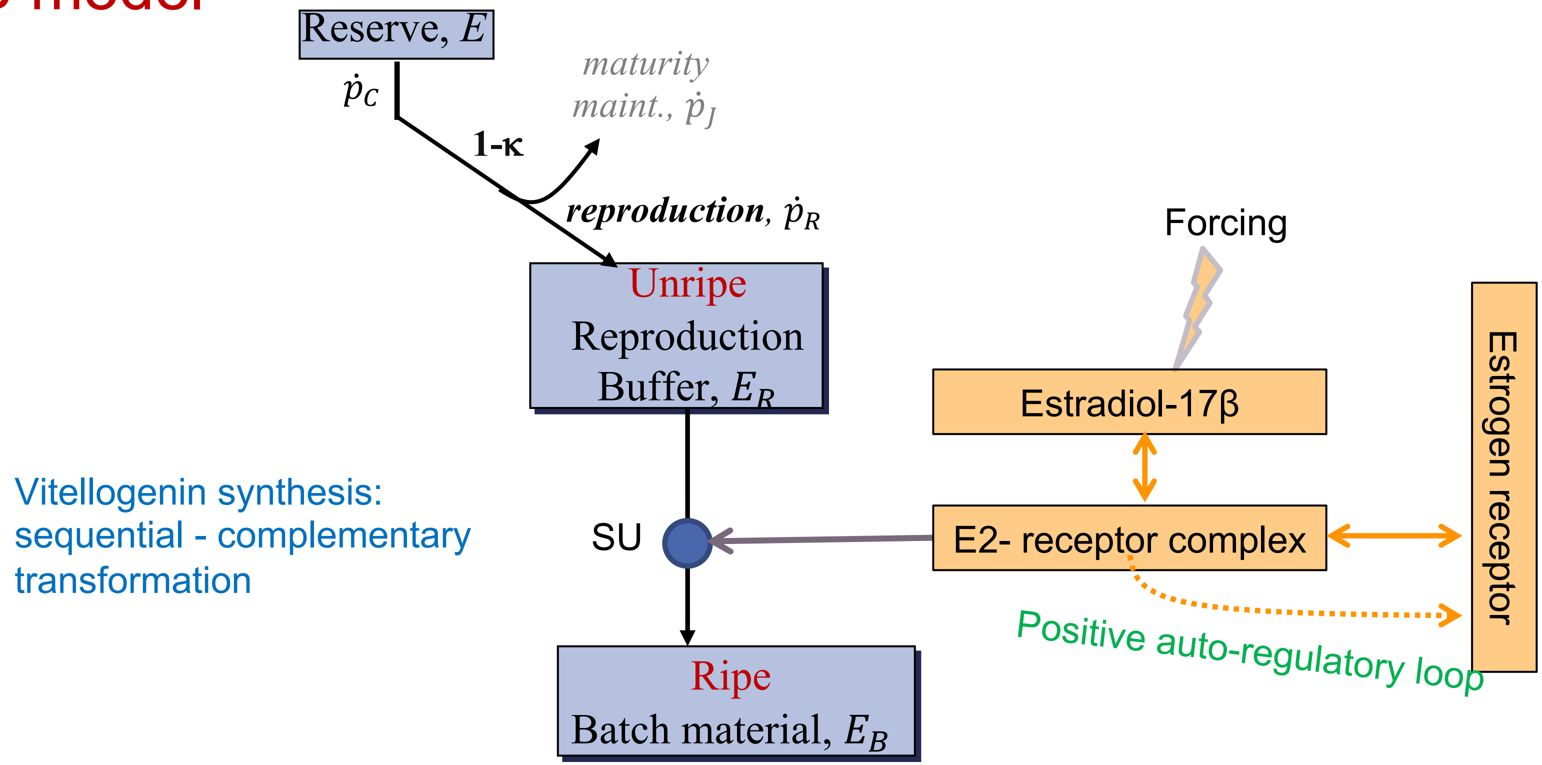
Pecquerie et al. (2009) Modeling fish growth and reproduction in the context of the Dynamic Energy Budget theory to predict environmental impact on anchovy spawning duration. J. Sea Res. 62:93-105

Augustine et al. (2012) Effects of uranium on the metabolism of zebrafish, Danio rerio. J. Sea Res. 62:93-105

Reproduction hormone module



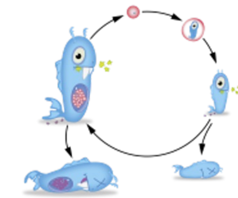
Link hormone dynamics underlying egg production to a DEB model



Murphy et al. (2018) Incorporating Suborganismal Processes into Dynamic Energy Budget Models for Ecological Risk Assessment . *IEAM* 14(5):615–624

Firkus, Lika, Murphy (2023) The consequences of sea lamprey parasitism on lake trout energy budgets. *Conserv Physiol* 11(1): coad006

Starvation in DEB context



Starvation rules depend on species and environmental conditions

- When mobilized reserves cannot meet somatic maintenance (i.e. $\kappa\dot{p}_C - \dot{p}_S < 0$) different rules may apply
    - somatic maintenance can be paid from the (ripe or unripe) reproduction matter
    - Shrink in structural mass to pay the somatic maintenance

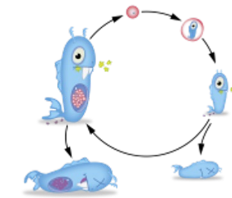
- When mobilized reserves cannot meet maturity maintenance (i.e. $(1-\kappa)\dot{p}_C - \dot{p}_J < 0$)
    - Rejuvenation may occur

Death-rules

- If shrinking is allowed, death by starvation occurs if shrinking of structure exceeds a given fraction of the structure at the onset of ceasing growth.
- When the reserve is depleted to a certain extent we can assume that starvation-induced death strikes

Starvation rules

Redirect energy from reproduction

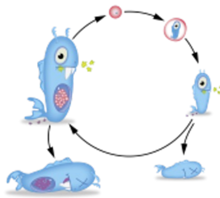


- If somatic maintenance costs cannot be paid from reserve, they are paid from the reproduction buffer. If the reproduction buffer is empty and if the somatic maintenance costs cannot be paid from reserve, the individual dies. (Pecquerie et al., 2009)
- If somatic maintenance costs cannot be paid from reserve, they are paid from the reproduction buffer and/or gametes (Pethybridge et al., 2013; Fircus et al., 2023).

Pecquerie et al. (2009) Modeling fish growth and reproduction in the context of the Dynamic Energy Budget theory to predict environmental impact on anchovy spawning duration. J. Sea Res. 62:93-105

Pethybridge, et al. (2013) Responses of European anchovy vital rates and population growth to environmental fluctuations: An individual-based modeling approach. Ecol. Model. 250, 370–383. https://doi.org/10.1016/j.ecolmodel.2012.11.017

Firkus, Lika, Murphy (2023) The consequences of sea lamprey parasitism on lake trout energy budgets. *Conserv Physiol* 11(1): coad006

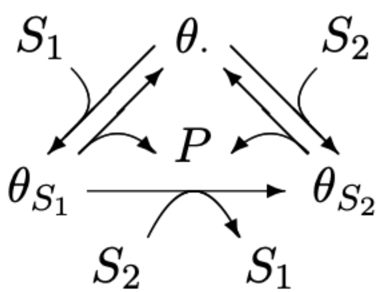


Starvation rules[1]

Shrink during starvation

Use of SUs (4.1.5 DEB3 and comments)

- The somatic maintenance-SUs receive a reserve flux and a structure flux
- Reserve and structure are **substitutable** compounds for somatic maintenance, with a strong **preference** for reserve.
- Shrinking comes with extra parameters
- Payment via structure involves an extra transformation, so extra losses.

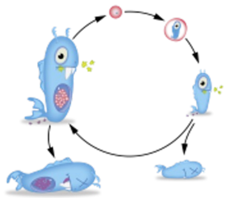


S_1: Structure
S_2: Reserve
P: maintenance products

Figure 3.8 in DEB3

Starvation rules^2

Shrink during starvation



Absolute priority for reserve (4.1.5 DEB3 and comments)

- Mobilization rate

$$\dot{p}_C = E\left(\frac{\dot{v}}{L} - \dot{r}\right)$$

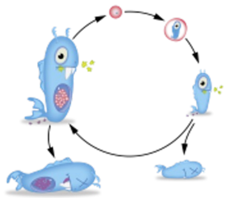
Growth rate

When $\frac{[E]\dot{v}}{L} > [\dot{p}_M]/\kappa$

$$\dot{r} = \frac{[E]\dot{v}/L - [\dot{p}_M]/\kappa}{[E] + [E_G]/\kappa}$$

otherwise

$$\dot{r} = \frac{[E]\dot{v}/L - [\dot{p}_M]/\kappa}{[E] + \kappa_G[E_G]/\kappa}$$



Starvation rules

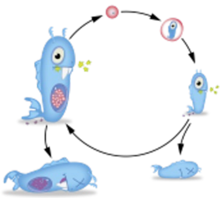
Rejuvenation during starvation

When mobilized reserves cannot meet maturity maintenance (i.e. $(1-\kappa)\dot{p}_C - \dot{p}_J < 0$)

- If the reproduction buffer is not empty, rejuvenation can be delayed by draining this buffer to supplement maturity maintenance.
- Else E_{H} decays exponentially (rejuvenation).

(4.1.5 comments on DEB3)

Augustine et al. (2013) Stochastic feeding in fish larvae and their metabolic handling of starvation. J of Sea Res 66 (2011) 411–418 ξα σου



Thank you for your attention!!!

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