Drivers of Diel Vertical Migration in a Changing Climate

Manuel García–Quismondo

Icahn School of Medicine at Mount Sinai

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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*

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No Fish

Fish
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 × width) model.

- Based on data from The Jefferson Project at Lake George, NY, USA.
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.
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 \( \Rightarrow \) UV light is less intense at greater depths.
  \[ \star \quad \text{Lim}_{\text{Light}}(z, t) = \]
  \[ \text{Lim}_{\text{Light}} \times (I(0, x, t) - \frac{I(z, x, t))}{(\text{Att}(z, x, t) \times z_{\text{max}})} \]

- UV light intensity promotes algae abundance, and low nutrient concentration (\( P \) and \( C \)) limits algae abundance.
  \[ \star \quad [\text{Ph}(\text{Conc}_{z,x})]_{z,x} \rightarrow [\text{Ph}(\text{Conc}_{z,x} + \text{Photo}(z, x, t) - \text{PhMort}(z, x, t) - \sum_i \text{num}_{i,t} \times \text{Conc}_{z,x} \times \text{gr})]_{z,x} \]
  \[ \star \quad \text{Photo}(z, x, t) = \]
  \[ \text{Lim}_{\text{Nut}}(z, t) \times \text{Lim}_{\text{Light}}(z, x, t) \times \text{Ph}(\text{Conc}_{z,x}) \]
Nutrient concentration is larger at greater depths.

\[
\text{Lim}_{\text{Nut}}(z, t) = \frac{\text{NutLim}_a \times \text{Conc}_{\text{Nut}}(t)}{\text{NutLim}_b + \text{Conc}_{\text{Nut}}(t)}
\]
Daphnia mortality

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

- Changes in Daphnia weight are modeled as follows:
  * \( num_{i,t+1} = num_{i,t} - \text{Mort}(num_{i,t}) \)

  \[
  \begin{align*}
  \text{somat}_{i,t+1} &= \text{somat}_{i,t} - \frac{\text{somat}_{i,t}}{\text{Mort}(num_{i,t})} + num_{i,t+1} \times \\
  & \quad \text{Conc}_{z,x} \times gr \times (1 - \text{GonProp}(\text{somat}_{i,t} + \text{gonad}_{i,t}))
  \end{align*}
  \]

  \[
  \begin{align*}
  \text{gonad}_{i,t+1} &= \text{gonad}_{i,t} - \frac{\text{gonad}_{i,t}}{\text{Mort}(num_{i,t})} + num_{i,t+1} \times \\
  & \quad \text{Conc}_{z,x} \times gr \times \text{GonProp}(\text{somat}_{i,t} + \text{gonad}_{i,t})
  \end{align*}
  \]
The number of \textit{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.

\[ D_{A, num_{i,t}, somat_{i,t}, gonad_{i,t}} z, x \rightarrow D_{A, num_{i,t}, somat_{i,t}, gonad_{i,t} - gonad_{i,t+1}/(eggw \times eggn), Egg0, eggn} z, x \]
Eggs incubate for a given time and hatch

- Eggs incubate and hatch at time $H$:
  - $[\text{Egg}_t, \text{eggn}]_{z,x} \rightarrow [\text{Egg}_{t+1}, \text{eggn}]_{z,x}$
  - $[\text{Egg}_H, \text{eggn}]_{z,x} \rightarrow [\text{D}_0, \text{eggn}, \text{somat}_{0,t}, 0]_{z,x}$

- Juveniles develop as egg-laying adults.
  - $[\text{D}_s, \text{num}, \text{somat}_i, t, 0]_{z,x} \rightarrow [\text{D}_{s+1}, \text{num}, \text{somat}_i, t, 0]_{z,x}$
  - $[\text{D}_a, \text{num}, \text{somat}_i, t, 0]_{z,x} \rightarrow [\text{D}_A, \text{num}, \text{somat}_i, t, 0]_{z,x}$
Daphnia lifecycle

sexual cycle

sexual egg

mating

hatching after diapause

parthenogenetic cycle

parthenogenetic daughter

haploid egg formation

parthenogenetic son
Daphnia migration dynamics

- *Daphnia* groups explore their vicinity $\text{diff}_z, \text{diff}_x$.
- *Daphnia* hide from predators in deep, dark waters.
- *Daphnia* migrate to shallow waters where the algae abundance is larger.
Daphnia migration dynamics

\[
[D_{s, \text{num}_i, t, \text{somat}_i, t, \text{gonad}_i, t}] z, x \xrightarrow{mprob} [D_{s, \text{num}_i, t+1, \text{somat}_i, t+1, \text{gonad}_i, t+1}] z', x'
\]

- \(z - \text{diff}_z, \ldots, z', \ldots, z + \text{diff}_z\) and
- \(x - \text{diff}_x, \ldots, x', \ldots, x + \text{diff}_x\)

\[
mprob = \exp(-\log(0.5) \times (\text{Conc}(z', x') - \text{Conc}(z, x)) / \text{ConcExpDiff})
\]

- Neighboring regions are excluded if risk of predation \(\text{PRP}_{\text{max}}\) and UV light intensity \(I_{\text{max}}\) tolerable
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

**Center of biomass (low cover)**

**Center of biomass (high cover)**

- **Variable**
  - Daphnia
  - Phytoplankton

- **Depth of center of biomass**

- **Simulated day**

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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

![Graphs showing the relationship between the proportion of cloudy days, average phytoplankton depth, and average Daphnia biomass.](image)
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 $\implies$ 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 $\implies$ 3D model.
Thank you!