Drivers of Diel Vertical Migration in a Changing Climate

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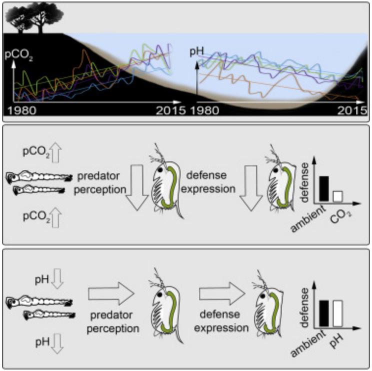
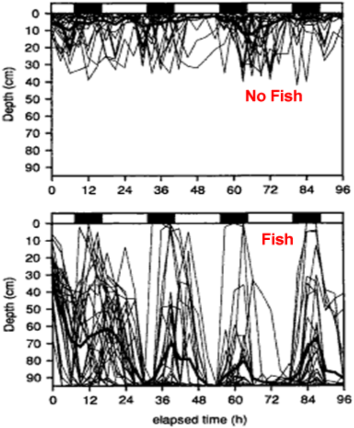
Migration dynamics of *Daphnia pulex*

- *Daphnia pulex* (commonly known as waterflea) is a freshwater crustacean species that lives in lakes.
- Top-bottom migration dynamics.
  - Shallow waters are richer in algae (food source).
  - *Daphnia* are more exposed to predators in shallow waters.
- Migration triggers.
  - Ultraviolet (UV) light.
  - Chemical cues emitted by predators.

Migration dynamics of *Daphnia pulex*





Climate change and *Daphnia* migration dynamics

- Climate change is altering rainfall patterns all across the globe.
- Rainy days are associated with cloudy days.
- The center of biomass of *Daphnia* is:
  - ⋆ Closer to the surface in cloudy days.
  - ⋆ Closer to the bottom in sunny days.

Questions of interest

- Is climate change disrupting *Daphnia* migration dynamics?
- How do different levels of UV light intensity and fear of predation affect *Daphnia* migration dynamics?

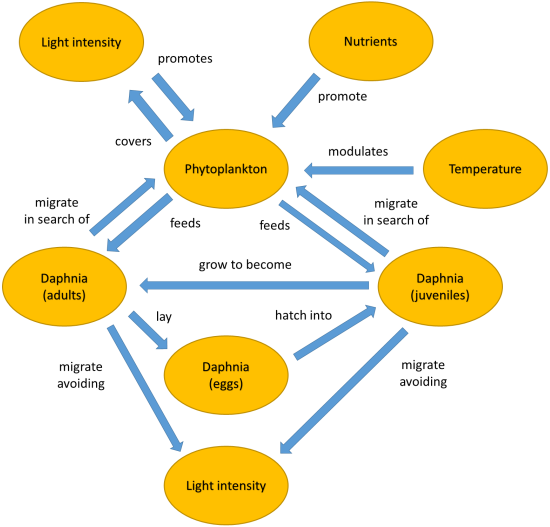
A case study

- A Membrane Computing model on the migration dynamics of *Daphnia pulex* is proposed.
- Spatially-explicit, 2D (depth $\times$ width) model.
- Based on data from The Jefferson Project at Lake George, NY, USA.

Model description

- An accurate model of this ecological system must represent continuous and discrete quantities.
  - ⋆ Membranes represent regions in the lake.
  - ⋆ Objects represent *Daphnia*.
  - ⋆ Phenomena affecting continuous quantities are captured using discrete-time finite difference equations.

Model description



Lake morphology

- A cross-section of the lake is modeled as a 2D (depth $\times$ width) membrane grid.
- Lake depth varies across regions $\implies$ The number of membranes in each column varies.

Algae growth

- UV light intensity is attenuated by water turbidity and algae abundance $\implies$ UV light is less intense at greater depths.
  - $\star$ $Lim_{Light}(z,t) =$
  $$Lim_{Light} \times (I(0,x,t) - \frac{I(z,x,t))}{(Att(z,x,t) \times z_{max})}$$
- UV light intensity promotes algae abundance, and low nutrient concentration (P and C) limits algae abundance.
  - $\star$ $[Ph(Conc_{z,x})]_{z,x} \rightarrow [Ph(Conc_{z,x} + Photo(z,x,t) - PhMort(z,x,t) - \sum_i num_{i,t} \times Conc_{z,x} \times gr)]_{z,x}$
  - $\star$ $Photo(z,x,t) = Lim_{Nut}(z,t) \times Lim_{Light}(z,x,t) \times Ph(Conc_{z,x})$

Nutrient concentration

- Nutrient concentration is larger at greater depths.
  - $\star$ $Lim_{Nut}(z,t) = NutLim_a \times Conc_{Nut}(t)/(NutLim_b + Conc_{Nut}(t))$

Daphnia mortality

- *Daphnia* can die of different causes:
  - ⋆ Natural mortality
  - ⋆ Starvation
  - ⋆ Predation

- Changes in *Daphnia* weight are modeled as follows:
  - ⋆ $num_{i,t+1} = num_{i,t} - Mort(num_{i,t})$
  - ⋆ $somat_{i,t+1} = somat_{i,t} - \frac{somat_{i,t}}{Mort(num_{i,t})} + num_{i,t+1} \times Conc_{z,x} \times gr \times (1 - GonProp(somat_{i,t} + gonad_{i,t}))$
  - ⋆ $gonad_{i,t+1} = gonad_{i,t} - \frac{gonad_{i,t}}{Mort(num_{i,t})} + num_{i,t+1} \times Conc_{z,x} \times gr \times GonProp(somat_{i,t} + gonad_{i,t})$

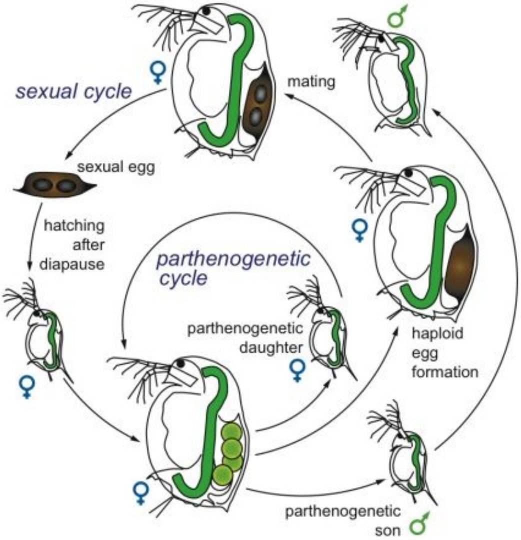
Daphnia abundance update and reproduction

- The number of *Daphnia* and the group weights are updated:
  - ⋆ $[D_{s,num_{i,t},somat_{i,t},gonad_{i,t}}]_{z,x} \rightarrow [D_{s,num_{i,t+1},somat_{i,t+1},gonad_{i,t+1}}]_{z,x}$
- Adults lay eggs proportionally to gonad weight.
  - ⋆ $[D_{A,num_{i,t},somat_{i,t},gonad_{i,t}}]_{z,x} \rightarrow [D_{A,num_{i,t},somat_{i,t},gonad_{i,t}-gonad_{i,t+1}//(eggw \times eggn)}, Egg_{0,eggn}]_{z,x}$

Eggs incubate for a given time and hatch

- Eggs incubate and hatch at time H:
  - $[Egg_{t,eggn}]_{z,x} \rightarrow [Egg_{t+1,eggn}]_{z,x}$
  - $[Egg_{H,eggn}]_{z,x} \rightarrow [D_{J_0,eggn,somat_{0,t},0}]_{z,x}$
- Juveniles develop as egg-laying adults.
  - $[D_{J_s,num,somat_{i,t},0}]_{z,x} \rightarrow [D_{J_{s+1},num,somat_{i,t},0}]_{z,x}$
  - $[D_{J_a,num,somat_{i,t},0}]_{z,x} \rightarrow [D_{A,num,somat_{i,t},0}]_{z,x}$

Daphnia lifecycle



Daphnia migration dynamics

- *Daphnia* groups explore their vicinity $diff_z, diff_x$.
- *Daphnia* hide from predators in deep, dark waters.
- *Daphnia* migrate to shallow waters where the algae abundance is larger.

Daphnia migration dynamics

- $$[D_{s,num_{i,t},somat_{i,t},gonad_{i,t}}]_{z,x} \xrightarrow{mprob} [D_{s,num_{i,t+1},somat_{i,t+1},gonad_{i,t+1}}]_{z',x'}$$
- $z - diff_z, \ldots, z', \ldots, z + diff_z$ and $x - diff_x, \ldots, x', \ldots, x + diff_x$
- $mprob = \exp(-\log(0.5) \times (Conc(z', x') - Conc(z, x))/ConcExpDiff)$
- Neighboring regions are excluded if risk of predation $> PRP_{\text{max}}$ and UV light intensity $> I_{\text{max tolerable}}$

System simulation

- The model was simulated for 2 years at a time scale of 1 hour and space scale of 1 meter under different cloud cover and fear of predation scenarios.

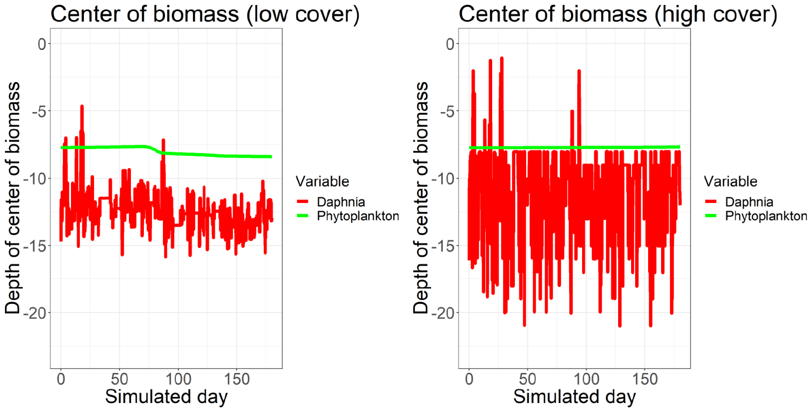
  - ⋆ UV light is brighter during daytime and dimmer during nighttime.

  - ⋆ UV light is dimmer in winter and autumn.

Simulation results

- A large proportion of cloudy days (low UV light intensity) increases *Daphnia* migration towards the water surface.
  - ⋆ Greater exposure to predators.

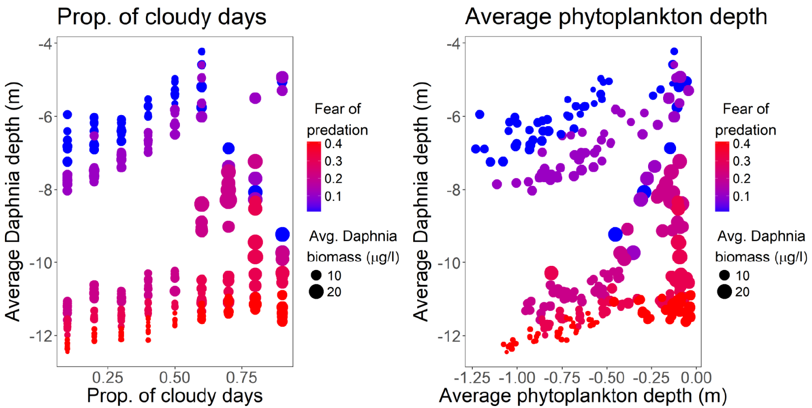
Center of biomass of *Daphnia* and algae



Simulation results

- *Daphnia* abundance is larger in scenarios where the center of biomass tends towards deep waters.
  - ⋆ Biomass gain in shallow waters due to algae abundance and greater grazing is not compensated by predation.
- Fear of predation has a larger effect on *Daphnia* abundance than proportion of cloudy days.

Effect of the proportion of cloudy days and fear of predation on *Daphnia* biomass



Future work

- Predation is modeled as a depth-dependent parameter.
  - ⋆ It is larger in shallow waters and decays exponentially with depth.
- Need for explicit predator dynamics $\Longrightarrow$ Include predators as a (meta) species in the system.
- Water circulation plays an important role in re-distributing algae and nutrients in lake ecosystems.
  - ⋆ Include water circulation.
  - ⋆ Need for 3D dynamics $\Longrightarrow$ 3D model.

Thank you!