NTNU

Norwegian University of Science and Technology

Modelling, instrumentation and control in Marine Larviculture

Morten Omholt Alver, September 2022

Larvi Symposium

My own involvement

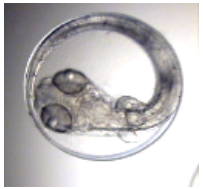
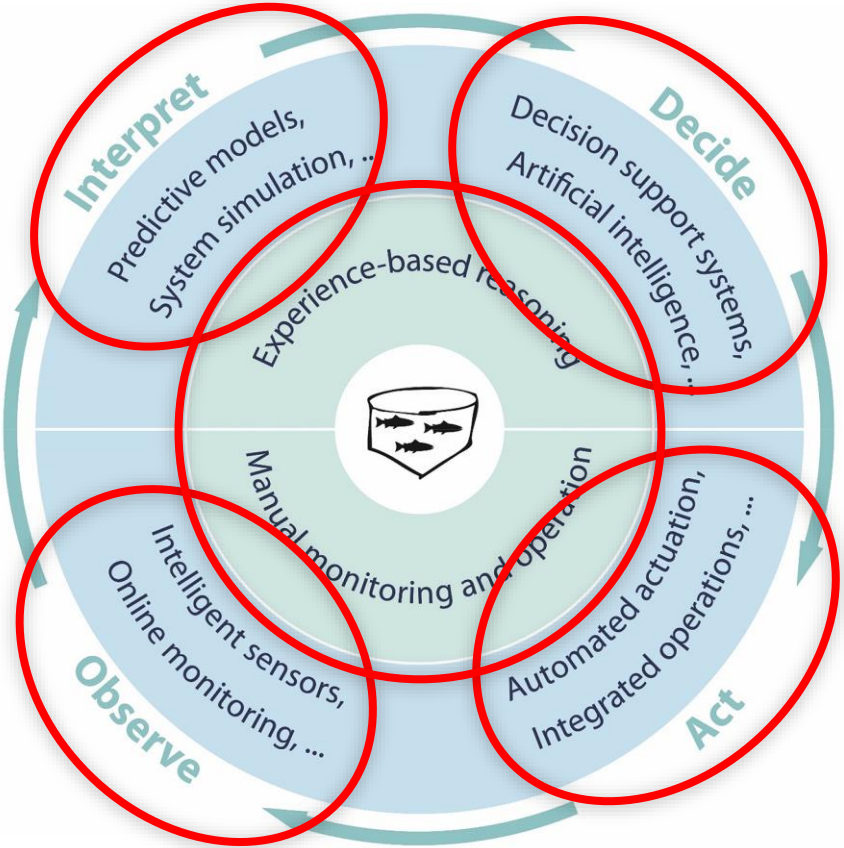


Photo: Tora Bardal

- PhD thesis in Engineering Cybernetics: “Modelling, instrumentation and control in Marine Larviculture” (2007)
- CODTECH project: “A process oriented approach to intensive production of juveniles with emphasis on cod” (2003-2008)
- Postdoc. (2007-2010)
- Contract research (SINTEF, 2009-2018), particularly within instrumentation for production of *Acartia tonsa*
- Last few years, mostly working in other areas

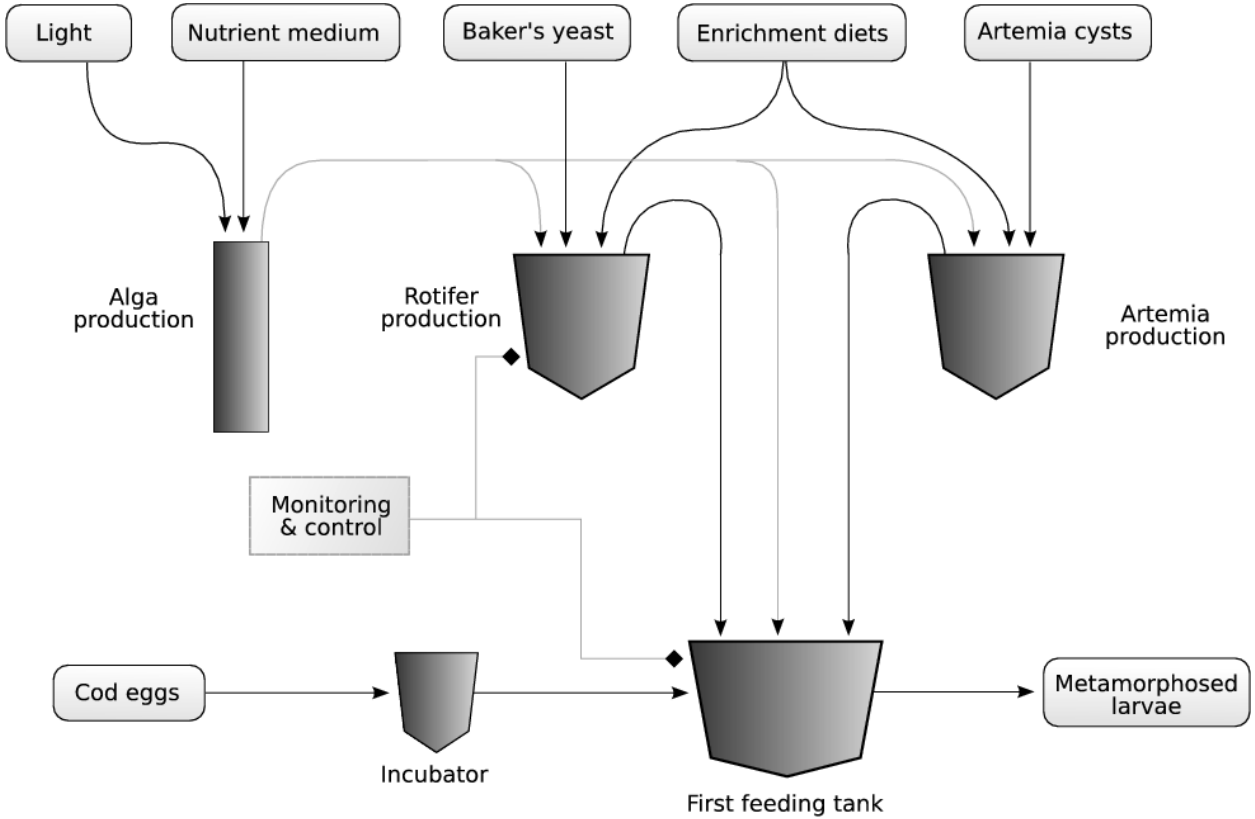
Precision Fish Farming

The PFF concept is useful in describing the components of automating and optimizing fish production



Føre, M. et al., 2018. Precision fish farming: A new framework to improve production in aquaculture. Biosystems engineering, 173, pp.176-193.

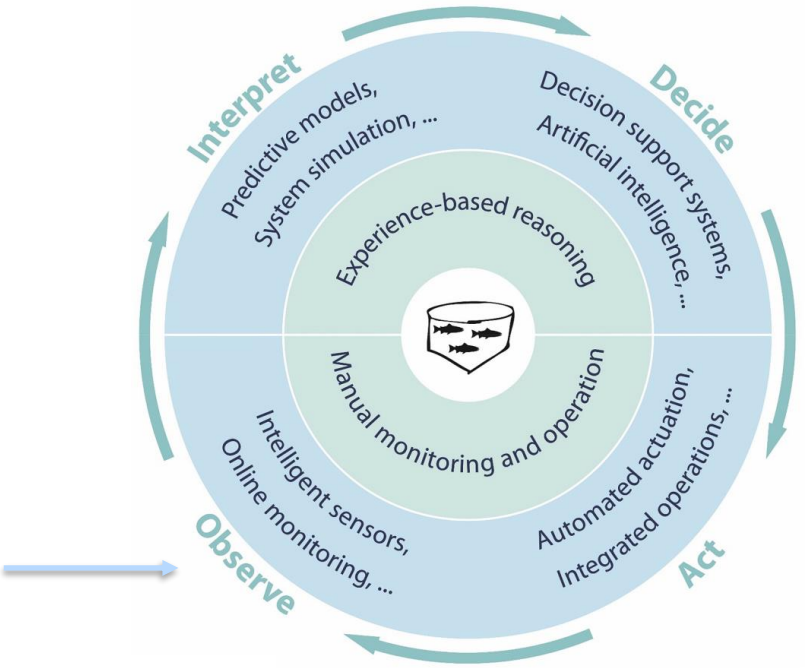
The cod larviculture process



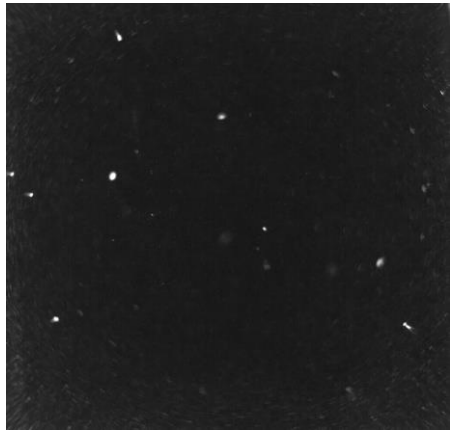
Precision larviculture

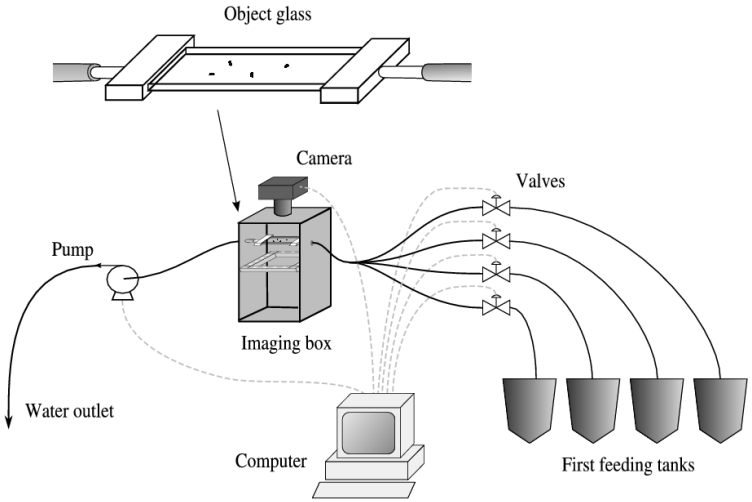
Instrumentation:

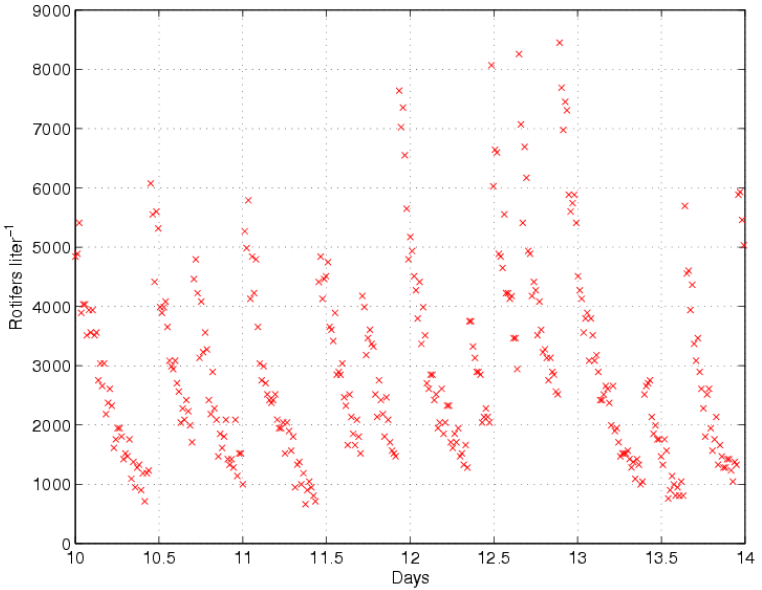
- Fish size / numbers / behaviour
- Feed density / quality
- Water quality
- Biofilter state



Rotifer Density Measurement





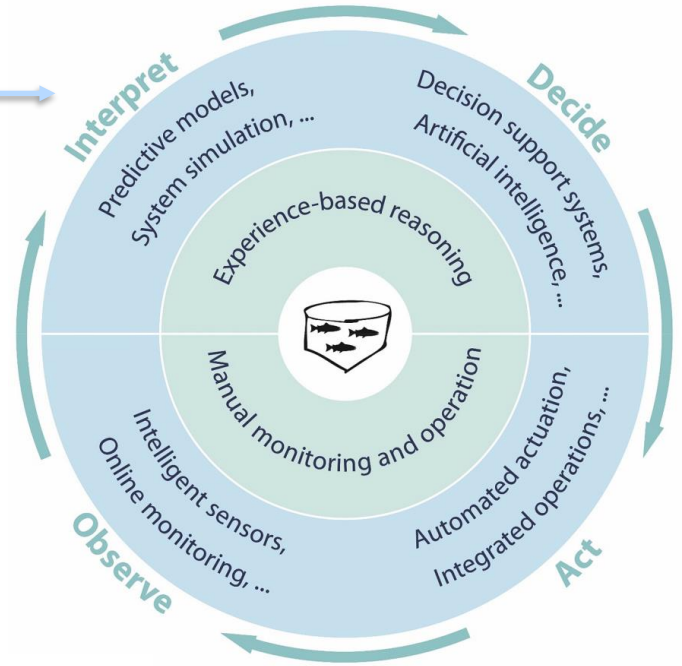


Alver, M.O., Tennøy, T., Alfredsen, J.A. and Øie, G., 2007. Automatic measurement of rotifer Brachionus plicatilis densities in first feeding tanks. Aquacultural Engineering, 36(2), pp.115-121.

Precision larviculture

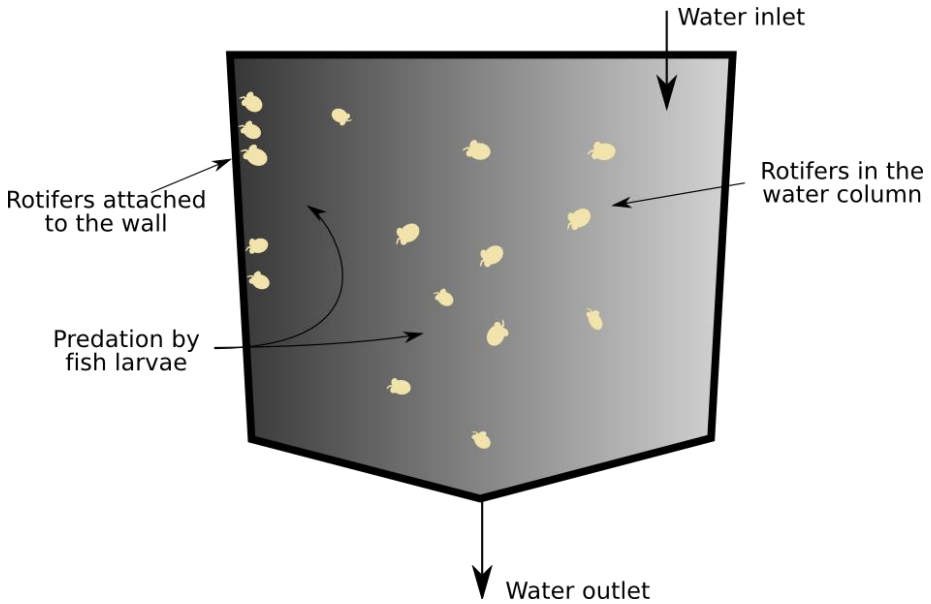
Mathematical models:

- Fish growth / behaviour
- Feed density / utilization / loss
- Water quality
- Biofilter dynamics



Modelling Rotifers in Larval First Feeding Tanks

- **Low temperature** and **short residence** time
- The dominant factors are **feeding**, **predation** by fish larvae and **dilution** due to water exchange



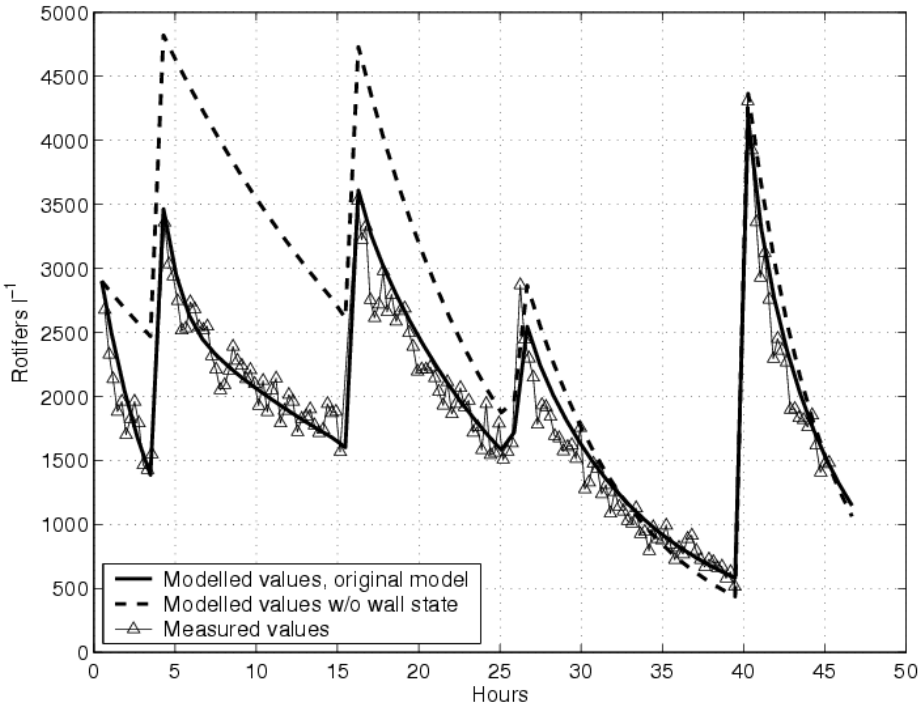
Model Equations

- N_c : The number of rotifers in the water column.
- N_w : The number of rotifers attached to the tank wall.
- E_c : The number of eggs carried by rotifers in the water column.
- E_w : The number of eggs carried by rotifers attached to the tank wall.

$$
\begin{aligned}
\frac{dN_c}{dt} &= u + (E_c + E_w)h_e - M_w + M_c - p_c - q_c \\
\frac{dN_w}{dt} &= M_w - M_c - p_w \\
\frac{dE_c}{dt} &= ue_u - E_c h_e - \frac{E_c}{N_c}(M_w + p_c + q_c) + \frac{E_w}{N_w}M_c \\
\frac{dE_w}{dt} &= -E_w h_e + \frac{E_c}{N_c}M_w - \frac{E_w}{N_w}(M_c + p_w)
\end{aligned}
$$

Example

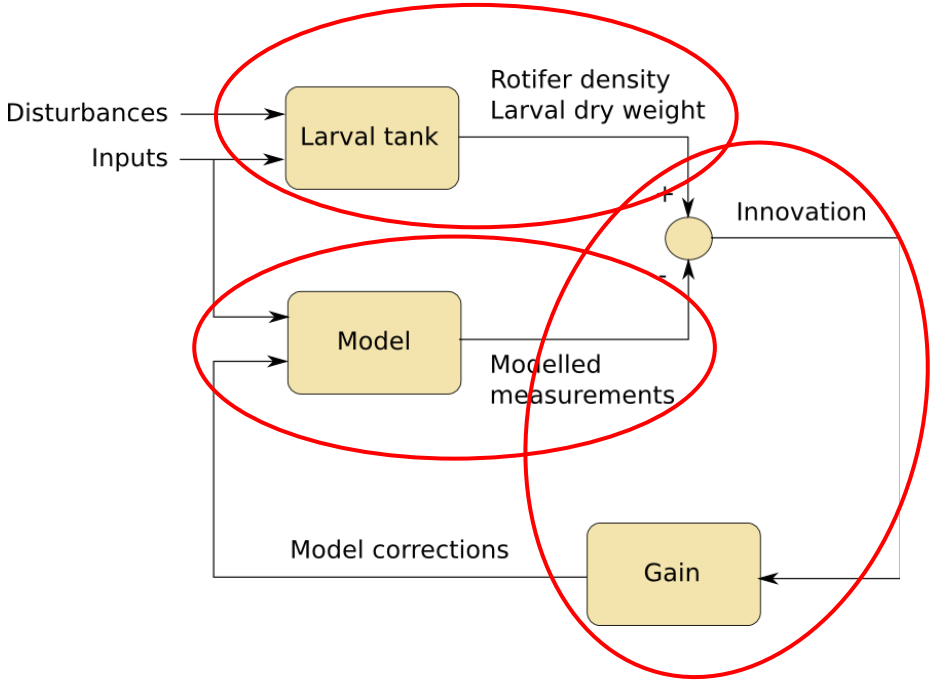
Comparison of model with and without including rotifers attached to the tank wall:



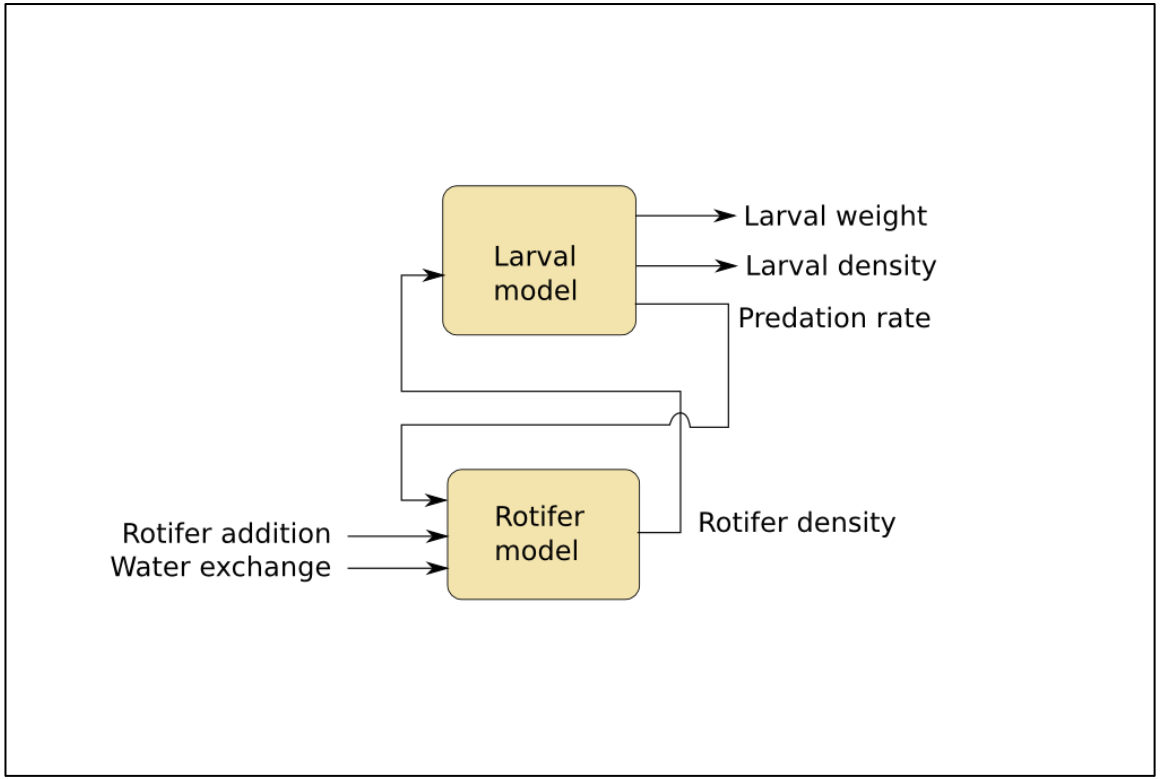
Estimating larval density

Larval density (or mortality) is hard to measure directly

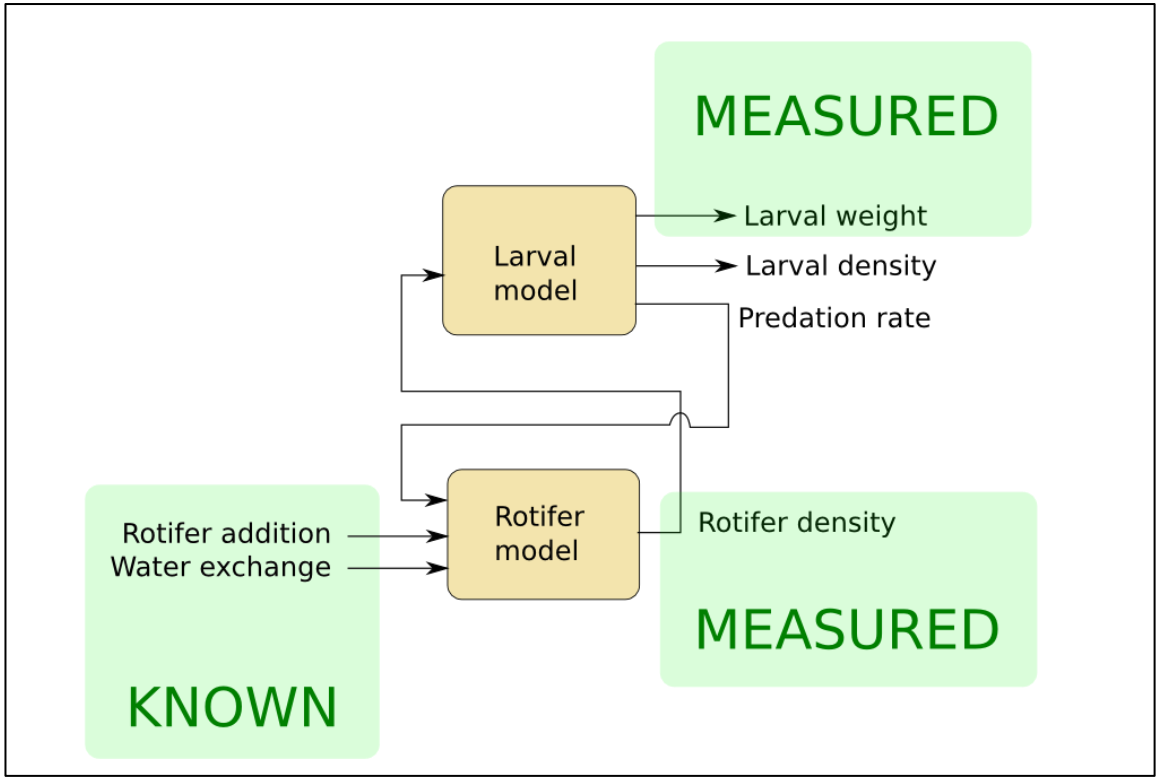
We can produce an estimate by combining a model with measurements:



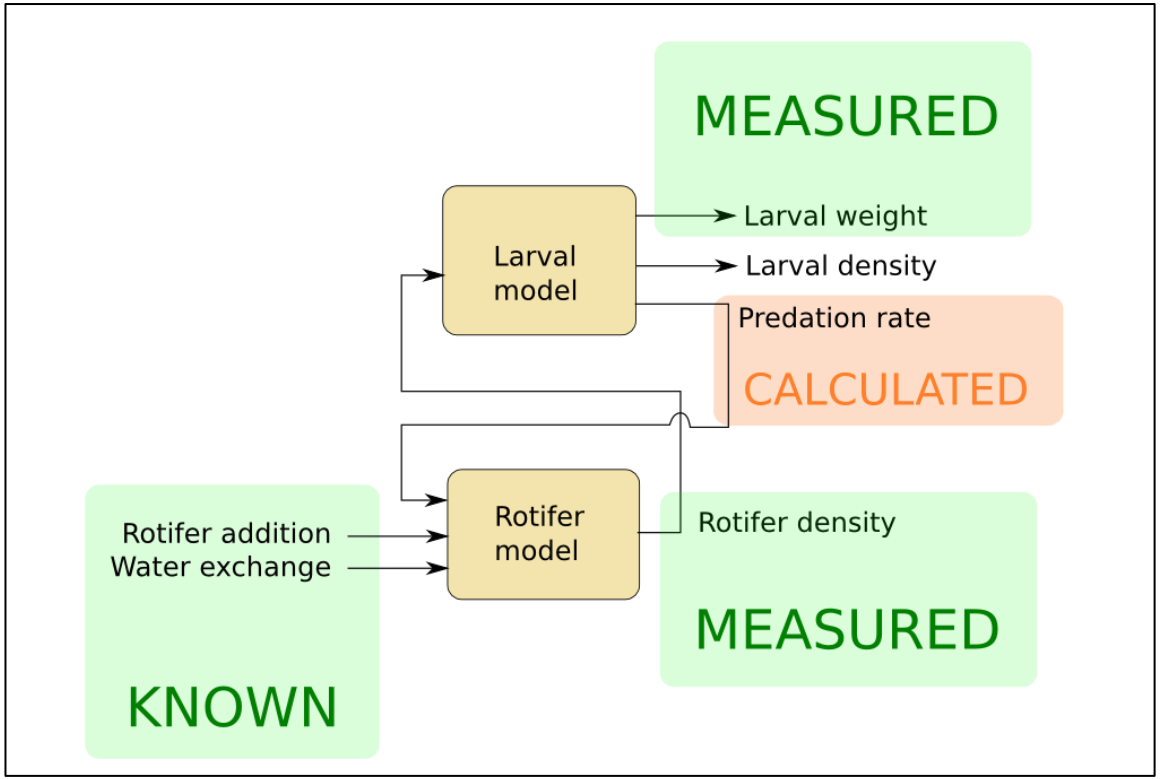
Model Based Estimation



Model Based Estimation



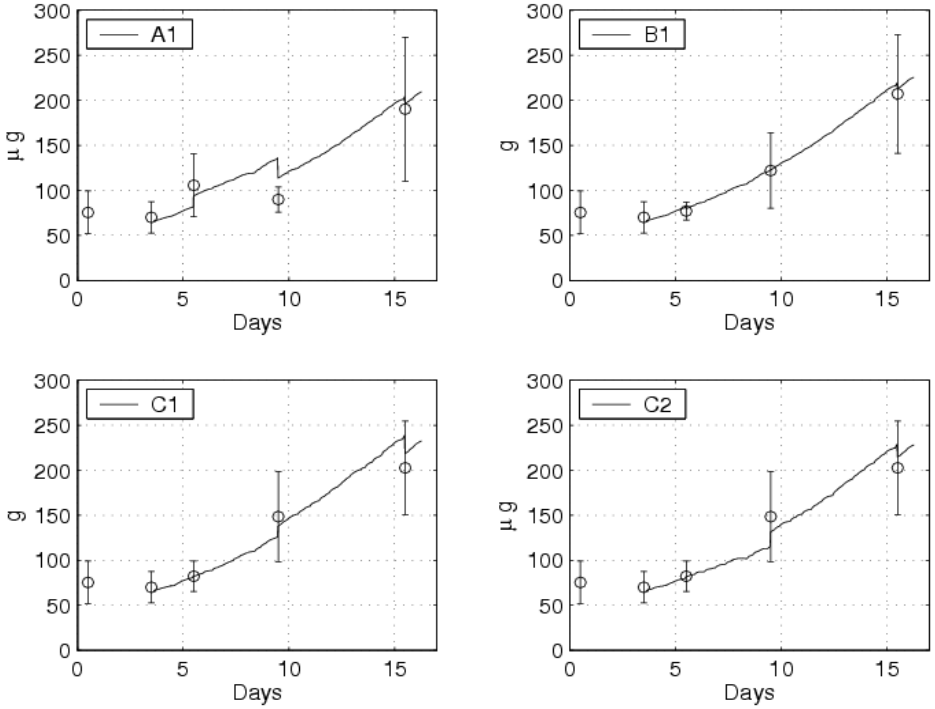
Model Based Estimation



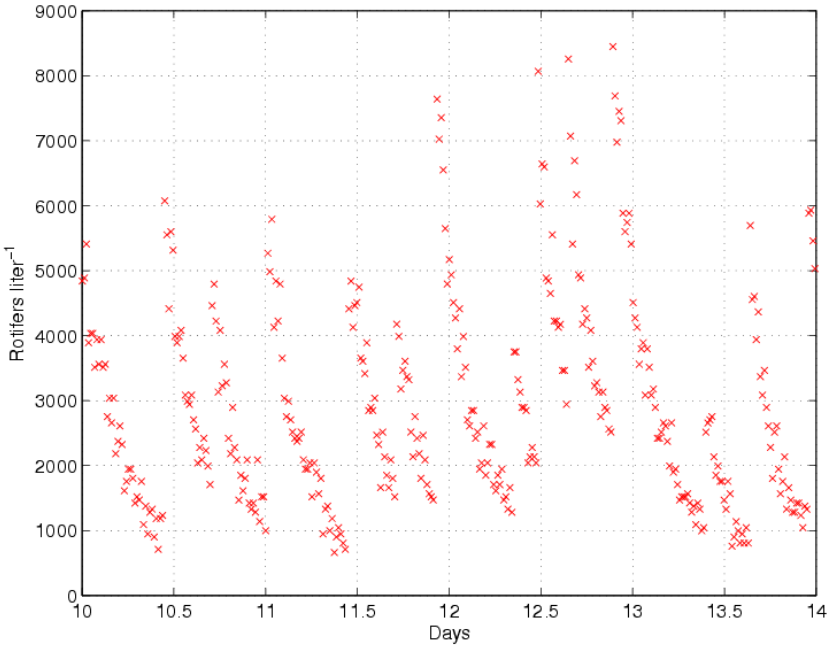
Start Feeding Experiment

- 9 tanks divided into 3 groups:
  - A: 20 larvae/l
  - B: 40 larvae/l
  - C: 80 larvae/l
- Rotifer density monitored in tanks A1, B1, C1 and C2
- Surviving larvae counted on day 16
- Dry weight measured on days 0, 3, 5, 9 and 15

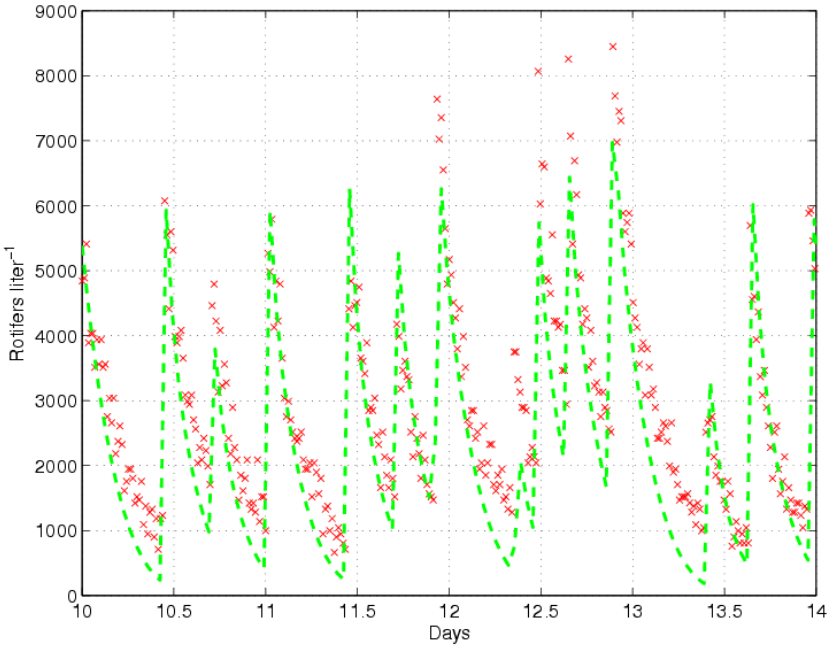
Larval Dry Weight



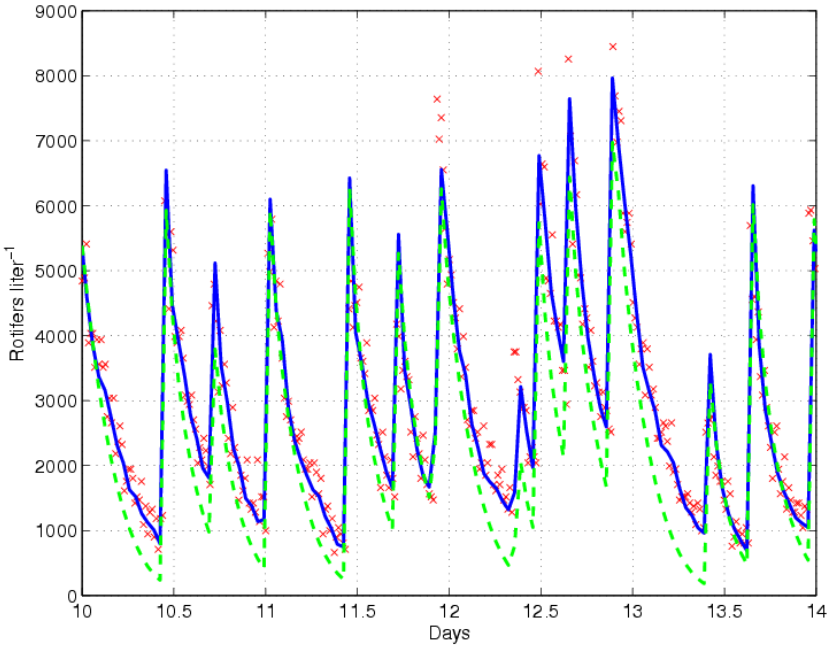
Rotifer Density



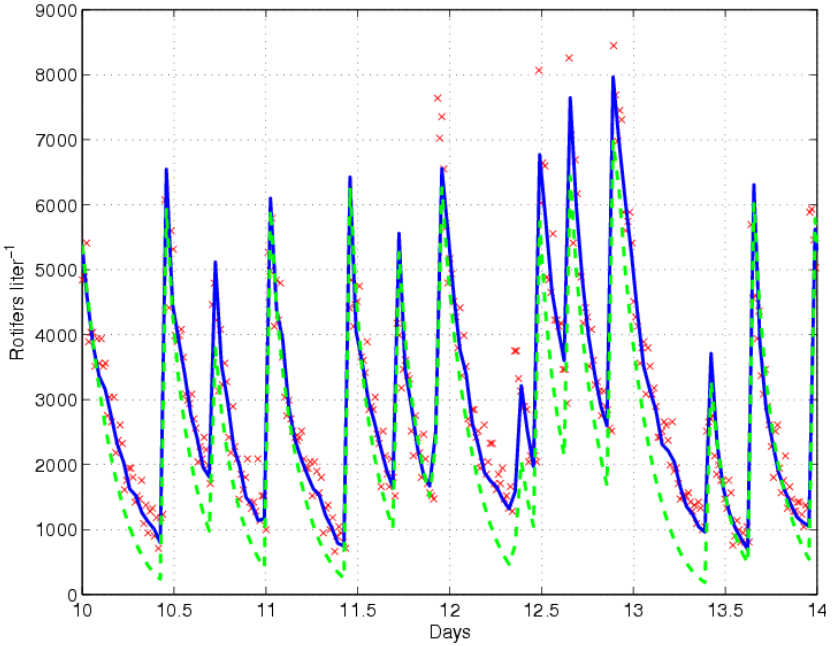
Rotifer Density

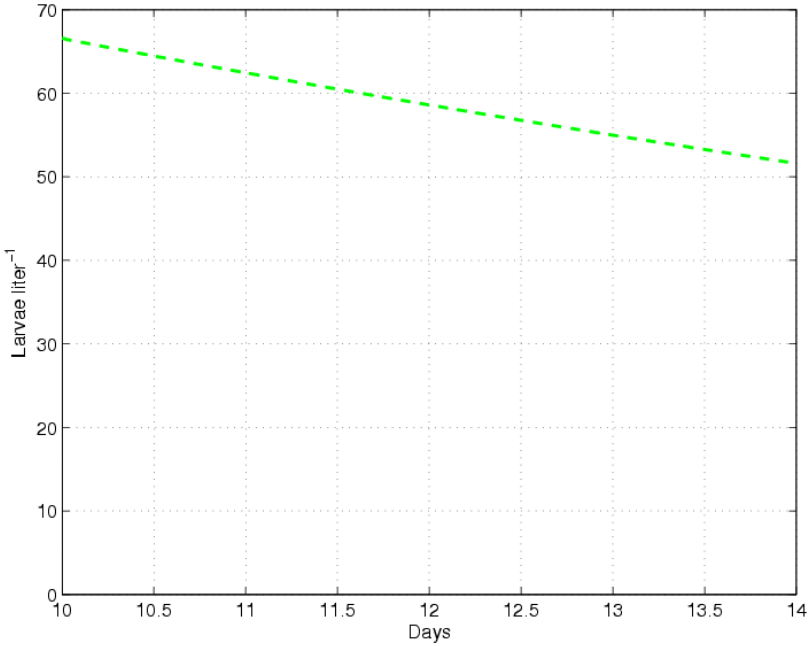


Rotifer Density

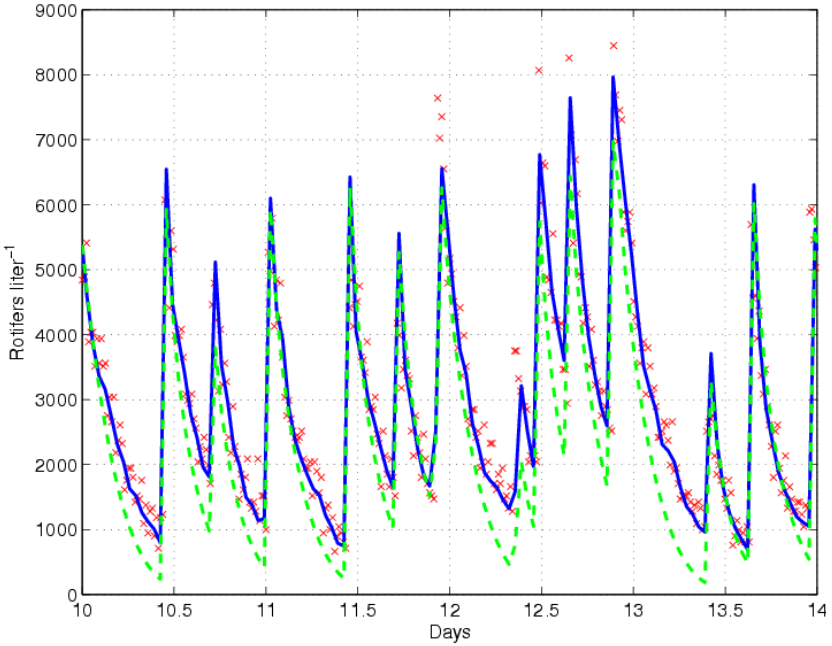


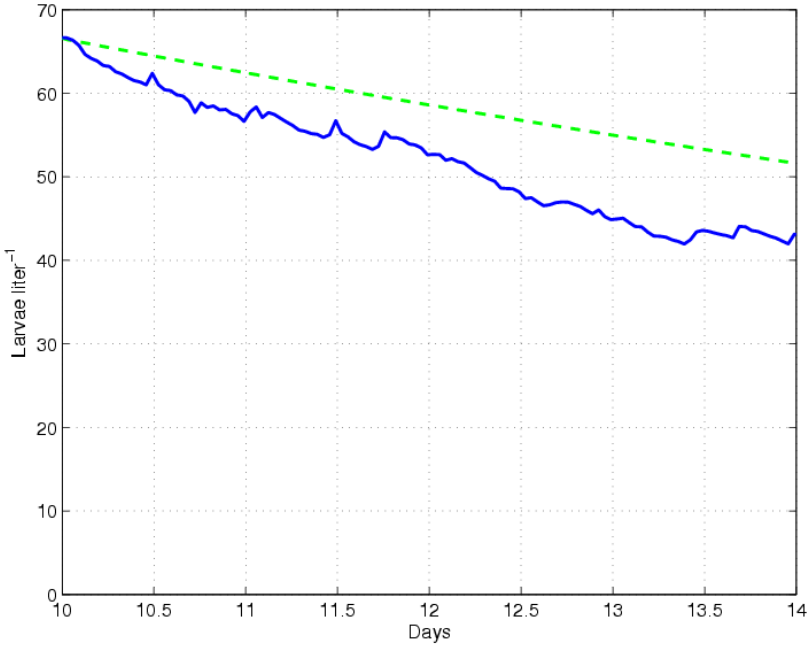
Estimated Larval Density



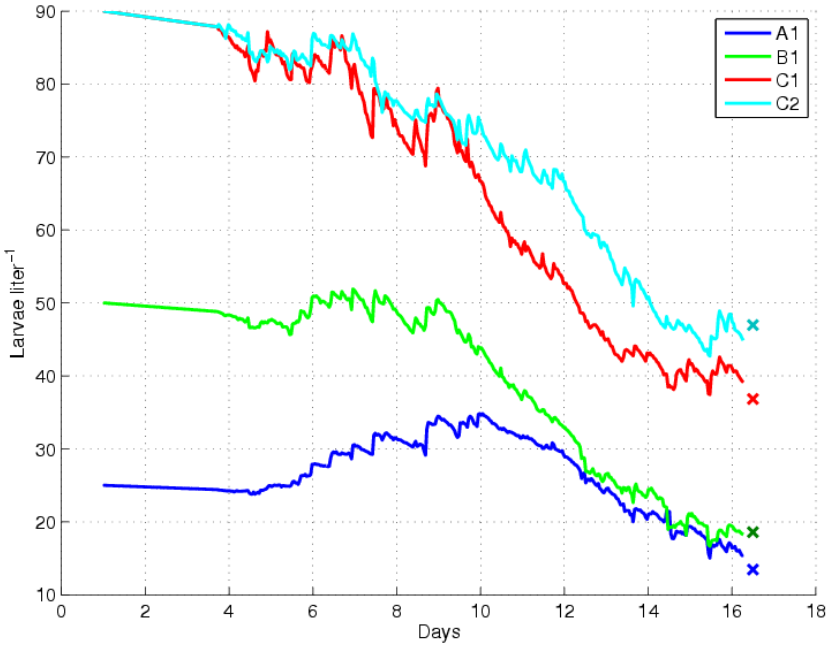


Estimated Larval Density

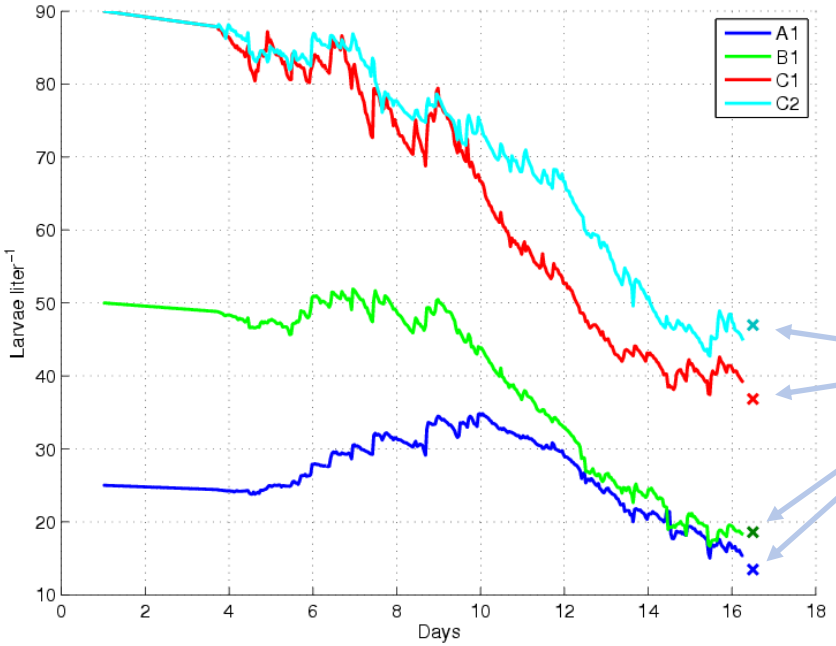




Estimated Larval Density

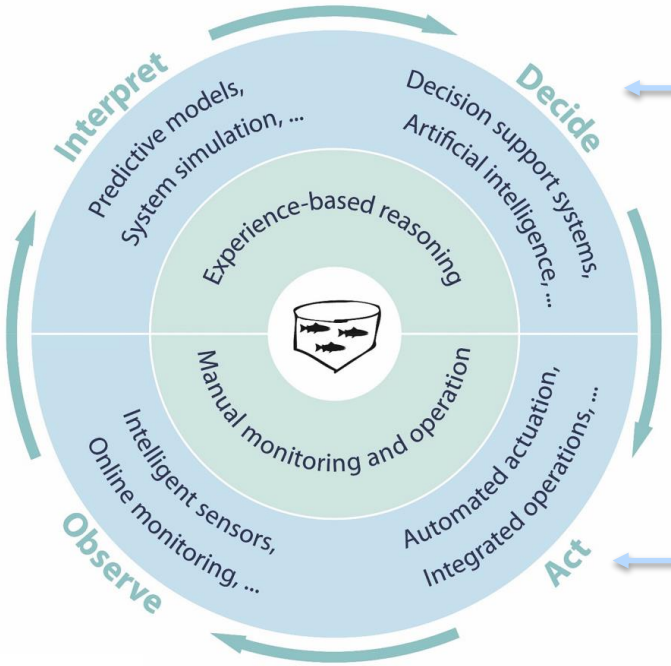


Estimated Larval Density



Final counts

Precision larviculture



Control algorithms:

- Automatic feeding
- Gas and water supply
- Biofilter control

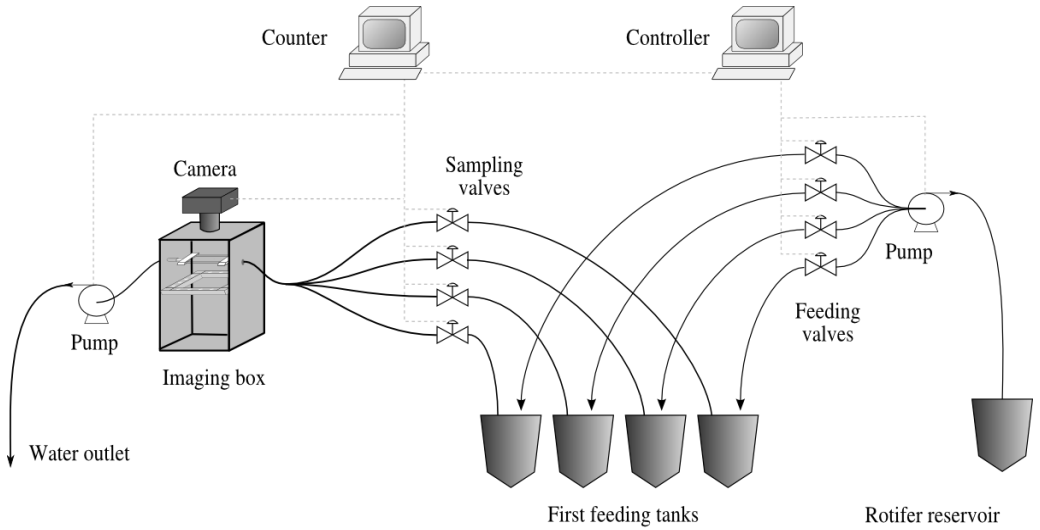
Actuators:

- Feeding robots
- Valves and pumps

Rotifer Controller

To ensure continuously high feed densities, we can add a controller for «apetite feeding»

Aim: keep the rotifer density at a given reference level



System Model

System model:

$$\dot{R}(t) = u(t) - q(t)R(t) - I(t) + v_D(t)$$
$$\dot{I}(t) = v_I(t)$$

$$\dot{x} = f(x,u) + I_2 v$$

$$f(x,u) = \begin{bmatrix} 1 \\ 0 \end{bmatrix} u + Ax$$

$$A = \begin{bmatrix} -q(t) & -1 \\ 0 & 0 \end{bmatrix}$$

Observable

Measurement model:

$$y(t) = R(t) + w(t) = Dx(t) + w(t)$$
$$\text{where } D = [1 \quad 0]$$

Control Algorithm

1. Simple model of rotifer density and ingestion rate
2. Noisy measurements of rotifer density are *Kalman filtered* to:
    1. Get more reliable estimate of the true density
    2. Estimate the ingestion rate in real time
3. Controller pumps enough rotifers to:
    1. Compensate for estimated ingestion rate
    2. Compensate for expected loss
    3. Compensate if density is too low

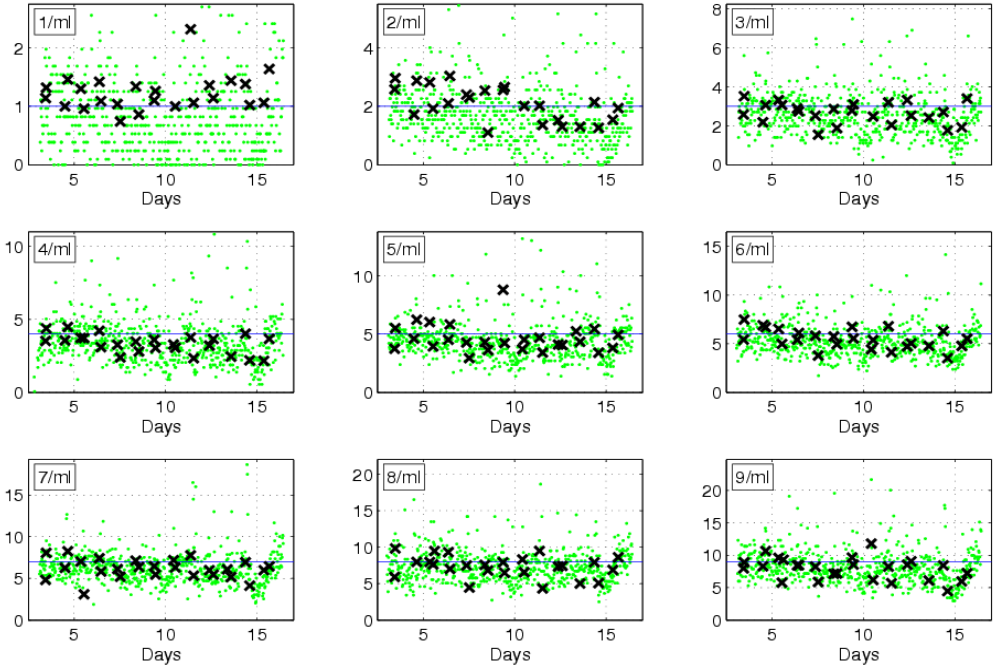
$$\dot{R}(t) = u(t) - q(t)R(t) - I(t) + v_D(t)$$
$$\dot{I}(t) = v_I(t)$$

$$u(t) = max\left(0, \left[\hat{I}(t) + (q(t) + K_p)r(t) - K_p\hat{R}(t) + h(t)\right]\right)$$

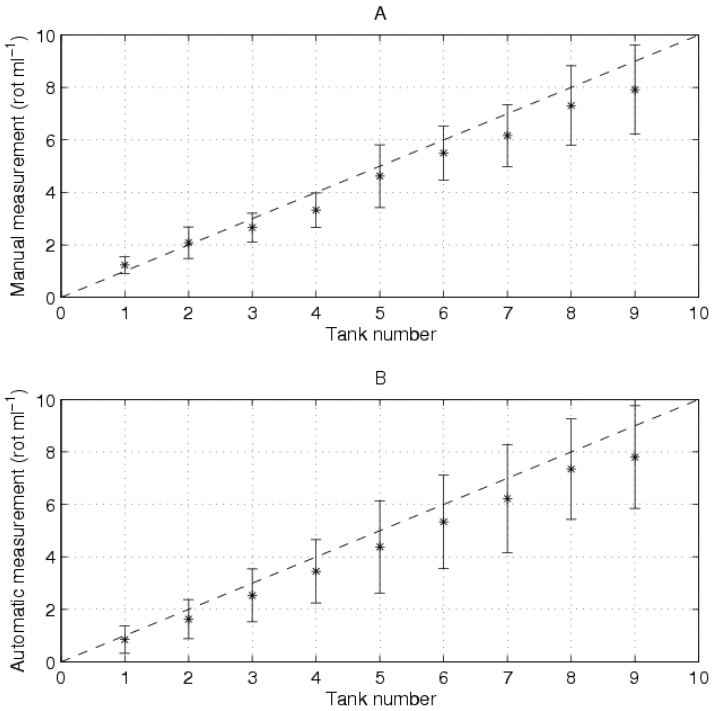
Start Feeding Experiment

- 9 tanks
  - Gradient of rotifer density setpoint 1-9 rotifers/ml
- Rotifer density measured manually 2 times per day
- Surviving larvae counted on day 16
- Dry weight measured on days 0, 5, 10 and 16

Results



Results


A
Manual measurement (rot ml^{-1})
Tank number
B
Automatic measurement (rot ml^{-1})
Tank number

Controlling rotifer cultures

Rotifer cultures have interesting dynamics:

- Age and ingestion rate affects egg rate
- Egg rate affects culture growth
- Dilution/harvesting rate counters growth

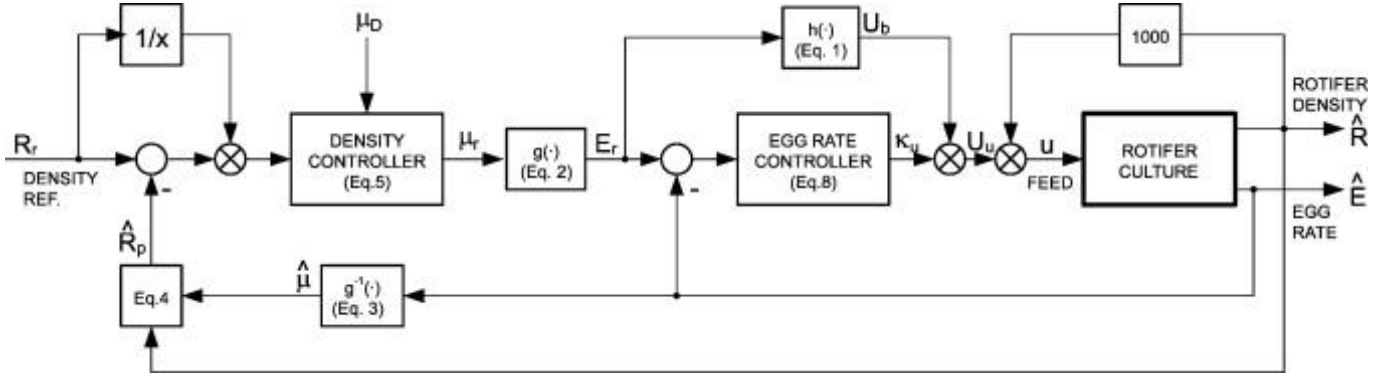
By measuring density and egg rate, can we control feeding rate to achieve:

- Fast growth to a reference density…
- … then stable density around reference?

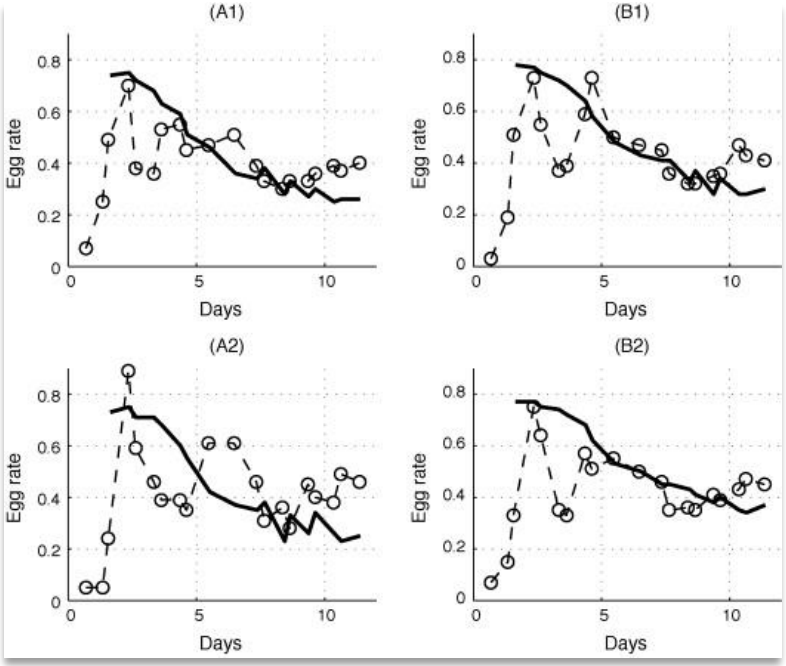
Controlling rotifer cultures

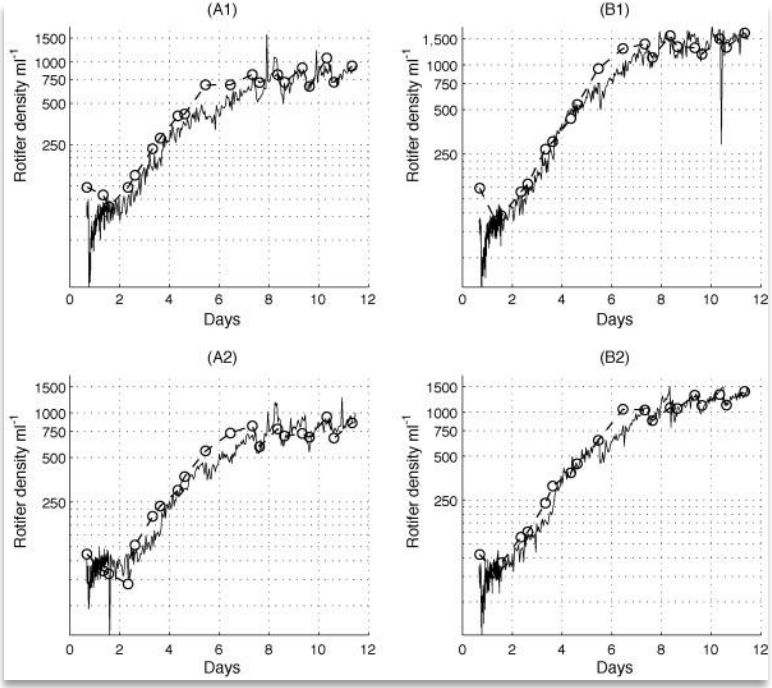
Controller concept: «Cascade control»

- «Inner controller» regulates feeding rate, seeking to control egg rate towards reference value
- «Outer controller»



Controlling rotifer cultures





What happened?

After CODTECH – not a lot in the area of Precision Fish Farming?

My own impression:

- Academically: few citations, hard to fund projects within this area
- Industry: generally very small uptake of automation techniques

Why?

On the academic side:

- Maybe we didn’t communicate our work well enough…
- … or there were too few people working with similar methods and aims
- There were many control engineers, many aquaculture biologists, but few in the cross-diciplinary field in between

Why?

For industry, the main reason is probably the innovation step:

- Academic prototypes are not directly useful for the industry (labour intensive / poorly documented / built for small scales)
  - If we test prematurely in industry, it can backfire!
- Innovative equipment industry is required to transform these into products
- The industry must be ready: the disconnect between today's technology and «the new stuff» must not be too great
- Timing: it's easier if the industry is profitable and growing
  - Cod farming in Norway was not doing well in 2005-2010 (diseases, escapes and overall too high expenses were contributing factors)

Moving forward

The prerequisites for moving forward are better today:

- The number of control engineers working in the aquaculture field is much larger
- Machine vision (and video) based instrumentation is much easier and cheaper
- Precision Fish Farming is a known concept
- «Digital twins» is one of the current buzzwords

However: to put these forces into work on marine larviculture, the industry needs to want it and be willing to invest!