Short Term Effects of Acid Precipitation on a Three Species Aquatic Ecosystem

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Problem

- 41% of lakes in the Adirondack Mountains are chronically acidic
- Species in these habitats are vulnerable to low pH levels (high acidity)
- Research over the last 30 years has suggested long term trends are responsible for reduction of species’ densities in some of these ecosystems
- Could short term fluctuations in pH cause extinction of these same species?
The Ecosystem

Pumpkinseed Sunfish

Daphnia

Chlorella
Typical Lake in the Adirondacks

- Most lakes in the Adirondack’s that are susceptible to Acidification are Thin Till Drainage Lakes

- Lakes are vertically stratified with two layers: the Epilimnion and Hypolimnion

- Daphnia migrate between the two layers to feed on Chlorella during the night and avoid predation from Sunfish during the day
Predator-Prey Relationship

- **Chlorella Equation:**
  \[
  \frac{dH}{dt} = rH \left(1 - \frac{H}{K_H}\right) - g(H) P_{epl}
  \]

- **Daphnia Equation in Epilimnion**
  \[
  \frac{dP_{epl}}{dt} = e_p g(H) P_{epl} \left(1 - \frac{P_{epl}}{K_P}\right) + \beta P_{hpl} - \alpha P_{epl} - d_p P_{epl} - g(P_{epl}) F
  \]

- **Daphnia Equation in Hypolimnion:**
  \[
  \frac{dP_{hpl}}{dt} = \alpha P_{epl} - \beta P_{hpl} - d_p P_{hpl}
  \]

- **Pumpkinseed Sunfish:**
  \[
  \frac{dF}{dt} = e_F g(P_{epl}) F - d_F F
  \]
Predator-Prey Parameters dependent on pH

- Three parameters from the predator-prey system are dependent on the pH of the lake: the reproduction rate of Chlorella, and the death rate of each of the higher level species.
Stratified Lake Model

- Volume in Epilimnion:
  \[
  \frac{dV_{epl}}{dt} = I + R - \mu - E
  \]

- Volume of Hypolimnion remains constant:
  \[
  \frac{dV_{hpl}}{dt} = 0
  \]

- Hydrogen in Epilimnion:
  \[
  \frac{dA_{epl}}{dt} = 10^{-pH} (I + .2R) - \lambda \left( \frac{A_{epl}}{V_{epl}} - \frac{A_{hpl}}{V_{hpl}} \right) - \mu \frac{A_{epl}}{V_{epl}}
  \]

- Hydrogen in Hypolimnion:
  \[
  \frac{dV_{hpl}}{dt} = \lambda \left( \frac{A_{epl}}{V_{epl}} - \frac{A_{hpl}}{V_{hpl}} \right)
  \]
Continuous Time Markov Chain

- A Markov chain was utilized to determine whether at any given time the weather is in a state of precipitation or non-precipitation.

- 10 years of weather data from Albany International Airport was analyzed to create the initial probability vector.
Discrete Distribution for Rainfall Data

**pH of Rain Distribution**

- pH of Rain: 4, 4.25, 4.5, 4.75, 5, 5.25, 5.5
- Probability: 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35

**Intensity of Rain Distribution**

- Intensity of Rain (inches/hour): 0.01, 0.02, 0.03, 0.04, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1, 1.5, 2, 2.5
- Probability: 0.05, 0.1, 0.15, 0.2, 0.25, 0.3
Runoff (inflow Rate) Function

Below is a plot of the second major source of inflow in the summer months, runoff. If the rainfall rate is below .05 inches per hour, runoff is not a considerable source of water input.

![Runoff Rate vs. Rainfall Rate Graph]

\[ R(l) = 0.618l - 2.784 \quad \text{if } l > .05 \text{ in/hr} \]
\[ R(l) = 0 \quad \text{if } l \leq .05 \text{ in/hr} \]
One Week Sample Simulation

Markov Chain

$pH = -\log_{10}\left(\frac{A}{V}\right)$

Mols of Hydrogen vs. Time

Mols of Hydrogen Epilimnion

pH vs. Time

Volume of Epilimnion vs. Time

Time (Hours)

Time
Solution: Lake pH Dynamics

- 50 simulations were run for a time interval of 3 months
Solution: Ecosystem Behavior

- The optimal pH level of 7 is utilized to determine the dependent parameter values and solve the system deterministically.

- A phase space of this optimal system is to the above right (6 months are shown to display the periodic behavior).

- It is important to note Daphnia’s migration behavior in the plot to the bottom right (every 12 hours the migration rates change).
Solution (continued)

- Using the average pH of each layer of the lake in the 50 stochastic simulations, 5.58 and 5.62, the system was solved deterministically. As documented in long term research: fish are the most vulnerable in such habitats and become sparse.
Solution (continued)

- In 22% of the 50 simulations, Pumpkinseed Sunfish became extinct. Chlorella’s tolerance for higher acidity allowed it to be unaffected by the stochastic simulations. Daphnia, the migrating middle species on average saw a decrease in population density by 26%, but at no point became extinct.
Conclusions

- A more familiar deterministic approach using the average pH yielded outcomes found similar in long term research: sparse fish population in vulnerable environments, yet did not imply extinction.

- Common long term deterministic methods do not capture potential extinction due to short term fluctuations found in the empirical based stochastic model.
Questions?
References


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