SMARTER Summer School
27-30 March 2023 – Toulouse, France

Module 2: mechanistic and statistical modelling of resilience and feed efficiency

Allocation theory in farm animals: from concepts to code

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(MoSAR unit)

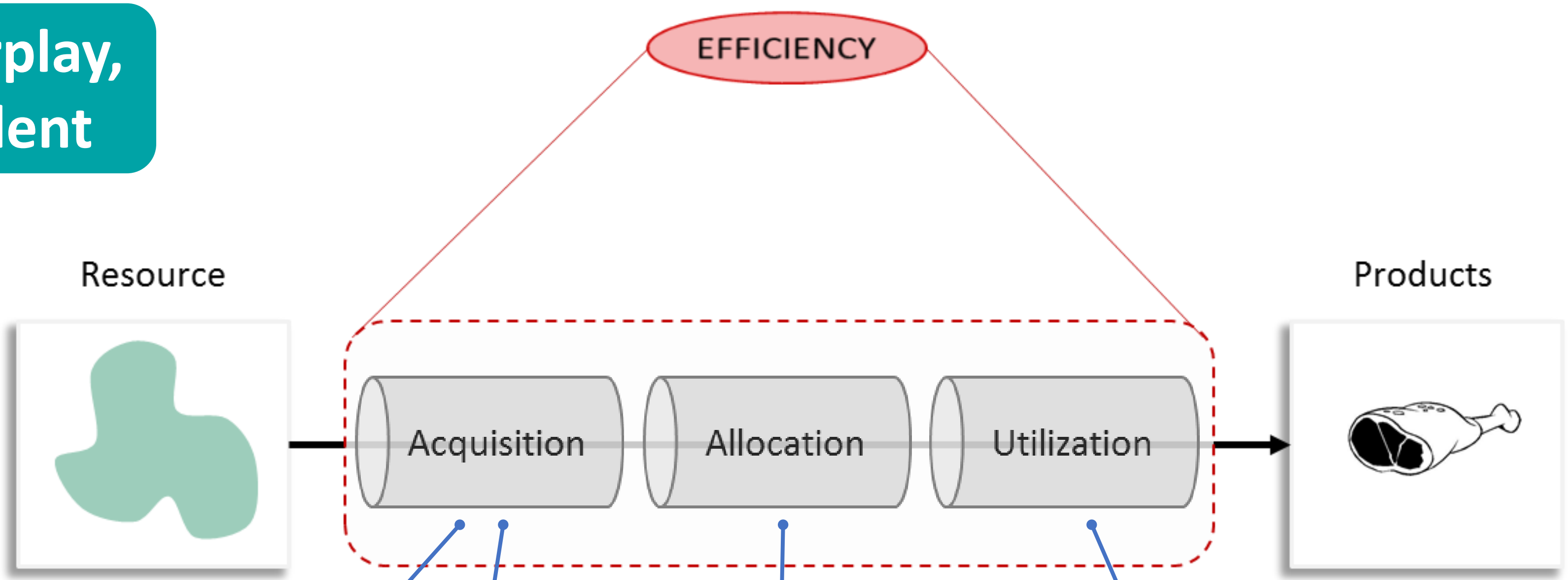
SMAll RuminanTs breeding for Efficiency and Resilience

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Grant Agreement n°772787

Complex features of feed efficiency

Dynamic interplay, time-dependent

Difficult to measure



Dry matter intake

Digestive processes (feces, urine, CH_4)

Nutrient partitioning

Tissues metabolism

Sub-traits combination

Trade-offs

Sustainable genetic selection for feed efficiency

- What are the long-term effects of selection?
- Is there any side effect?
- Are we selecting the mechanisms we want?
- High merit animals for FE → able to accommodate different environments?
- High merit animals for FE → still resilient?

DISCLAIMER

One of the possible research avenue!

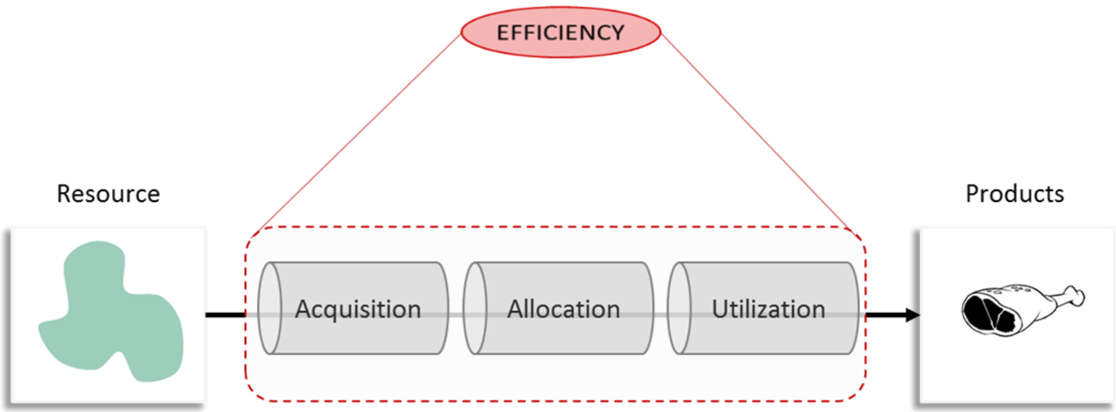
Part 2: link with nutrition modelling

Simulation model

Dynamic and process-based

Part 1: a concept from ecology

Incorporating allocation



Resource allocation theory in ecology

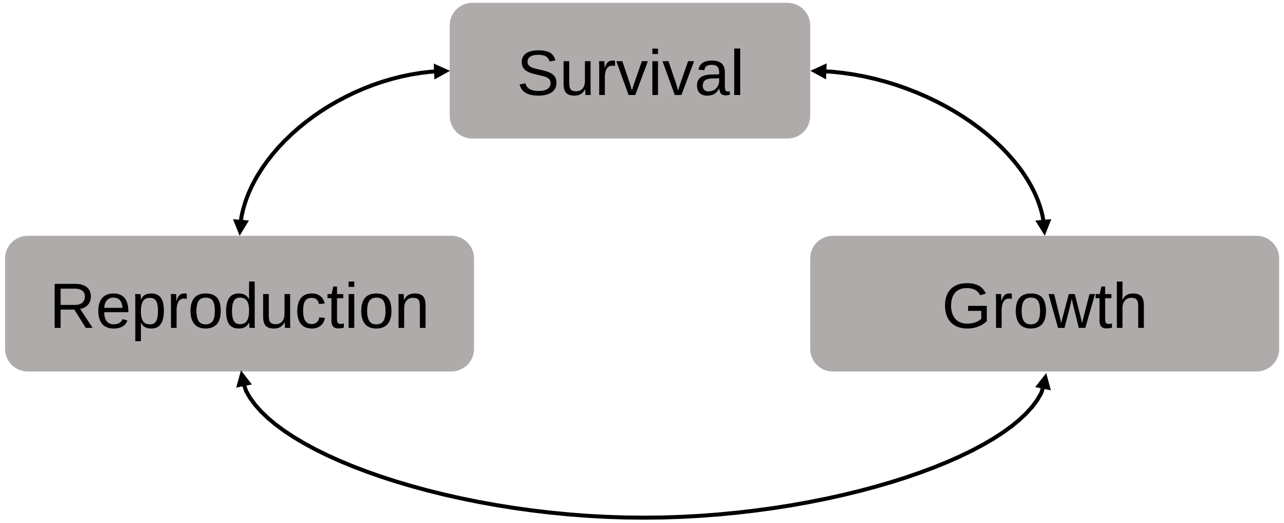
Different life-history strategies exist

Mus musculus

Lifespan: 3 y
Age at maturity: 45 d
Parturition: 6/y
Litter size: 7

Loxodonta africana

Lifespan: 60 y
Age at maturity: 11y
Parturition: 1/5y
Litter size: 1

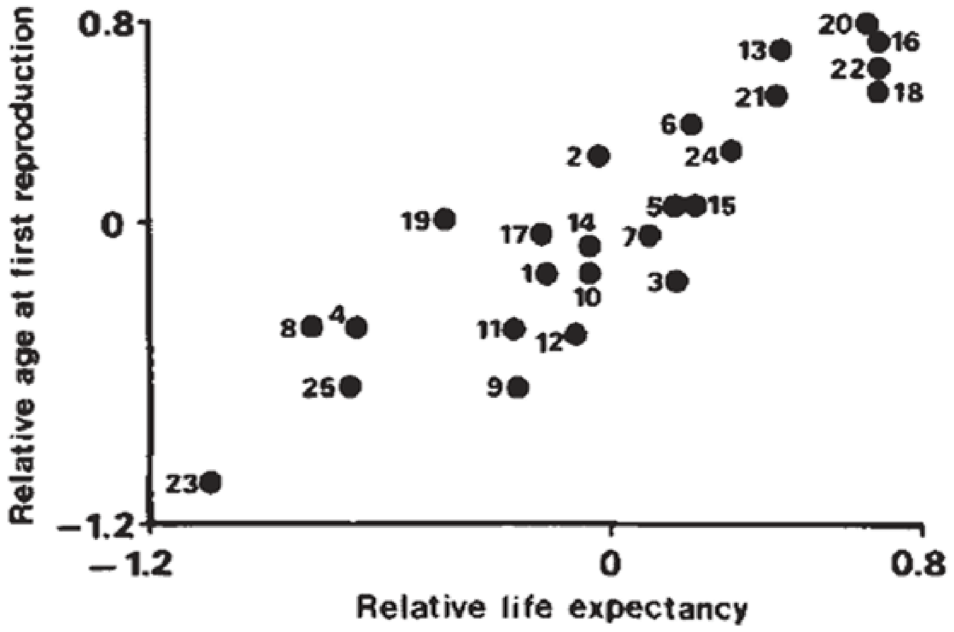


Resource allocation theory in ecology

- Variation among living organisms is not new: basis for evolution (see Darwin 1859)

- Covariance among traits
  - Slow-fast continuum of strategies
  - Trade-offs in resource allocation

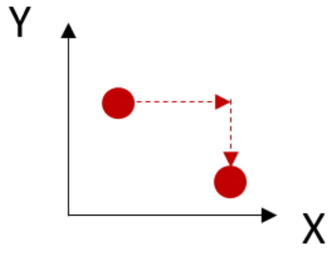
"Resources available for an individual are limited, so that individuals should allocate resources optimally among growth, survival, and reproduction in order to maximize their fitness" (Stearns 1992)



Harvey and Zammuto, 1985

Resource allocation theory in ecology

- Trade-off
  - Increase in X → decrease in Y
  - “Darwinian demon” doesn’t exist



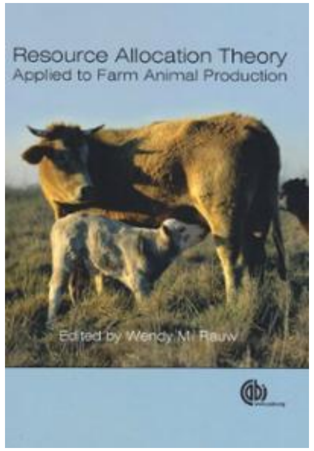
- Use of the concept by Cody (1966)
  - Clutch size in birds = f(allocation predator avoidance | competition for resource)
- Life history strategy is a genetically inherited pattern of resource allocation that has evolved through the process of natural selection
- Cost/benefit analysis to predict the optimal strategy (= maximize fitness) and therefore organisms that will adapt to the environment and evolve

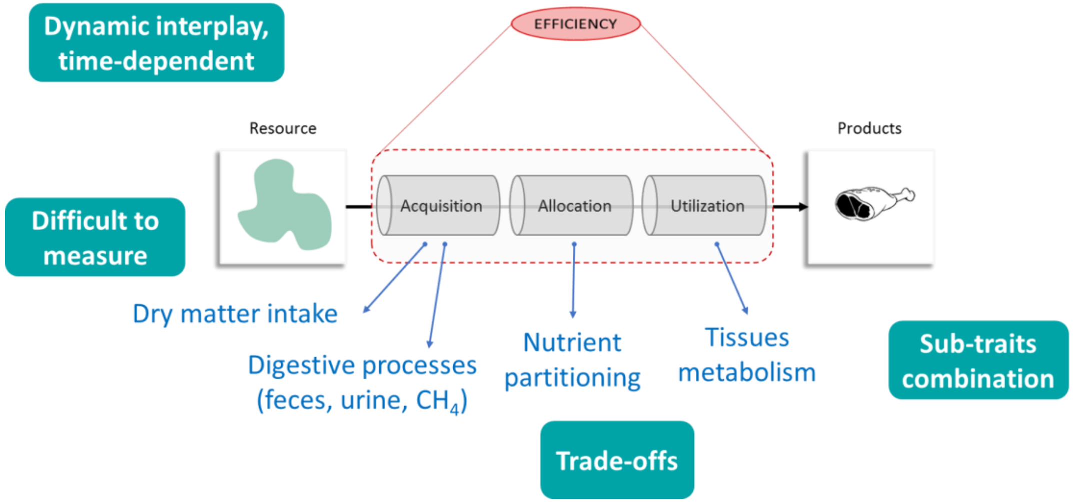
Resource allocation theory in ecology

Wrap-up: a framework useful for…

- Describing trade-offs, interactions among traits | functions
- Understanding variation among individuals
- Predicting long-term effect on fitness

Potential interest for sustainable genetic selection for feed efficiency!





Rauw, 2008

Resource allocation in animal nutrition

- How to feed animals to obtain products (milk, meat…)?
- Nutritional energetics → how much energy lost | retained?
  - Relationships gas exchange / heat production
  - Evaluation of food to be related to requirements and expenditures
  - Causes of expenditures

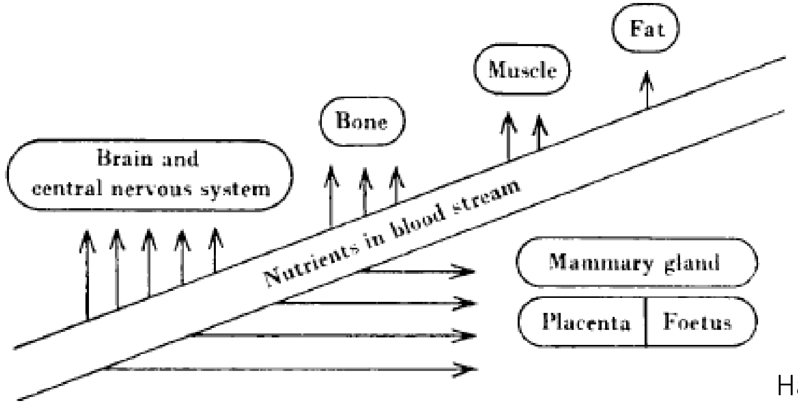
Lactation 50%

Lactation 70%

- Nutrient partitioning (≈ resource allocation) → core of feeding tables/feeding systems
  - Starch Equivalent system (Kellner and Köhler, 1900)
  - Physiological Fuel Values system (Atwater and Bryant, 1900)

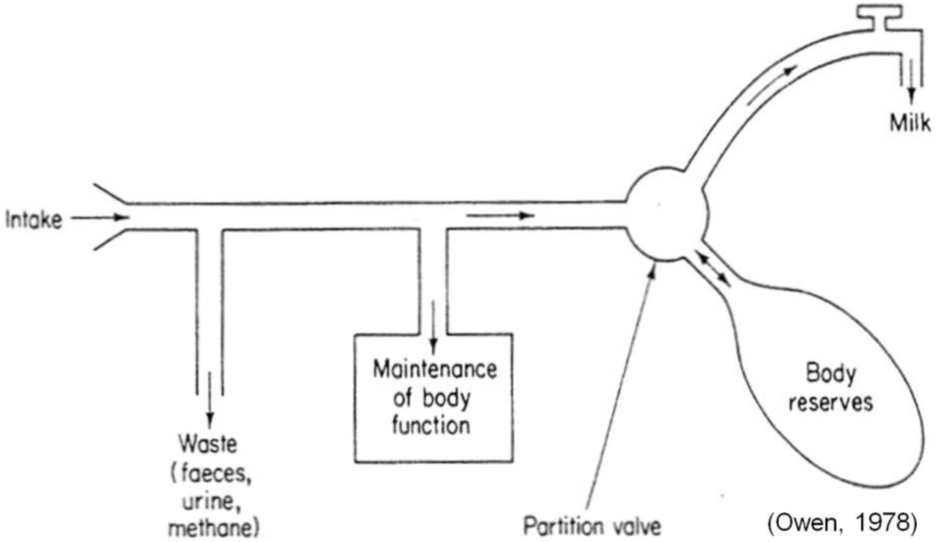
Resource allocation in animal nutrition

A long-standing concern



Hammond, 1947

Fig. 7. Priority of partition of nutrients according to metabolic rate.



(Owen, 1978)

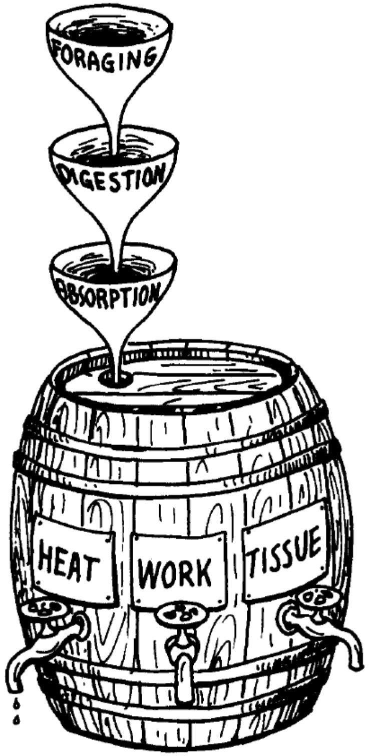


Fig. 2. The barrel model' of an organism's energy balance. Input constraints (maximum rates of foraging, digestion, and absorption) are engaged in series; outputs (heat production, mechanical work, tissue growth) are parallel and independently controlled. If the sum of output rates does not match the input, the balance is buffered by the storage capacity of the system. Note that the first spigot always 'leaks' (basal heat loss of the organism).

Weiner, 1992

Resource allocation in animal nutrition

A long-standing concern

One	cow	gave	1·85	kg.	more	milk	and	29	g.	more	fat
Another	,,	,,	2·24	,,	less	,,	,,	66	,,	less	,,
,,	,,	,,	0·01	,,	more	,,	,,	21	,,	,,	,,
,,	,,	,,	0·71	,,	,,	,,	,,	6	,,	,,	,,

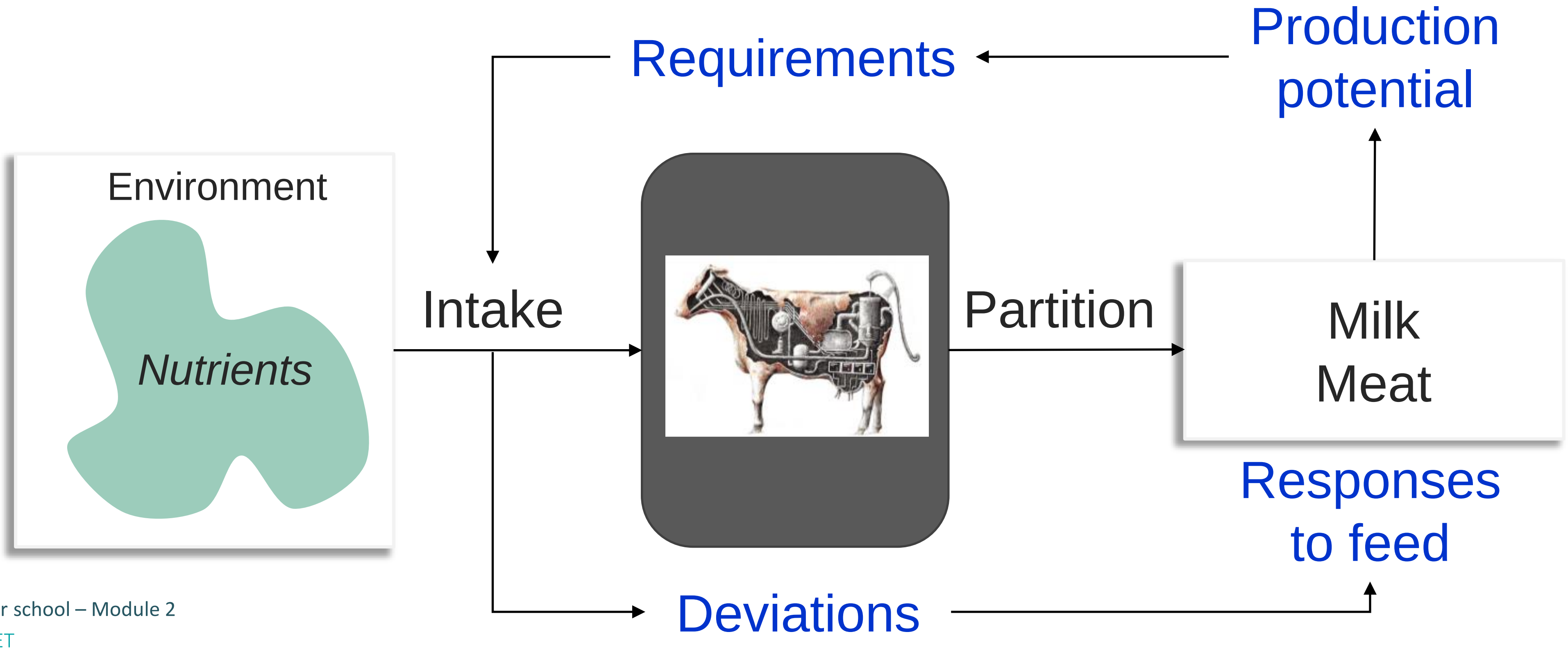
Observations of this kind, which anybody can make in practice, show how extraordinarily changeable is the influence of individuality upon the production of milk. They teach also how deceptive are the results of experiments carried out upon a small number of animals.

Kellner, 1908

Resource allocation in animal nutrition

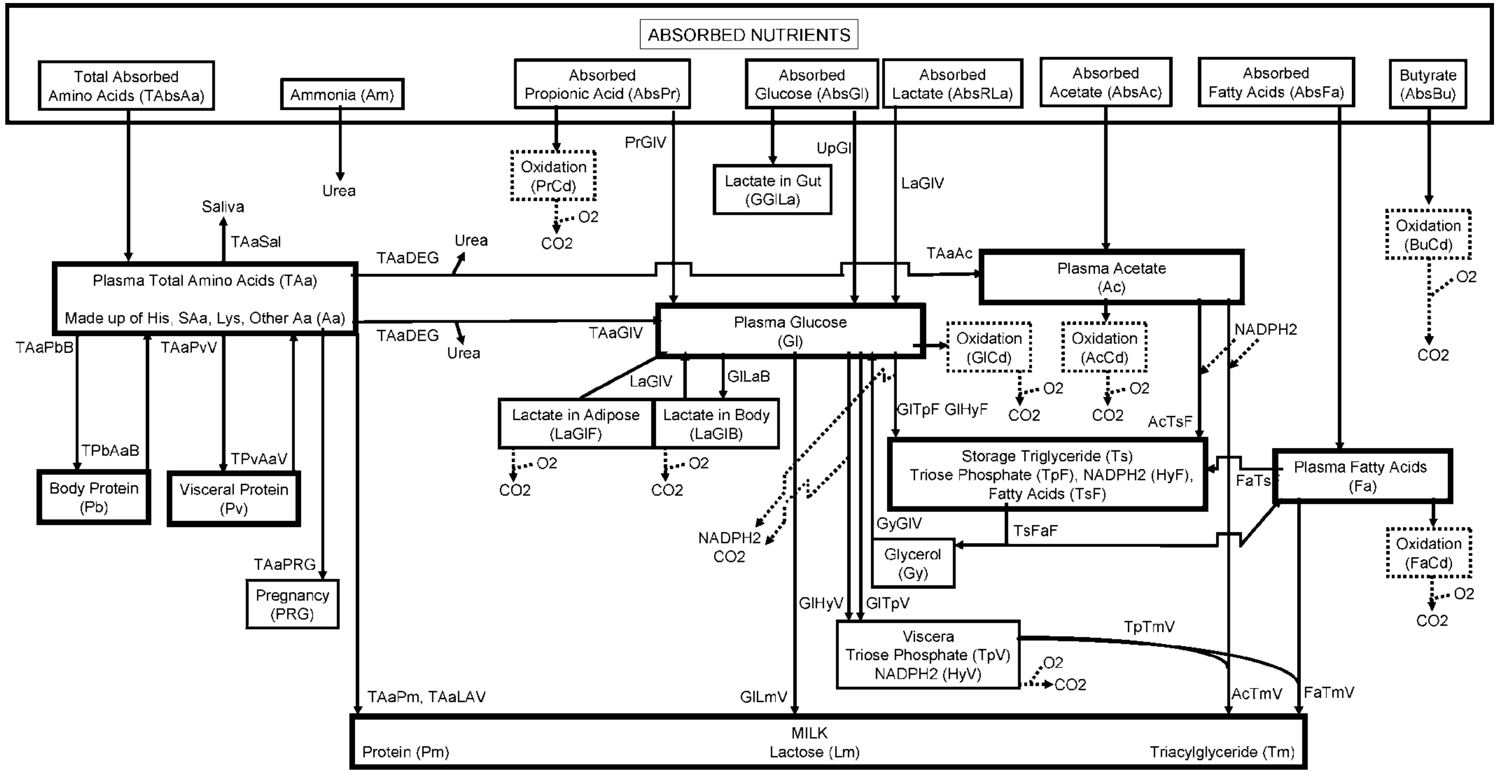
A concept that has evolved

- Starting point → the animal as biochemical convertor
- Nutrient partitioning → consequences of production potential



Resource allocation in animal nutrition

- Biochemical models: for ex., dairy cow model Molly (Baldwin, 1987)
- Biological processes = metabolism



Johnson et al., 2005

Resource allocation in animal nutrition

- From a passive convertor to an active biological entity
  - The animal is a regulated organism
  - Short-term regulations: homeostasis (for ex. glucose regulations)
  - Long-term regulations: homeorhesis | teleophoresis

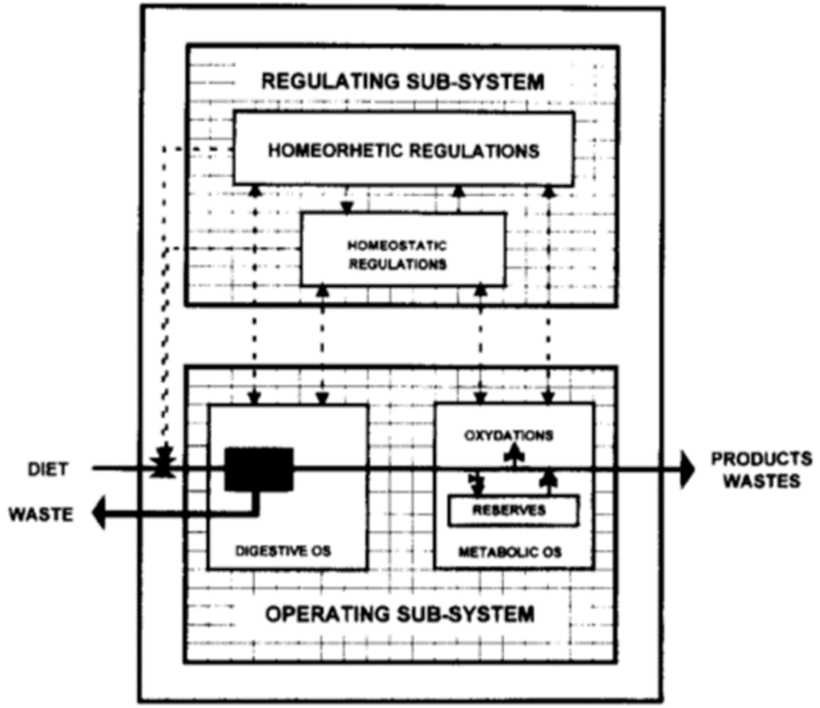
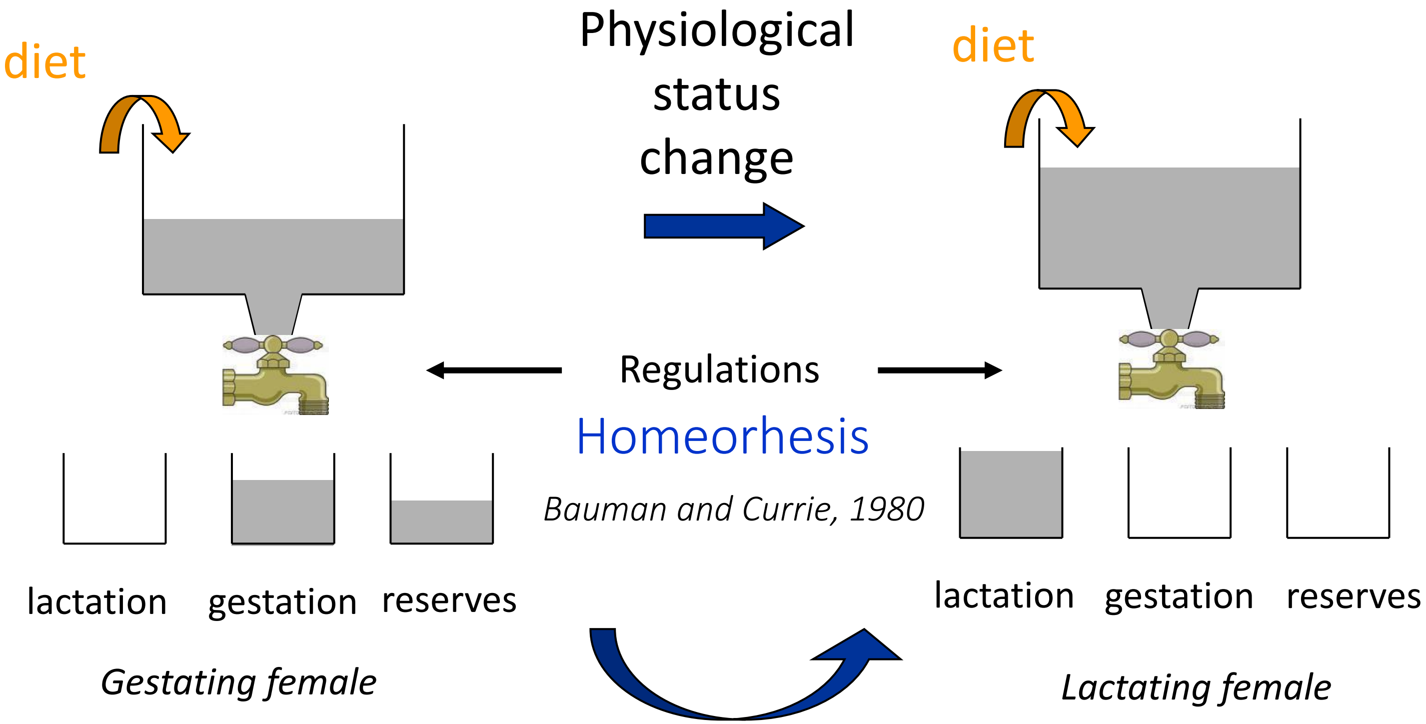


Fig. 1. The live organism as a regulated system.

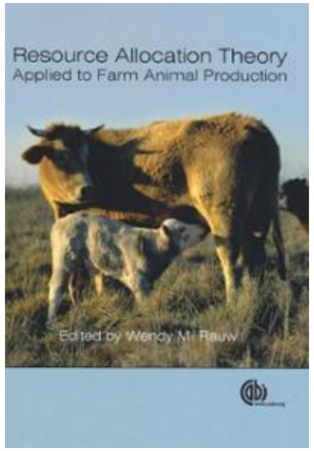
Sauvant, 1994

Resource allocation in animal nutrition



Trade-offs among biological functions

Key role of body reserves



Genetic differences in nutrient partitioning?

Starting point to connect nutrition|genetics

Priority change between functions → Dynamic expression of genes throughout life → Genetically-driven trajectories

Friggens and Newbold, 2007

Resource allocation in animal nutrition

Example of body reserves mobilization in early lactation

- Classical view: intake doesn't increase as fast as lactation energy requirements

  Mobilization is a consequence

- Experimental evidence: rich diet doesn't abolish mobilization

  See review by Friggens and Newbold, 2007; Friggens et al., 2011

- Mobilization has a genetic component

  Evolutive role of body reserves in lactation

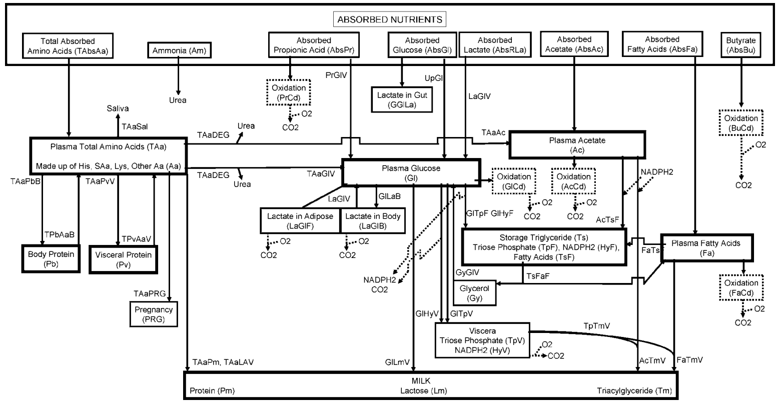
  The dairy female is a mammal!

→ Life history strategy is a **genetically inherited pattern of resource allocation** that has evolved through the process of natural selection

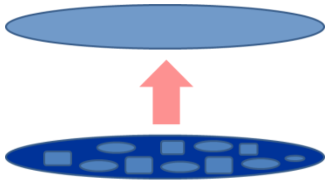
Resource allocation in animal nutrition

Homeorhesis regulations reflect genetic drives of nutrient partitioning

How to introduce this level of control in nutrition models? (and up scaling at lifetime level!)



Bottom-up approach:
let regulations emerge



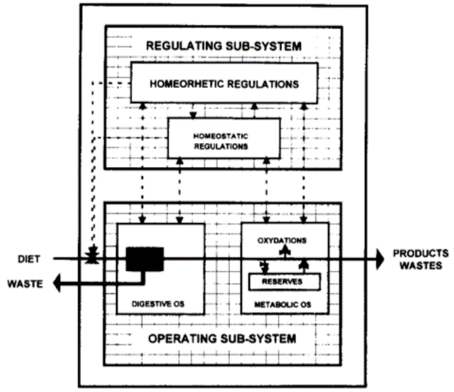
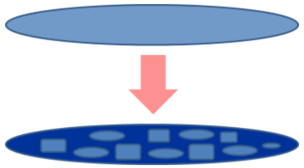


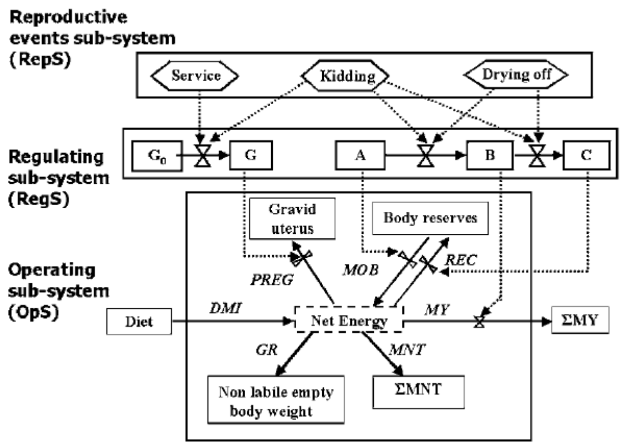
Fig. 1. The live organism as a regulated system.

Top-down approach:
impose regulations

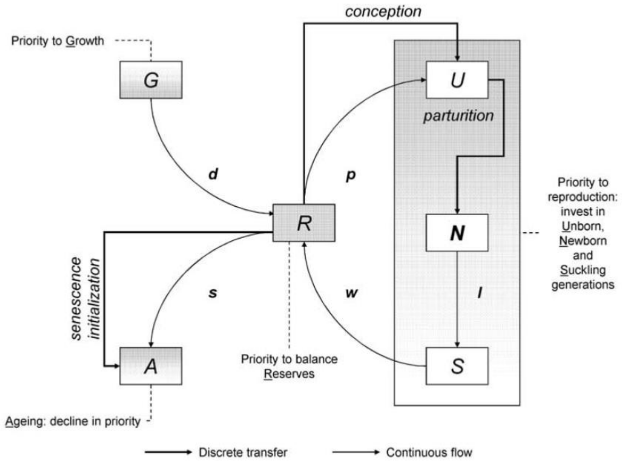


See Friggens et al., 2011 for review

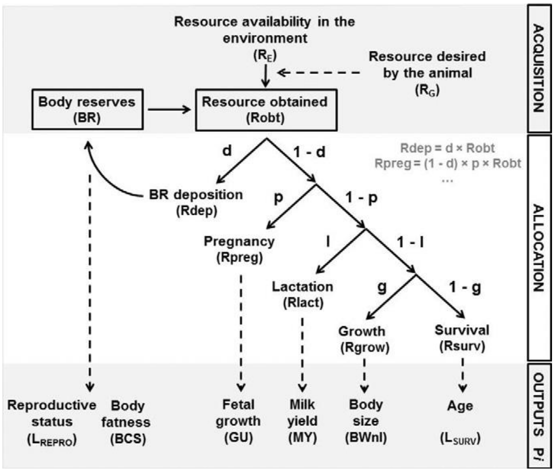
Resource allocation in animal nutrition



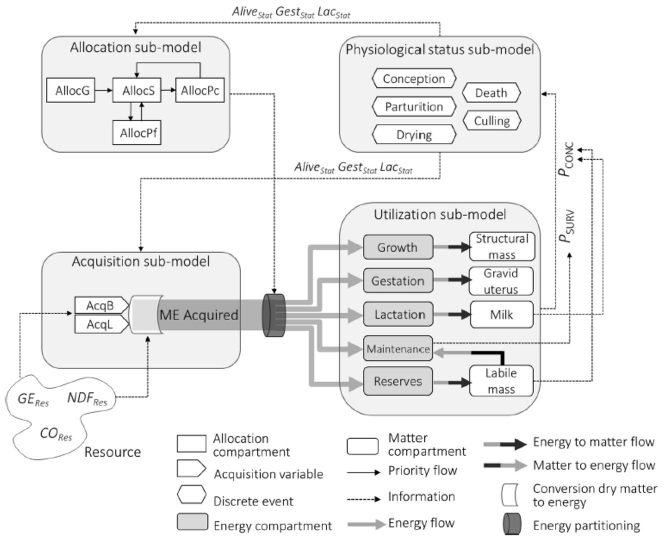
Puillet et al., 2008



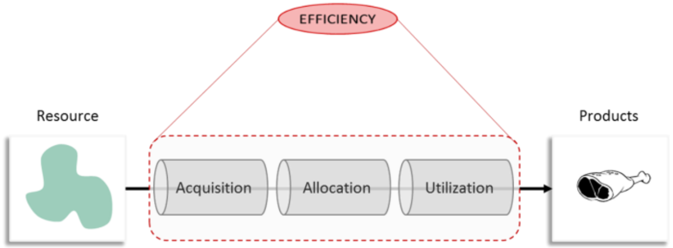
Martin et Sauvant, 2010



Douhard et al., 2014



AQAL model, next part

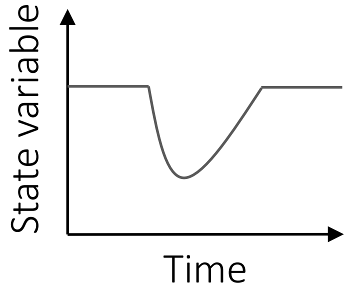


Effort to split acquisition and allocation to introduce genetics at both levels

Puillet et al., 2016

Resource allocation in animal nutrition

What about resilience?



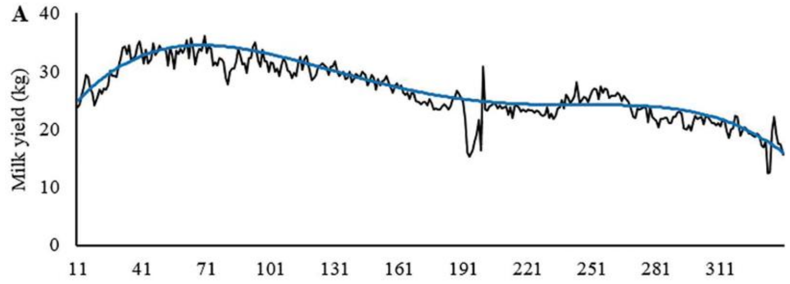
Ability to cope with short-term challenge

Deviation from the **baseline trajectory**, induced by a perturbation

Allocation models provide this baseline trajectory

State of reserves at the time of perturbation

Re-allocating nutrients



Poppe *et al.*, 2020

Development for dairy goat thanks to SMARTER project

Research effort for health and reproduction functions!

Smarter
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Manipulating acquisition and allocation parameters to generate variability in production trajectories

- Get your hands dirty!

  A little bit, due to short time…

  More details in articles

Puillet, L., Réale, D. & Friggens, N.C. Disentangling the relative roles of resource acquisition and allocation on animal feed efficiency: insights from a dairy cow model. *Genet Sel Evol* 48, 72 (2016) https://doi.org/10.1186/s12711-016-0251-8

Puillet L., Ducrocq V., Friggens N.C., Amer P. Exploring underlying drivers of genotype by environment interactions in feed efficiency traits for dairy cattle with a mechanistic model involving energy acquisition and allocation. Journal of Dairy Science, 104, 5, 5805-5816 (2021) https://doi.org/10.3168/jds.2020-19610

- Play with AQAL model to generate concrete simulations of allocation trajectories

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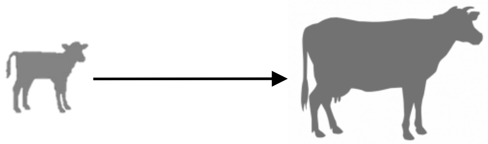
AQAL model (Acquisition-Allocation)



Birth

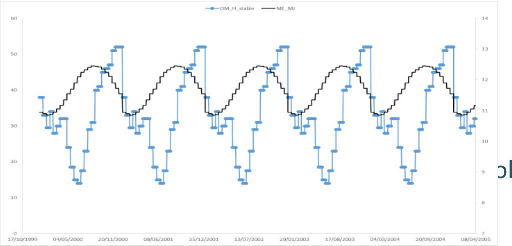
Culling
Death

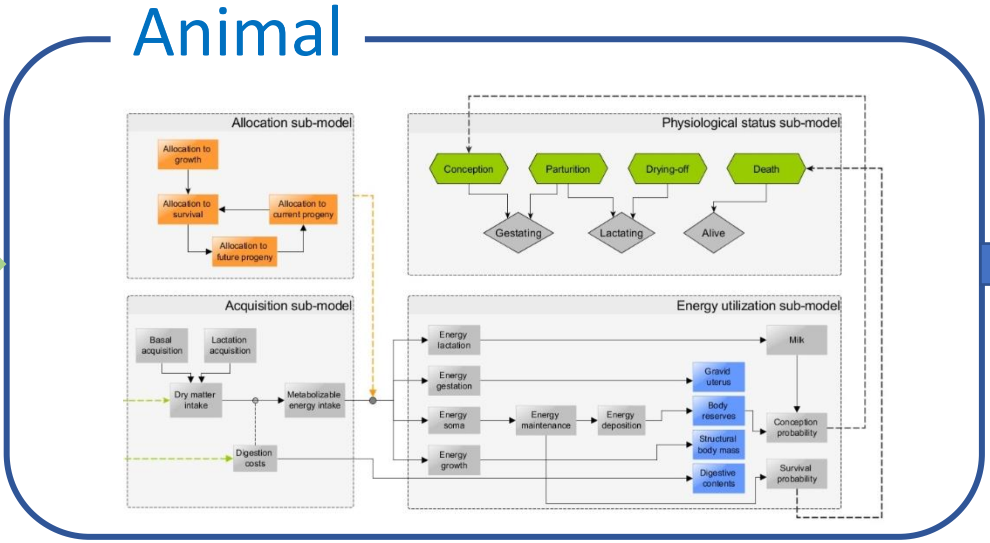
A dynamic model, simulating traits through life

Feed resource converted into traits based on energy processes

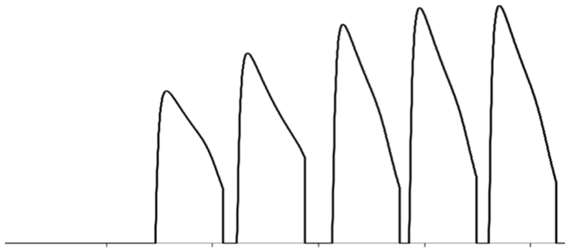
Dry matter
offer (kg/d)

Energy content
(ME/kg DM)

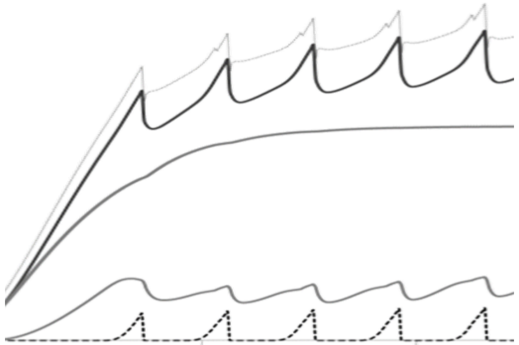




Milk production



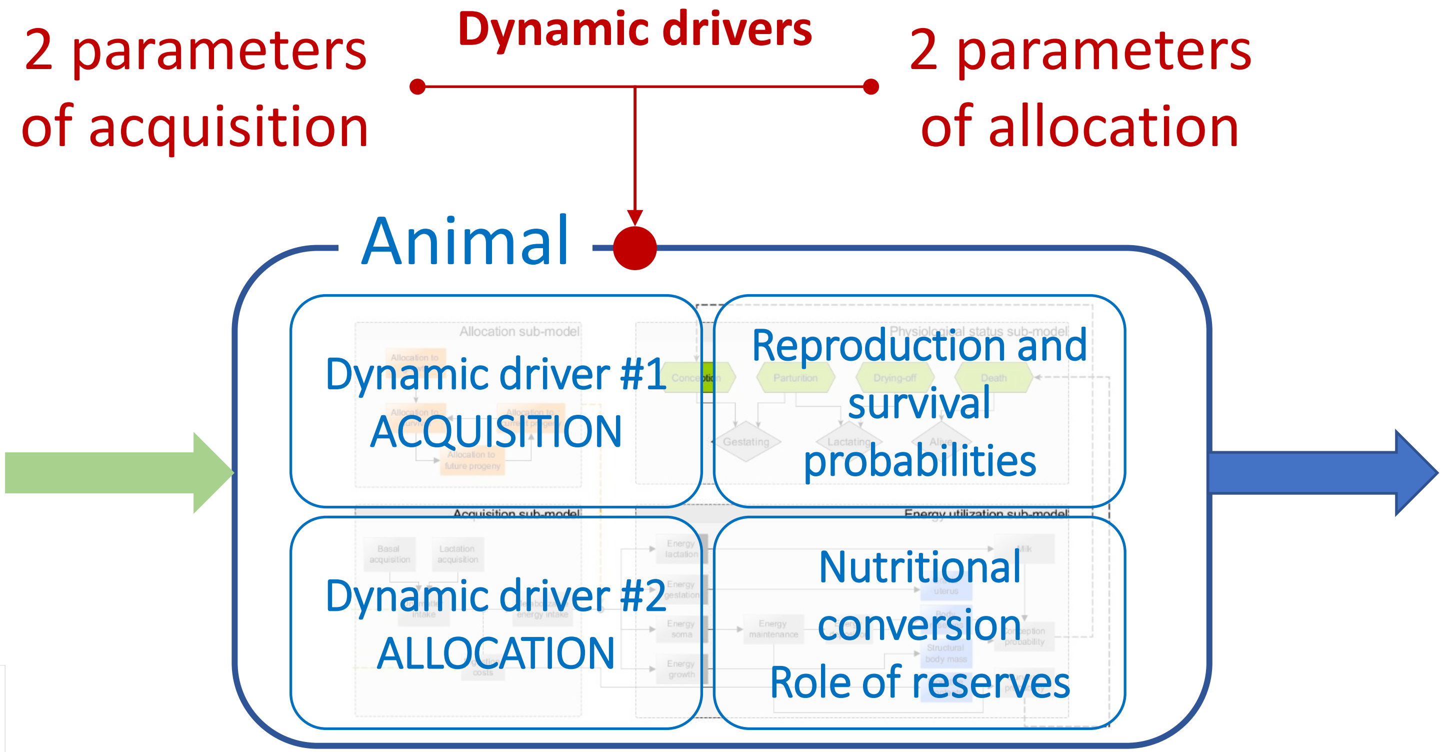
Body mass component



AQAL model (Acquisition-Allocation)

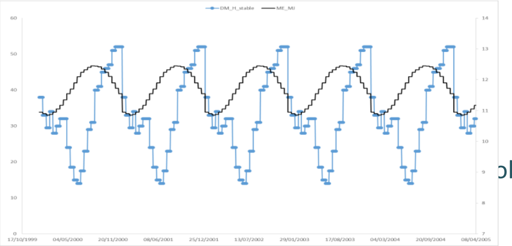
How many feed resource can get the cow ?

What is the cow strategy to distribute energy among functions?

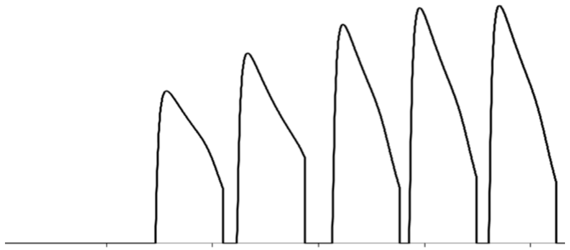


Dry matter offer (kg/d)

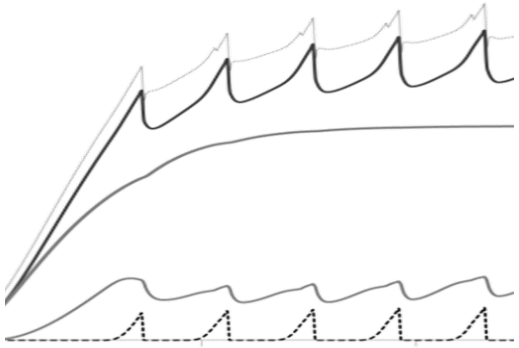
Energy content (ME/kg DM)



Milk production



Body mass component



Nb of lactations and longevity → outputs of simulation

AQAL model (Acquisition-Allocation)

Genetic-scaling parameters, used to simulate ≠ animals

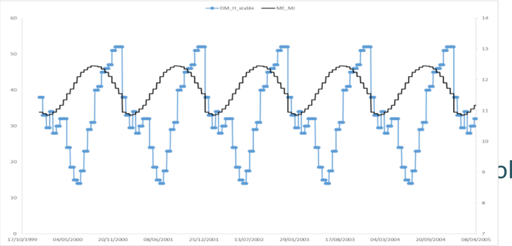
Dynamic drivers

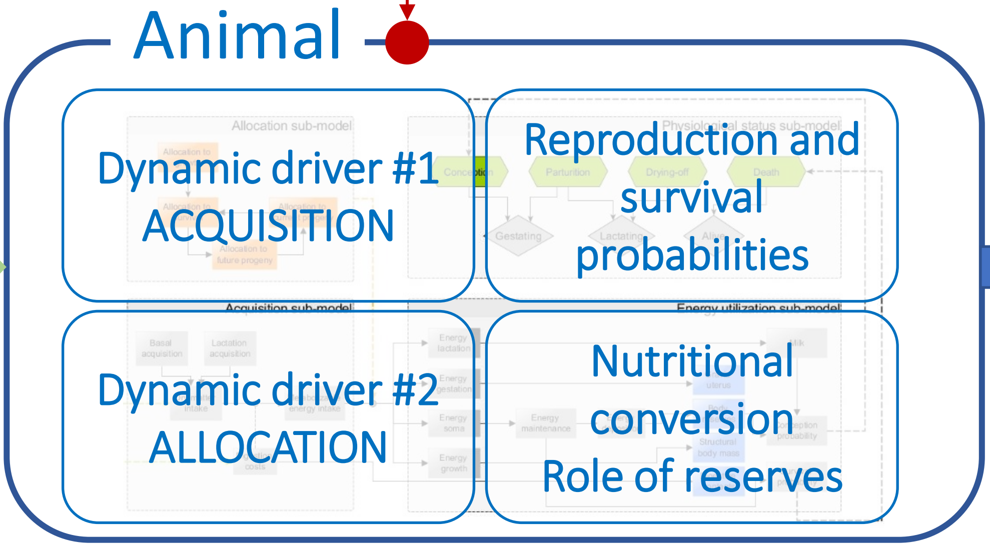
2 parameters of acquisition

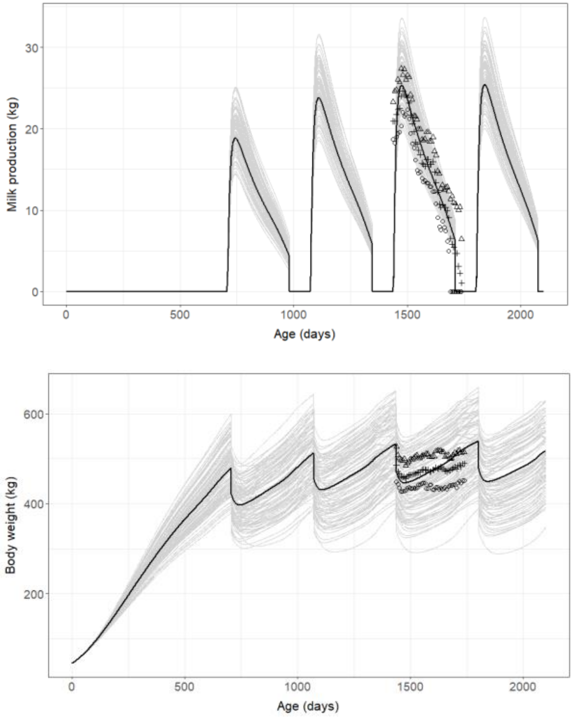
2 parameters of allocation

Dry matter offer (kg/d)

Energy content (ME/kg DM)







Nb of lactations and longevity → outputs of simulation

AQAL model (Acquisition-Allocation)

General (nutritional) principles

$$ME_{intake} = DryMatter_{intake} \cdot GE_{resource} \cdot \%MEinGE$$

kcal | kg | kcal/kg | Proportion of energy lost in feces, urine and methane

Static view here but the model is dynamic (daily time-step)

kcal | kcal | proportion

$$ME_{survival} = ME_{intake} \cdot Alloc_{survival}$$

$$ME_{growth} = ME_{intake} \cdot Alloc_{growth}$$

$$ME_{lactation} = ME_{intake} \cdot Alloc_{lactation}$$

$$ME_{gestation} = ME_{intake} \cdot Alloc_{gestation}$$

$$\sum ME_{functions} = ME_{intake} \cdot \boxed{\sum Alloc_{function}}$$

= 1 → energy conservation

$$NE_{lactation} = ME_{lactation} \cdot k_{lactation}$$

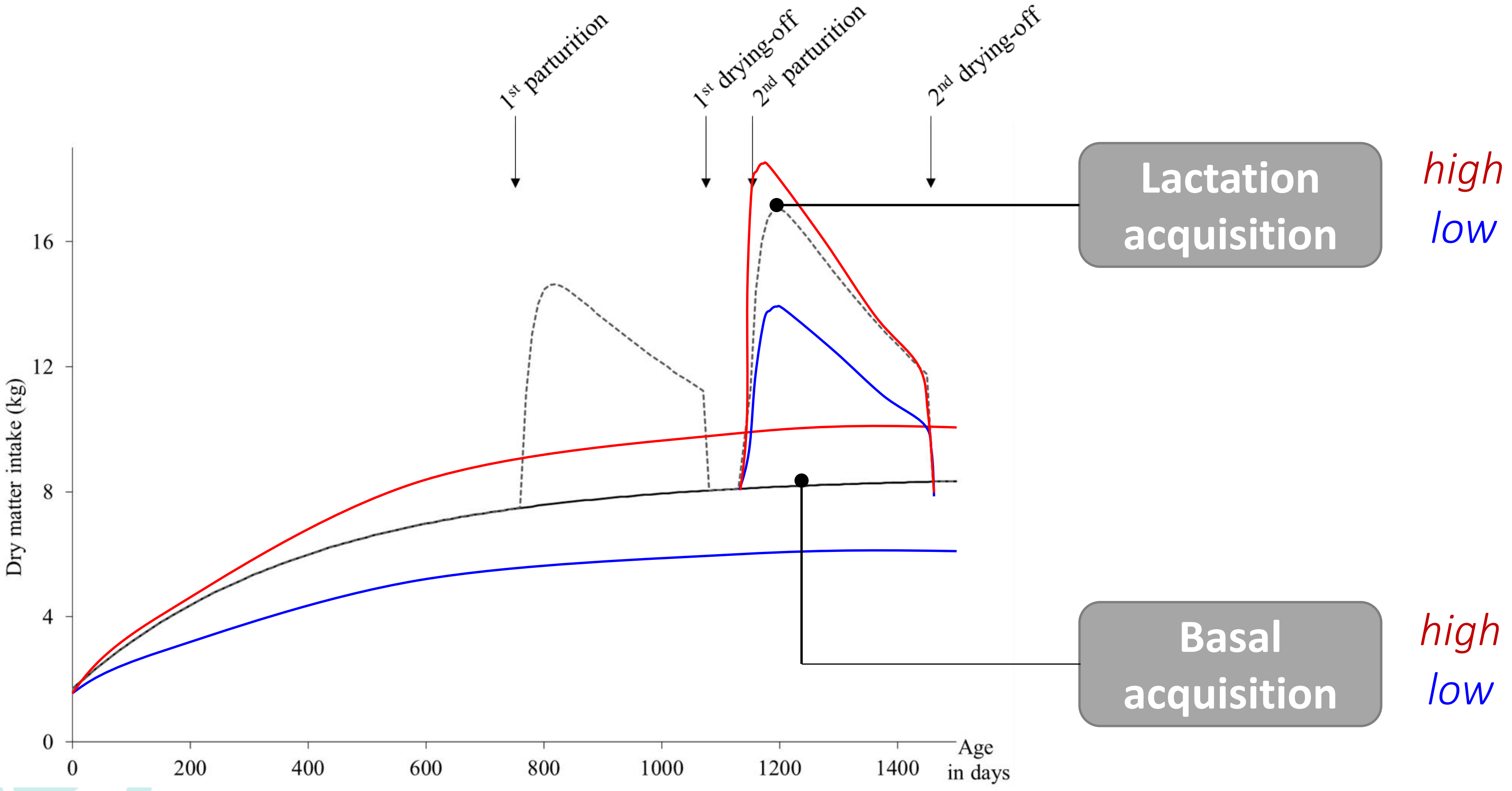
Heat production

$$Milk = \frac{NE_{lactation}}{EV_{milk}}$$

kg | kcal | kcal/kg

AQAL model (Acquisition-Allocation)

Focus on acquisition



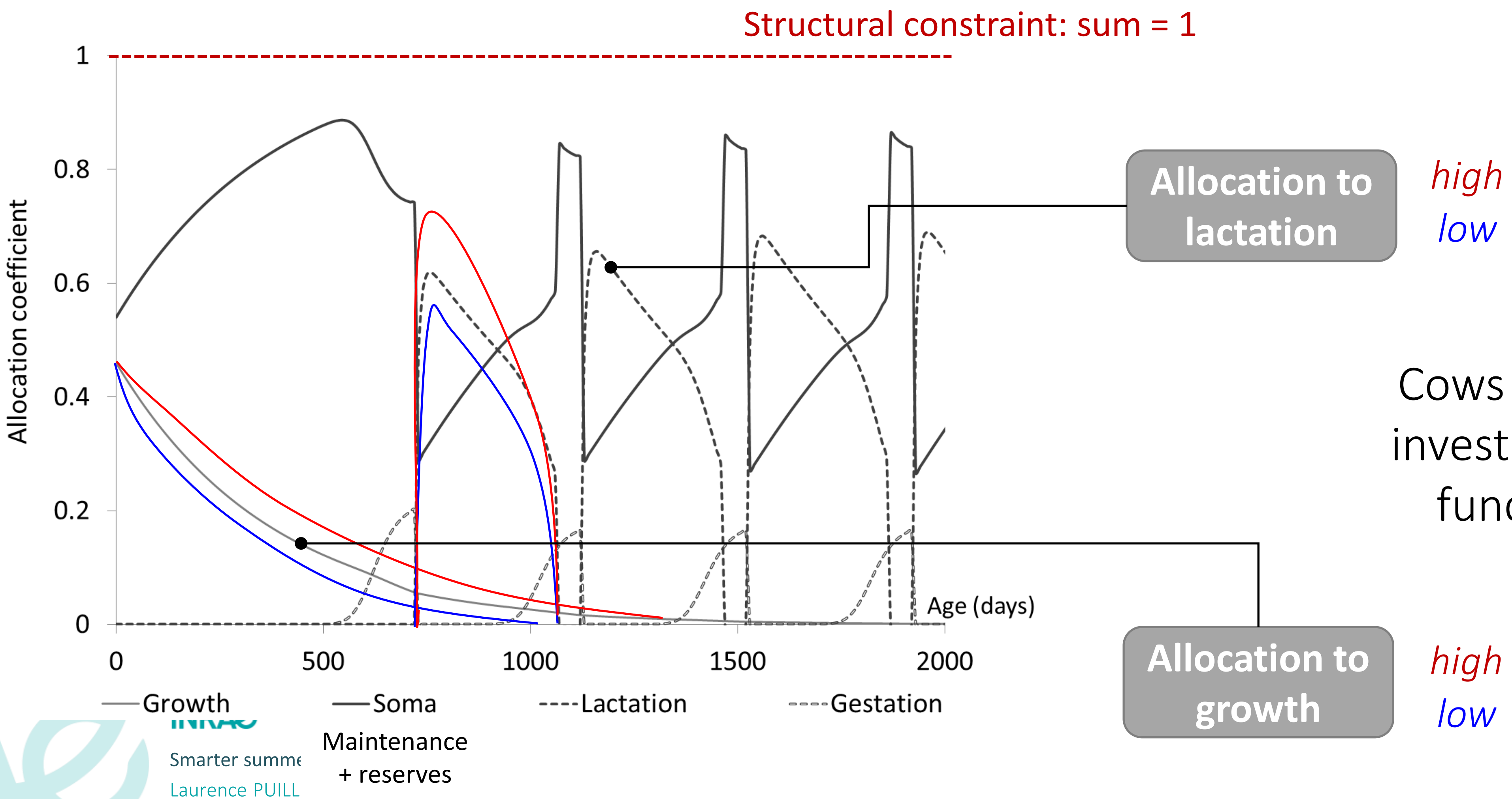
≠ combinations of parameters → variability of cow's capacities to acquire resource

$$basal_{acq} = \frac{GSP}{1 + \alpha \cdot e^{-\beta \cdot age}}$$

AQAL model (Acquisition-Allocation)

Focus on allocation

Dynamics of priorities among functions
Inherited patterns of energy allocation



Cows with ≠ strategies of investment into biological functions (trade-offs)

AQAL model (Acquisition-Allocation)

Focus on allocation

A closed network of 4 compartments, with a quantity of 1 (virtual, dimensionless) flowing

→ At any time step, sum of compartments = 1 (no leak)

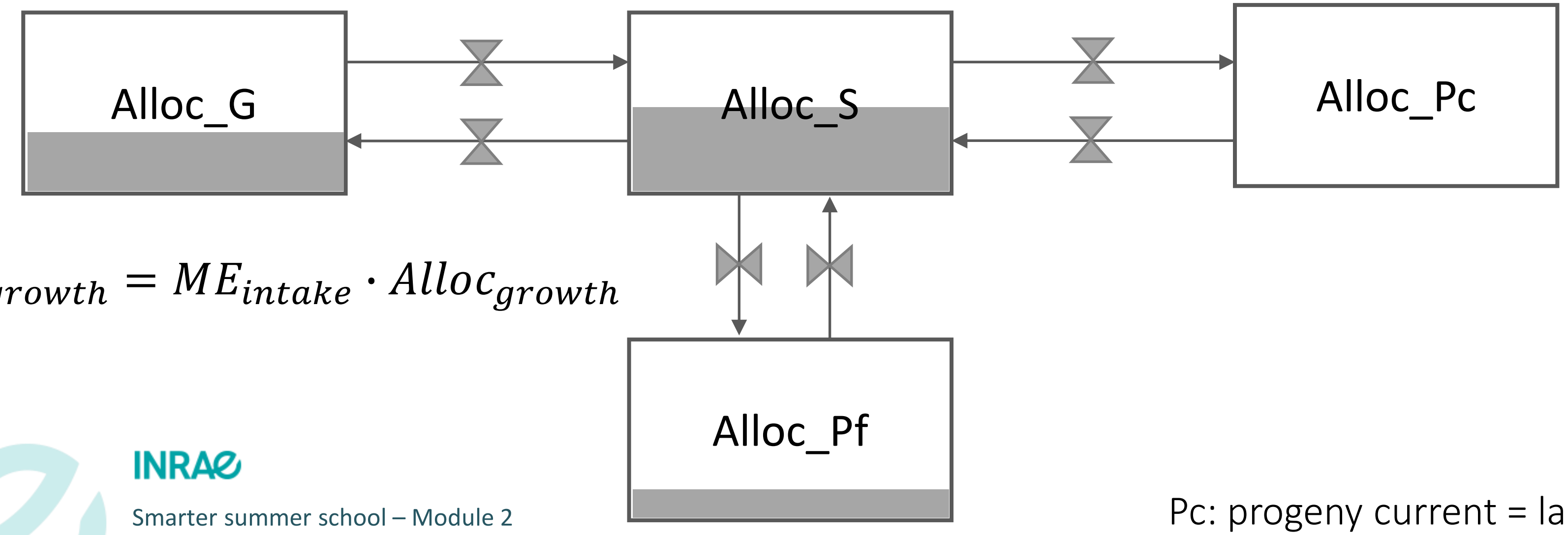
Compartment value = allocation coefficient value (level of priority)

System dynamics approach (Forrester diagram)

Flows control = (genetic-scaling) parameters | boolean (physiological status)

ODE formalism, with numerical integration

$$\frac{dAlloc_G}{dt} = k_G \cdot Alloc_G$$



$$ME_{growth} = ME_{intake} \cdot Alloc_{growth}$$

Modeller's choice: where to put genetics = GSP versus "normal" parameter

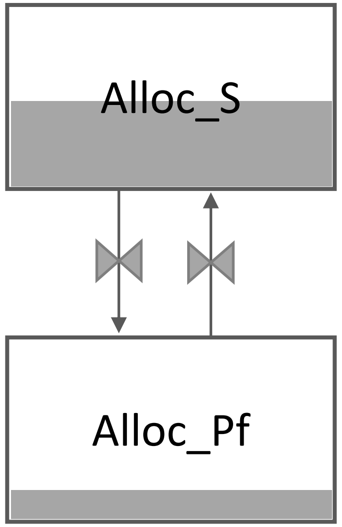
Pc: progeny current = lactation

Pf: progeny future = gestation

AQAL model (Acquisition-Allocation)

Dynamic transmission: example of gestation

@ conception:
gest_status = 1

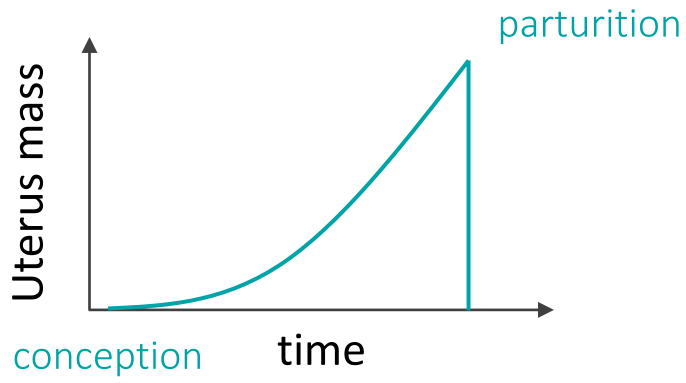


@ parturition:
Alloc_S = Alloc_S + Alloc_Pf
Alloc_Pf = 0

$$NE_{gestation} = ME_{intake} \cdot Alloc_{gestation} \cdot k_{eff}$$

$$flow_{GravidUterus} = \frac{NE_{gestation}}{EV_{GravidUterus}}$$

$$\frac{dMass\_Uterus}{dt} = flow_{GravidUterus}$$



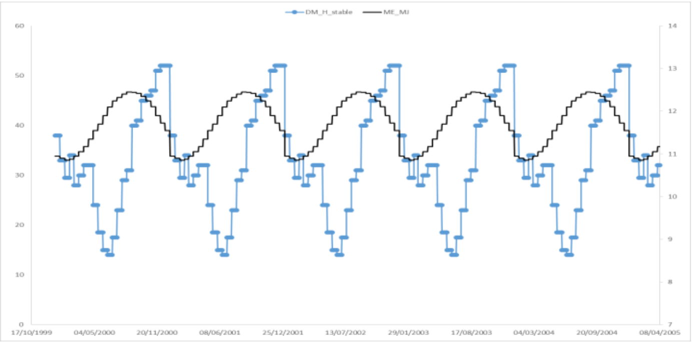
AQAL model (Acquisition-Allocation)

Need a "minimal" environment

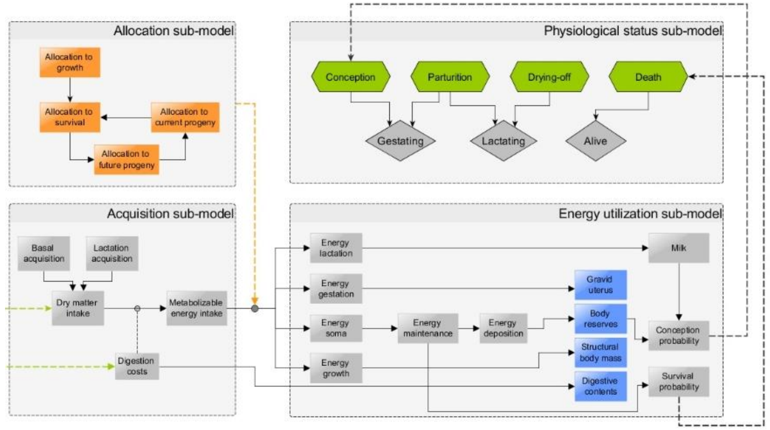
Potential limitation of acquisition

Dry matter offer (kg/d)

Energy content (ME/kg DM)



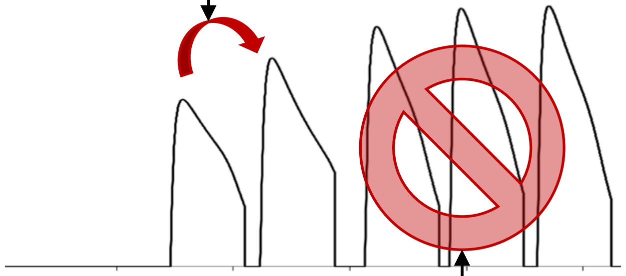
Animal



Changes in physiological stages

$P_{conception} = f(MY, BCS, EB)$

Reproduction management



$P_{death} = f(\text{cover maintenance})$

Culling rules

Thanks for your attention and let's move to the *in silico* part of the lecture!

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Grant Agreement n°772787