Eco-evolutionary dynamics in aquatic communities: From mathematical to organismal models

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OUTLINE

• Preface 1
• Preface 2
• Preface 3
• Preface 4
• Chapter 1: Simple N-P-Z
• Chapter 2: N-P-Z(stage-structured)
• Chapter 3: N-P(genotypes)-Z
• Chapter 4: Z-P-Z(adaptive trait) +ENV
PREFACE 1: Assigned readings

### PREFACE 2: Hierarchy of models and systems

<table>
<thead>
<tr>
<th>MODEL</th>
<th>ENVIRONMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>single species</td>
<td>+</td>
</tr>
<tr>
<td>2 species w/ interaction</td>
<td></td>
</tr>
<tr>
<td>many species community</td>
<td></td>
</tr>
<tr>
<td>local ecosystem</td>
<td></td>
</tr>
<tr>
<td>global ecosystem</td>
<td></td>
</tr>
</tbody>
</table>

**Diagram Explanation:**
- **Model Levels:**
  - Single species
  - 2 species with interaction
  - Many species community
- **Environment Levels:**
  - Local ecosystem
  - Global ecosystem
What I cover

- single species
- 2 species with interaction

MODEL

ENVIRONMENT
“Trophic Interaction, Complexity and Emergence”

Approach to Complexity: 
DECONSTRUCTIVISM

Advantage: 
DIRECT EXPERIMENTAL VALIDATION
PREFACE 3: AIMEN –

Approches Innovantes de Modélisation de l’Environnement Marin
AIMEN —

Approches Innovantes de Modélisation de l’Environnement Marin
AIMEN –
Approches Innovantes de Modélisation de l’Environnement Marin

Freshwater
Asexual or parthenogenetic
Fast reproduction
Little structure

\[
\frac{dN}{dt} = \ldots
\]
PREFACE 4: Experimental Approach: Microcosms
Experimental Approach: Microcosms

Chemostat  Lake + River  Embayment, Lagoon
Chapter 1. Intrinsic dynamics of simple aquatic communities

The Question

- Can a simple mathematical model predict an experimental predator-prey system, including its bifurcation structure?

The System

- Rotifer-phytoplankton food chain in chemostats
Experimental System

*Brachionus calyciflorus* herbivorous rotifer

*Chlorella vulgaris* green alga

*Nutrients* nitrogen limitation
The Model

- **Zooplankton**
  \[
  \frac{dZ}{dt} = \frac{a_Z PZ}{k_Z + P} - (\delta + m)Z
  \]

- **Phytoplankton**
  \[
  \frac{dP}{dt} = \frac{a_P NP}{k_P + N} + \frac{1}{\epsilon} \frac{a_Z PZ}{k_Z + P} - \delta P
  \]

- **Nutrients**
  \[
  \frac{dN}{dt} = \delta (N_{in} - N) - \frac{a_P NP}{k_P + N}
  \]
Predator-Prey Dynamics in the Chemostat

Math. Model

Chemostat Culture

Prediction

Observed Chemostat Dynamics

\[ \frac{dZ}{dt} = \frac{a_Z}{k_Z + P} \left( \delta + m \right) Z \]

\[ \frac{dP}{dt} = \frac{a_P}{k_P + N} \frac{NP}{k_P + P} \frac{1}{\delta + m} \left( \delta + m \right) Z \]

\[ \frac{dN}{dt} = (\delta N_{in} - N) \frac{a_P}{k_P + N} \]

Days

Days

Relative population size

Relative population size

Chlorella

Brachionus
Predictions of the Simple Model in Parameter Space

- Extreme Oscillations -> Extinction
- Oscillations
- Equilibria
- Extinction

Diagram showing the relationship between nitrogen concentration ($N$, μmol/liter) and dilution rate ($\delta$, per day).
The Model Successfully Predicts Qualitative Aspects of Real Dynamics

Model Prediction

Experimental Community Dynamics

Fussmann et al., Science (2000)
1. Intrinsic dynamics of simple aquatic communities

**The Importance**
- A simple model predicts equilibrium and stable limit dynamics of a live predator-prey community

**The Team**
- Cornell University

S. Ellner
N. Hairston
G. Fussmann
Chapter 2. The persistence of predator-prey cycles

<table>
<thead>
<tr>
<th>The Question</th>
<th>The System</th>
</tr>
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<td>• Long-lasting predator-prey cycles – a reality?</td>
<td>• Rotifer-phytoplankton food chain in chemostats</td>
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</table>
Experimental predator-prey cycles

Weevil-Wasp (Utida 1957)

Gause 1934

2 ciliates

Luckinbill 1973
Long-lasting predator-prey cycles – a reality?

(a) Time Series  
(b) Phase Portrait  
(c) Wavelet Coherency  
(f) Relative phase difference
Long-lasting predator-prey cycles – a reality?

The Results

Rudolf et al. (resubmission in prep.)
Relative phase difference
Real data  Stage-structured, stochastic model

Rudolf et al. (resubmission in prep.)
2. The persistence of predator-prey cycles

The Importance

- Predator-prey cycles can be a persistent dynamical signal of communities
- Structure and stochasticity capture abandon of and return to cycles

The Team

- PhD student Lars Rudolf
- U Potsdam, U Oldenburg, McGill

L. Rudolf  G. Weithoff  U. Gaedke  B. Blasius
Chapter 3. Genetic diversity and eco-evolutionary dynamics

The Questions

• Do the dynamics of genetically diverse and genetically uniform communities differ?

• Can ecological and evolutionary dynamics happen at the same time scale?

The System

• Rotifer-phytoplankton food chain in chemostats

Monoclonal
Phytoplankton

Polyclonal

(A)  (B)
Phase shifts

„Something is wrong with our predator-prey cycles“

Dynamics with **monoclonal algae**


**PREY EVOLUTION**

Model
(algae: single variable)

Experiment
Dynamics with polyclonal algae

**PREY EVOLUTION**

Model
(algae: multiple variables)

Experiment

Nutrients

Rotifers

Algae

Rotifers
Eco-evolutionary feedback cycle

Clonal population structure of algae

Alternating selection of palatable and slow-growing clones

Evolution/Selection

Community Dynamics

Predator-prey oscillations

Trait Distribution

Community Structure
Trait identified → Clumping of algae

3. Genetic diversity and eco-evolutionary dynamics

The Importance

• Genetic diversity can significantly alter community dynamics
• Classical ecological dynamics and evolutionary processes co-determine the community dynamics

The Team

• Cornell University, McGill

Fussmann  Ellner  Jones  Yoshida  Hairston
Applications of Eco-Evo?
Environmental change

- Occuring at unprecedented rates
- Geographical patterns

*IPCC: Projected surface temperature changes for the late 21st century*
The potential options for organisms

• Extinction

• Migration
  → Change of geographical distribution

• Adaptation
  (in the region where change occurs)
Adaptation in the region where change occurs

• Evolutionary rescue (ER) occurs when genetic adaptation allows a population to recover from demographic effects initiated by environmental change that would otherwise cause extirpation.
Evolutionary rescue

In theory
(Gomulkiewicz & Holt 1995 Evolution)
Evolutionary rescue

... and in experimental practice
(Bell & Gonzalez 2009 Ecol. Lett.)

In theory ...
Evolutionary rescue

... and in experimental practice
(Bell & Gonzalez 2009 *Ecol. Lett.*)

In theory ...

**BUT:**
**NO THEORY**
**FOR COMMUNITIES**
Chapter 4
Community Evolutionary Rescue

The System
An Armstrong-McGehee type competitive system

– Oscillatory dynamics
– External environmental change
– Trait evolution

N1

N2

R
Chapter 4
Community Evolutionary Rescue

The System
An Armstrong-McGehee type competitive system

- Oscillatory dynamics
- External environmental change
- Trait evolution

With Andrew Gonzalez, McGill
Chapter 4 -- Community Evolutionary Rescue

The Questions

• Can trait evolution allow ER, and ensure the community persists by preventing competitive exclusion during environmental change?

• Does ER bring about a change in the character of the oscillations (period, amplitude) governing coexistence before and after environmental change?
Chapter 4 – Community Evolutionary Rescue

The Model

2 × Rosenzweig-MacArthur = Armstrong-McGehee

\[
\frac{dR}{dt} = \mu R \left(1 - \frac{R}{K}\right) - f_1(R)N_1 - f_2(R)N_2 \\
\frac{dN_1}{dt} = \varepsilon_1 f_1(R)N_1 - m_1 N_1 \\
\frac{dN_2}{dt} = \varepsilon_2 f_2(R)N_2 - m_2 N_2 \\
\]

with: \( f_1(R) = \frac{a_1 R}{1 + b_1 R} \); \( f_2(R) = \frac{a_2 R}{1 + b_2 R} \)
The Model

Linear environmental change affects curvature of the functional response.

\[ \frac{dT}{dt} = p \]

\[ f_i(R) = \frac{(a_i + z_i T(p)) R}{1 + c_i (a_i + z_i T(p))^{q_i} R} \]
The Model

- Consumers can evolve to counter environmental change.
- Change of curvature of functional response (a quantitative trait) is proportional to fitness gradient.

\[
\frac{da_i}{dt} = v_i \frac{\partial}{\partial a_i} \left( \frac{1}{N_i} \frac{dN_i}{dt} \right) = v_i \frac{\partial}{\partial a_i} \left( \frac{\varepsilon_i}{1 + c_i (a_i + z_i T(p))^q_i} R - m_i \right) =
\]

\[
= v_i \varepsilon_i R \frac{1 + c_i (a_i + z_i T(p))^q_i R(1 - q_i)}{\left(1 + c_i (a_i + z_i T(p))^q_i R\right)^2}
\]
The Model

- Manipulate direction and intensity of
  
  - Environmental change: parameter $z_i$
  - Evolutionary change: parameter $v_i$

\[
\frac{d a_i}{d t} = v_i \frac{\partial}{\partial a_i} \left( \frac{1}{N_i} \frac{d N_i}{d t} \right) = v_i \frac{\partial}{\partial a_i} \left( \varepsilon_i \frac{(a_i + z_i T(p)) R}{1 + c_i (a_i + z_i T(p))^{q_i} R} - m_i \right) = \frac{\partial}{\partial a_i} \left( v_i \varepsilon_i R \frac{1 + c_i (a_i + z_i T(p))^{q_i} R (1 - q_i)}{\left(1 + c_i (a_i + z_i T(p))^{q_i} R\right)^2} \right)
\]
Results

- The baseline Armstrong-McGehee dynamics
Results

- Environmental change leads to extinction
Results

- Evolution can lead to extinction but doesn’t need to
Results

• Evolutionary rescue can occur
• Recovery dynamics can be reminiscent of the “U-shaped curve”
Results

• Dynamic regime pre-, during, and post-rescue differs

Wavelets courtesy of L. Rudolf, B. Blasius
Conclusions

• ER is capable of maintaining an oscillating community experiencing sustained environmental change.

• This is a case study, but ER occurred over a wide range of evolutionary strengths (or genetic variances) and, thus, did not depend on evolution being “just right.”
Conclusions

• Despite high-frequency changes of population abundances – adaptive evolutionary trait change can be gradual and directional, and therefore contribute to community rescue.

• Change in the character of community oscillations may be a signature that a community is undergoing ER.
Quote –
Elena Litchman’s father, last night at the buffet:

“Experiments without theory are blind, but theory without experiments is dead.”