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

AIMEN
Innovative Approaches in Marine Environment Modelling
Approches Innovantes en Modélisation de l'Environnement Marin
August 19-23 2013 IUEM, Brest, France

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McGill
Department of Biology

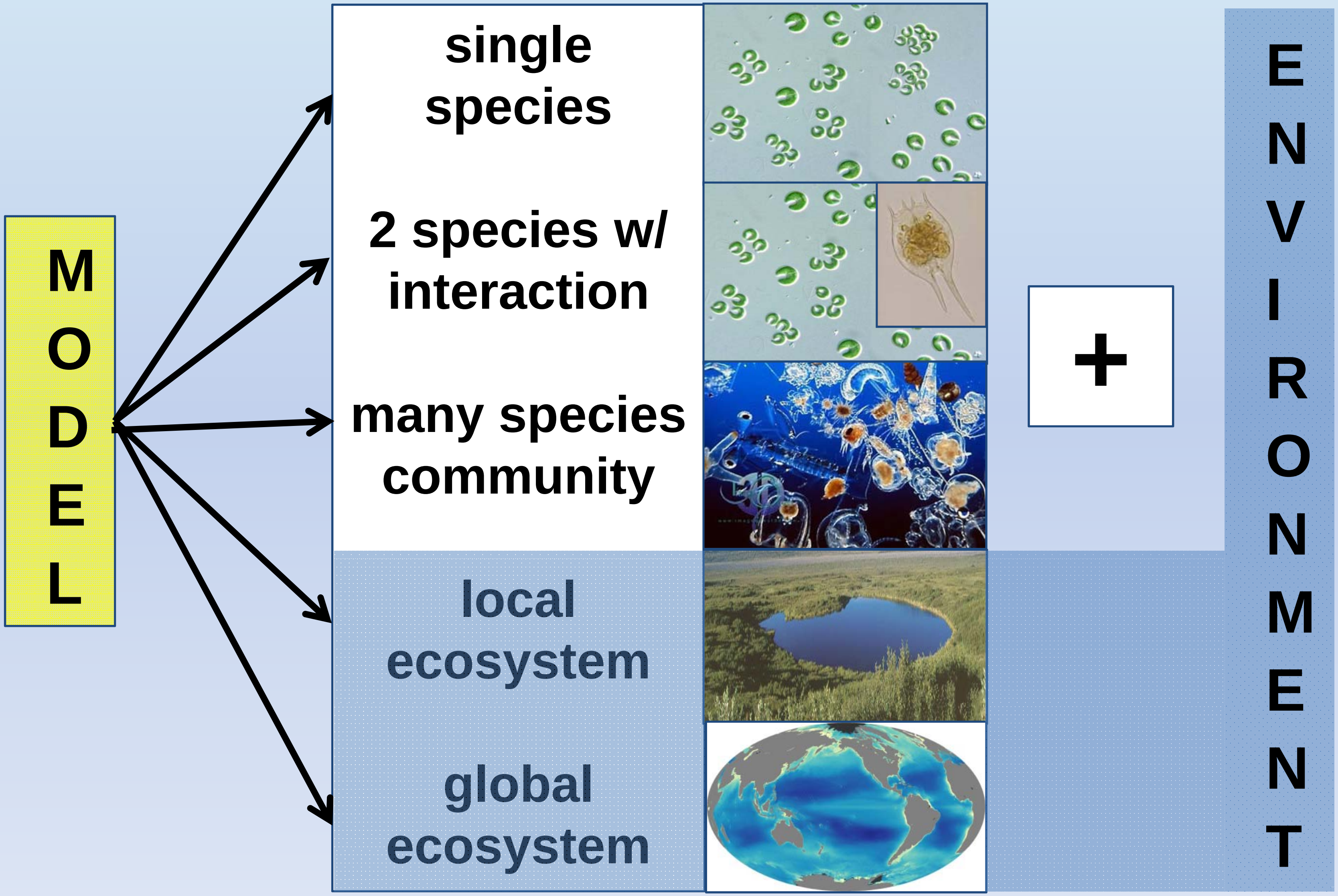
OUTLINE

- 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

- Becks L, Ellner SP, Jones LE, & Hairston NG. (2012) The functional genomics of an eco-evolutionary feedback loop: linking gene expression, trait evolution, and community dynamics. Ecol Lett 15, 492-501.
- Bell G & Gonzalez A. (2009) Evolutionary rescue can prevent extinction following environmental change. *Ecol Lett* **12**, 942-948.
- Fussmann GF, Loreau M, & Abrams PA. (2007) Eco-evolutionary dynamics of communities and ecosystems. *Funct Ecol* **21**, 465-477.
- Yoshida T, Jones LE, Ellner SP, Fussmann GF, & Hairston NG. (2003) Rapid evolution drives ecological dynamics in a predator-prey system. *Nature* **424**, 303-306.

PREFACE 2: Hierarchy of models and systems



What I cover

M
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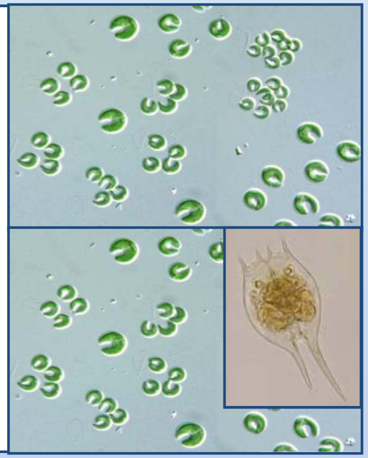
single species

2 species w/ interaction



+

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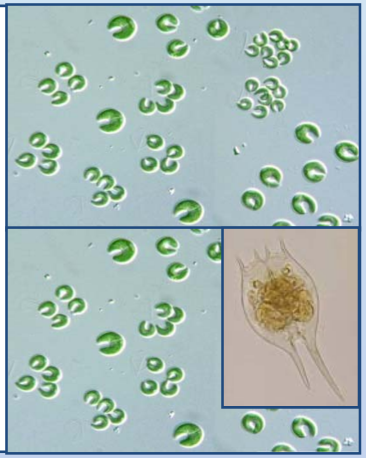
“Trophic Interaction, Complexity and Emergence”

M O D E L

single species

2 species w/ interaction



+

E N V I R O N M E N T

Approach to Complexity:
DECONSTRUCTIVISM

Advantage:
DIRECT EXPERIMENTAL VALIDATION

PREFACE 3: AIMEN –

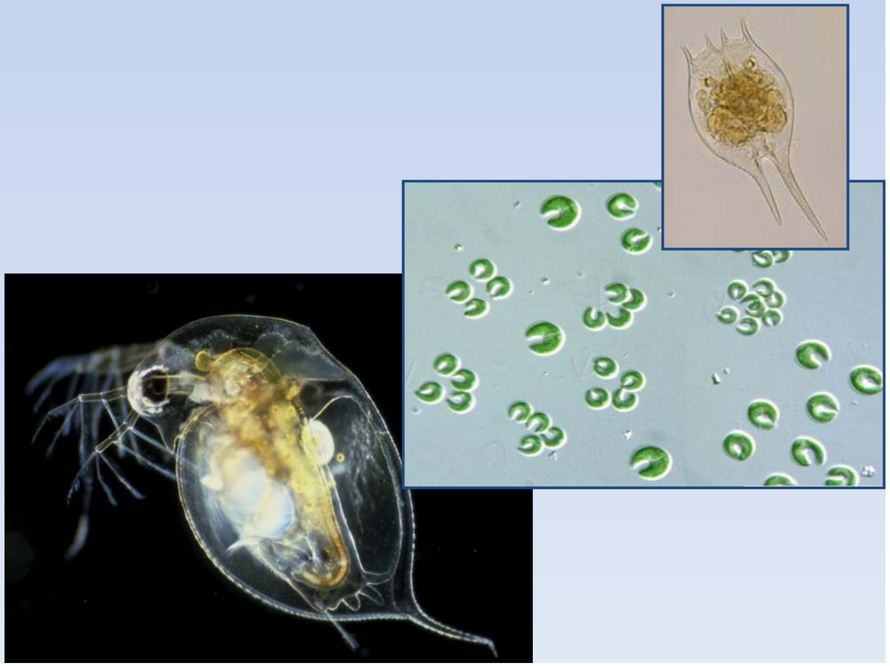
Approches Innovantes de Modélisation de l'Environment Marin

☑ ☑

AIMEN –

Approches Innovantes de Modélisation de l'Environment Marin

☑ ☑ ☹



AIMEN –

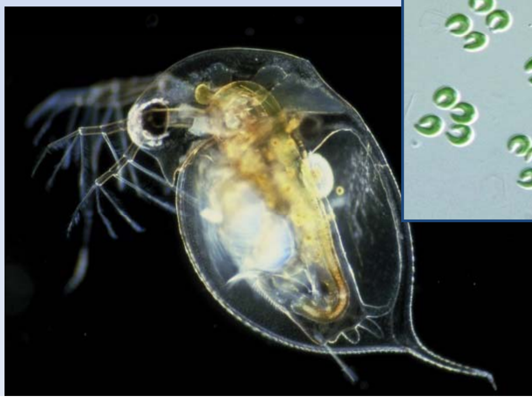
Approches Innovantes de Modélisation de l'Environment Marin

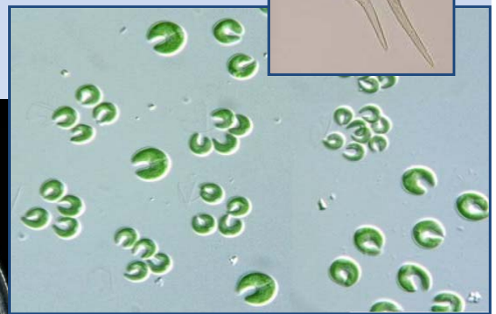
☑ ☑ ☹

<u>Freshwater</u>
Asexual or parthenogenetic
Fast reproduction
Little structure

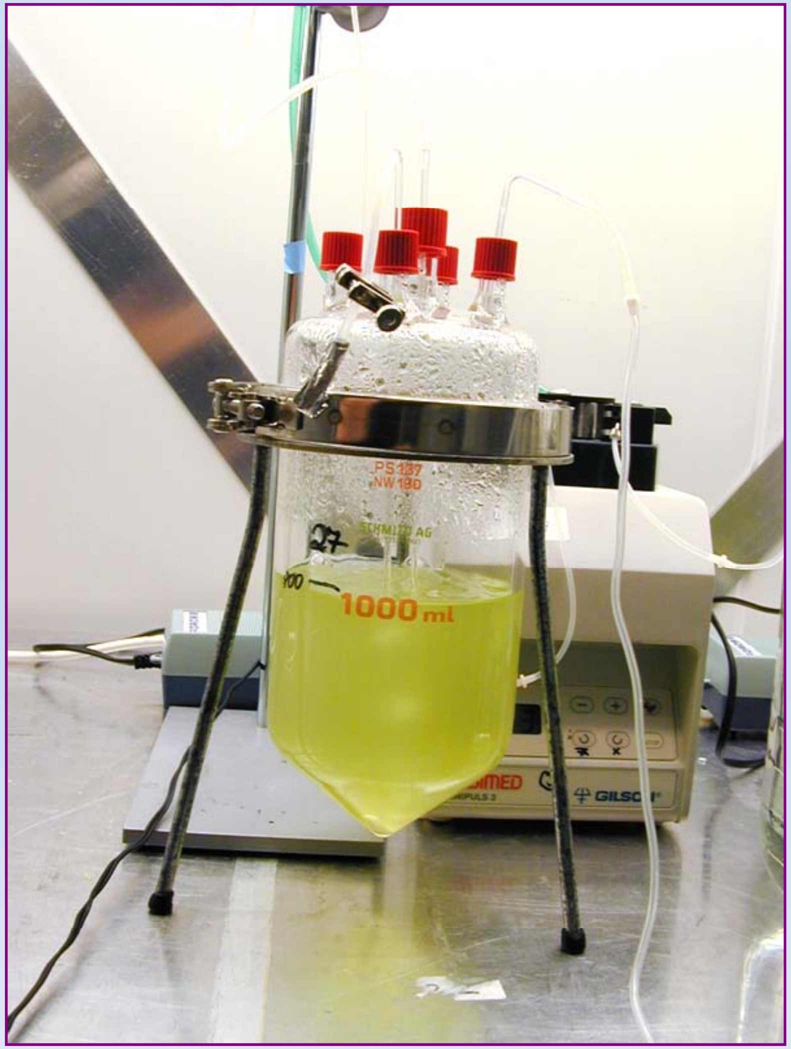
$$\frac{dN}{dt} = \dots$$

↔

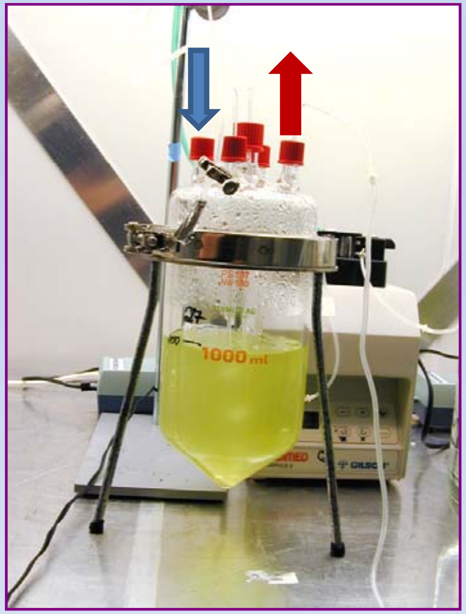




PREFACE 4: Experimental Approach: Microcosms



Experimental Approach: Microcosms



Chemostat

Lake + River

Embayment, Lagoon

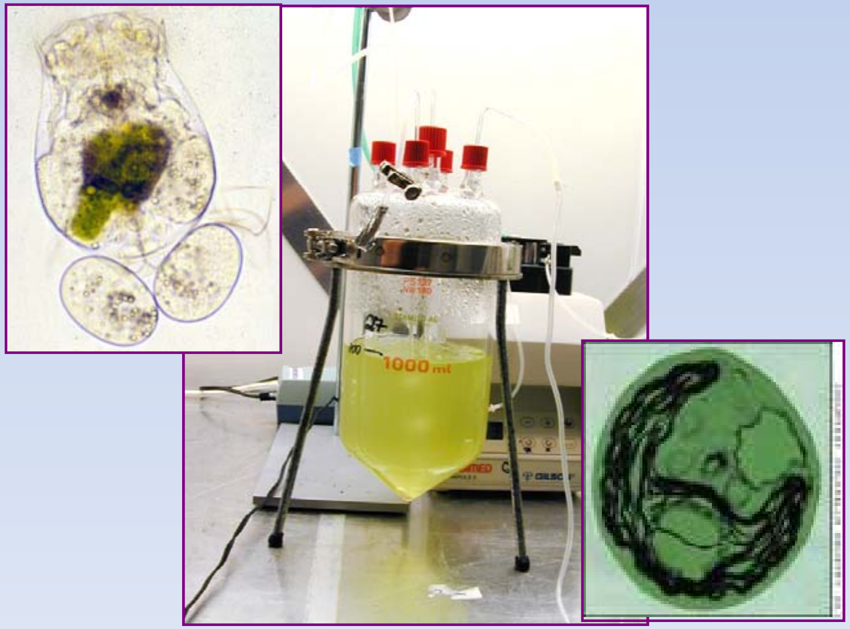
Chapter 1. Intrinsic dynamics of simple aquatic communities

The Question

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

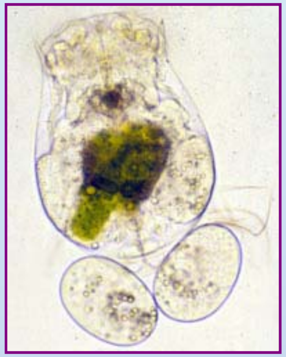
The System

- Rotifer-phytoplankton food chain in chemostats

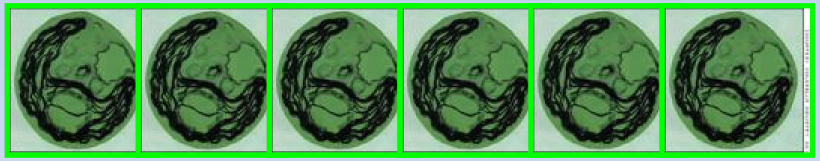


Experimental System

Brachionus calyciflorus
herbivorous rotifer

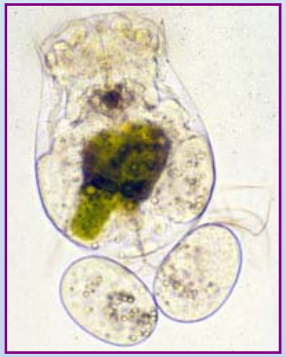


Chlorella vulgaris
green alga



Nutrients
nitrogen limitation

The Model



- **Zooplankton**

$$\frac{dZ}{dt} = \frac{a_Z PZ}{k_Z + P} - (\delta + m)Z$$

- **Phytoplankton**

$$\frac{dP}{dt} = \frac{a_P NP}{k_P + N} + \frac{1}{\varepsilon}\frac{a_Z PZ}{k_Z + P} - \delta P$$

- **Nutrients**

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

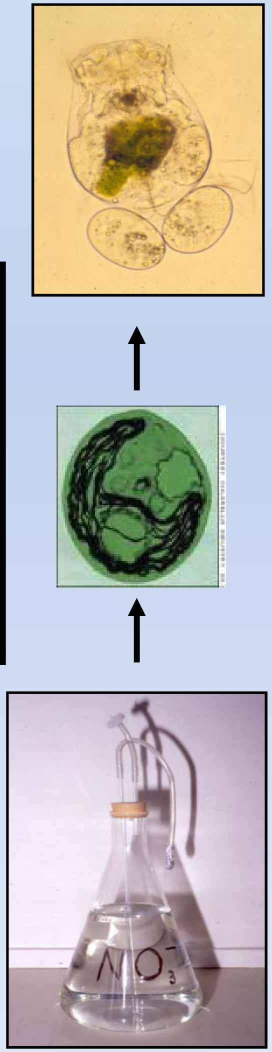
Predator-Prey Dynamics in the Chemostat

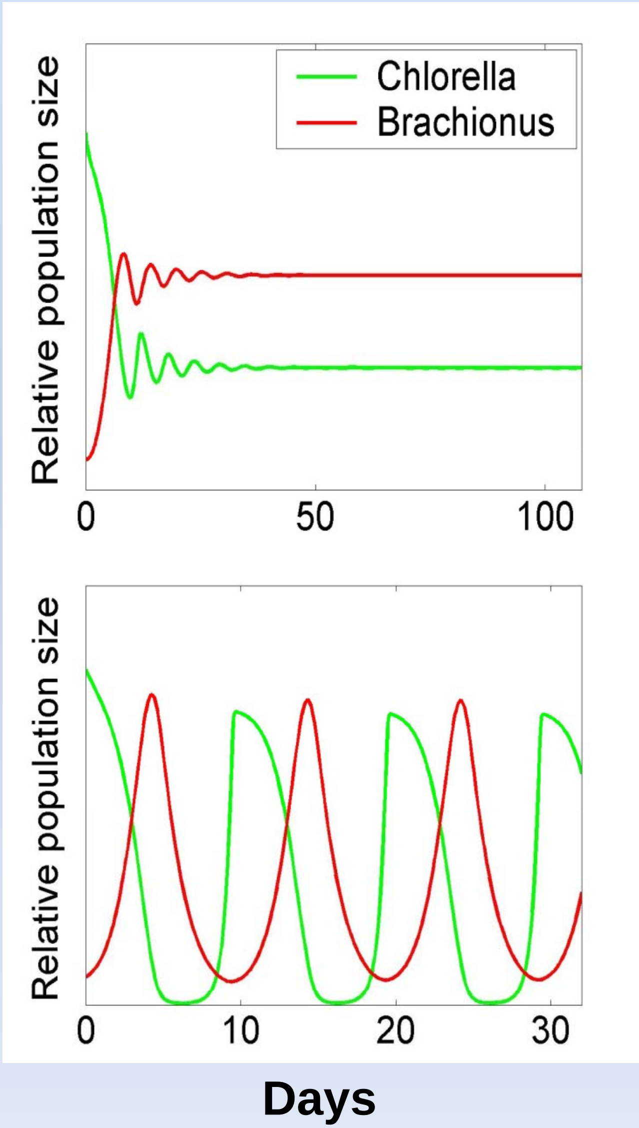
Math. Model | Chemostat Culture | Prediction | Observed Chemostat Dynamics

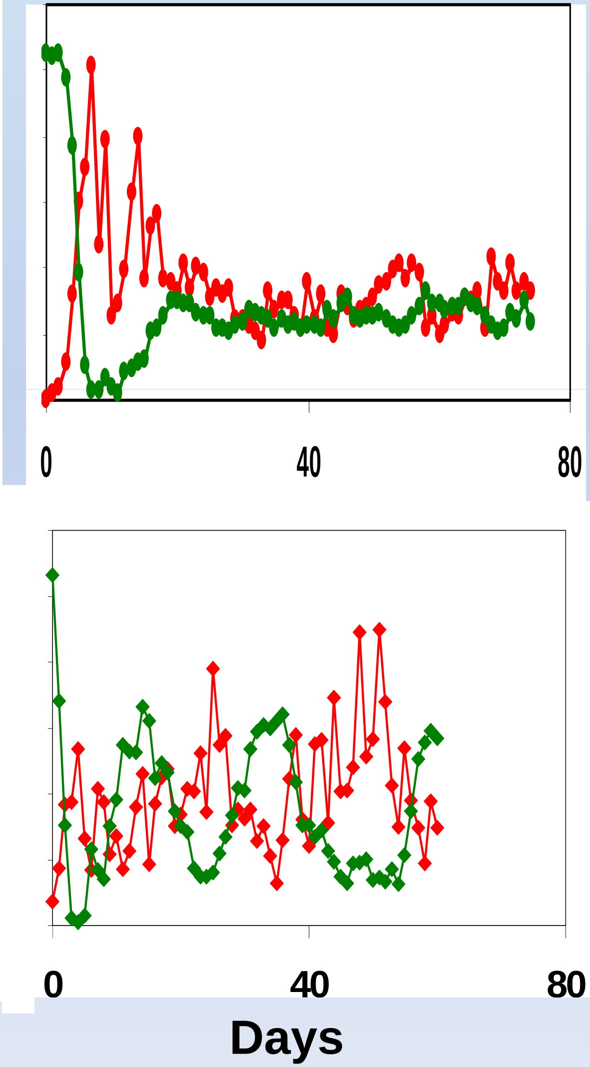
$$\frac{dZ}{dt} = \frac{a_Z P Z}{k_Z + P} - (\delta + m) Z$$

$$\frac{dP}{dt} = \frac{a_P N P}{k_P + N} + \frac{1}{\varepsilon} \frac{a_Z P Z}{k_Z + P} - \delta P$$

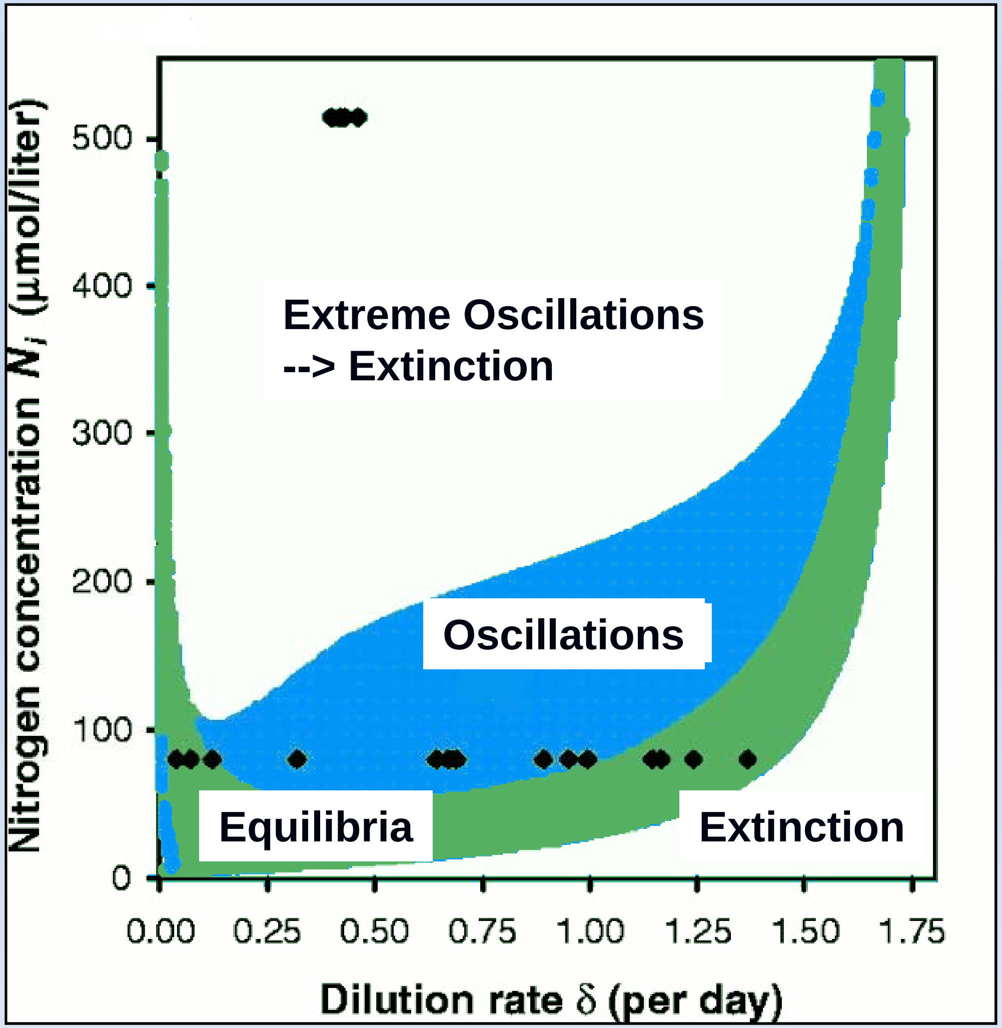
$$\frac{dN}{dt} = \delta (N_{in} - N) - \frac{a_P N P}{k_P + N}$$





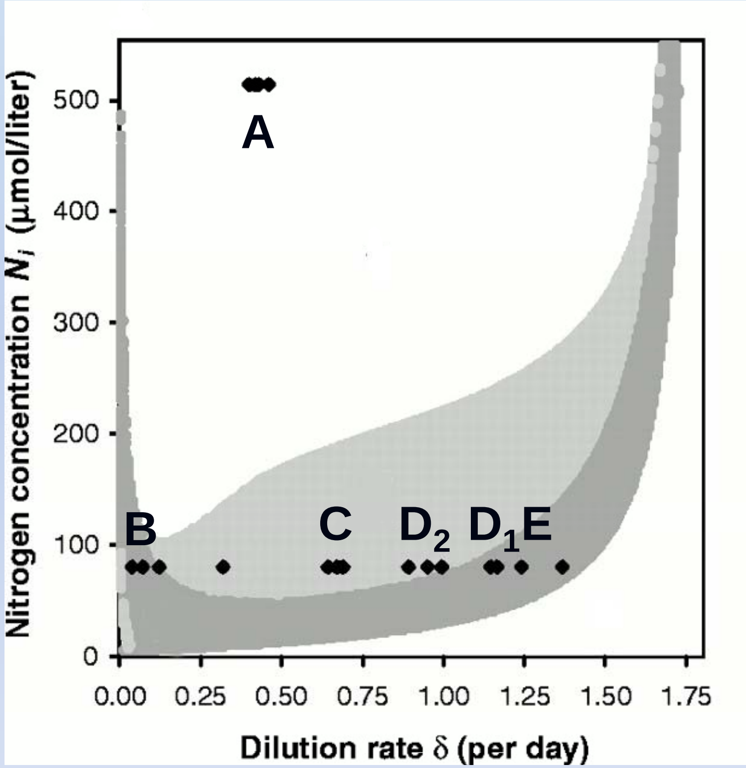


Predictions of the Simple Model in Parameter Space

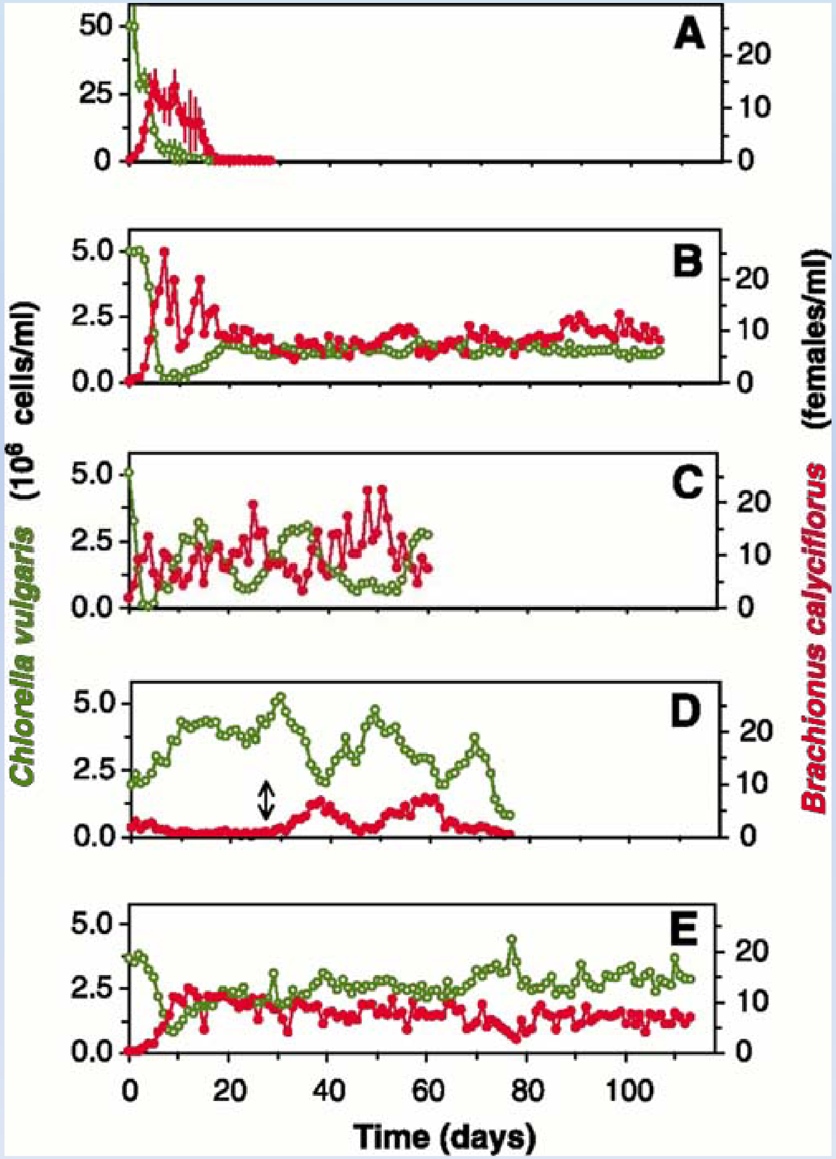


The Model Successfully Predicts Qualitative Aspects of Real Dynamics

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

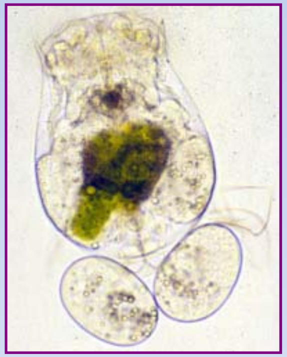
Chapter 2. The persistence of predator-prey cycles

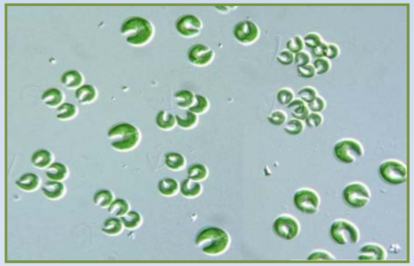
The Question

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

The System

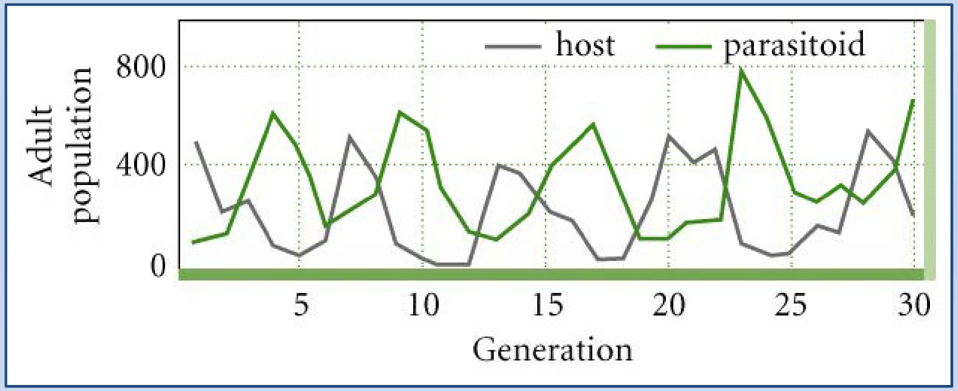
- Rotifer-phytoplankton food chain in chemostats





Experimental predator-prey cycles

Weevil-Wasp (Utida 1957)



Gause 1934

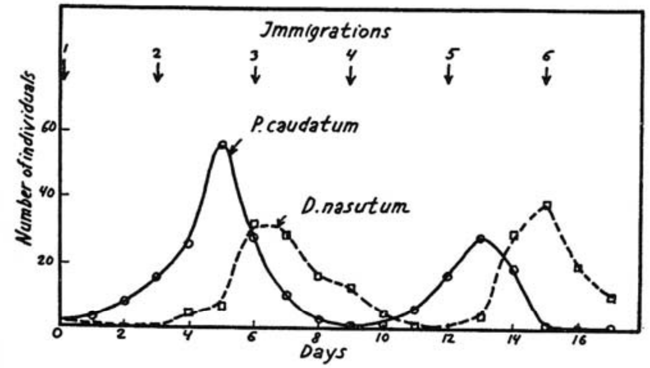


FIG. 32. The interaction between *Didinium nasutum* and *Paramecium caudatum* in a microcosm with immigrations (1 *Didinium* + 1 *Paramecium*). Causes of too low peak of *Didinium* in the first cycle of growth are known. From Gause ('34a).

2 ciliates

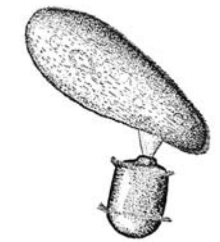


FIG. 27. *Didinium nasutum* devouring *Paramecium caudatum*

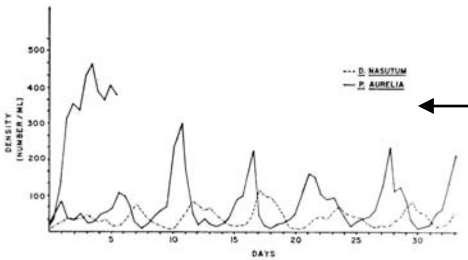
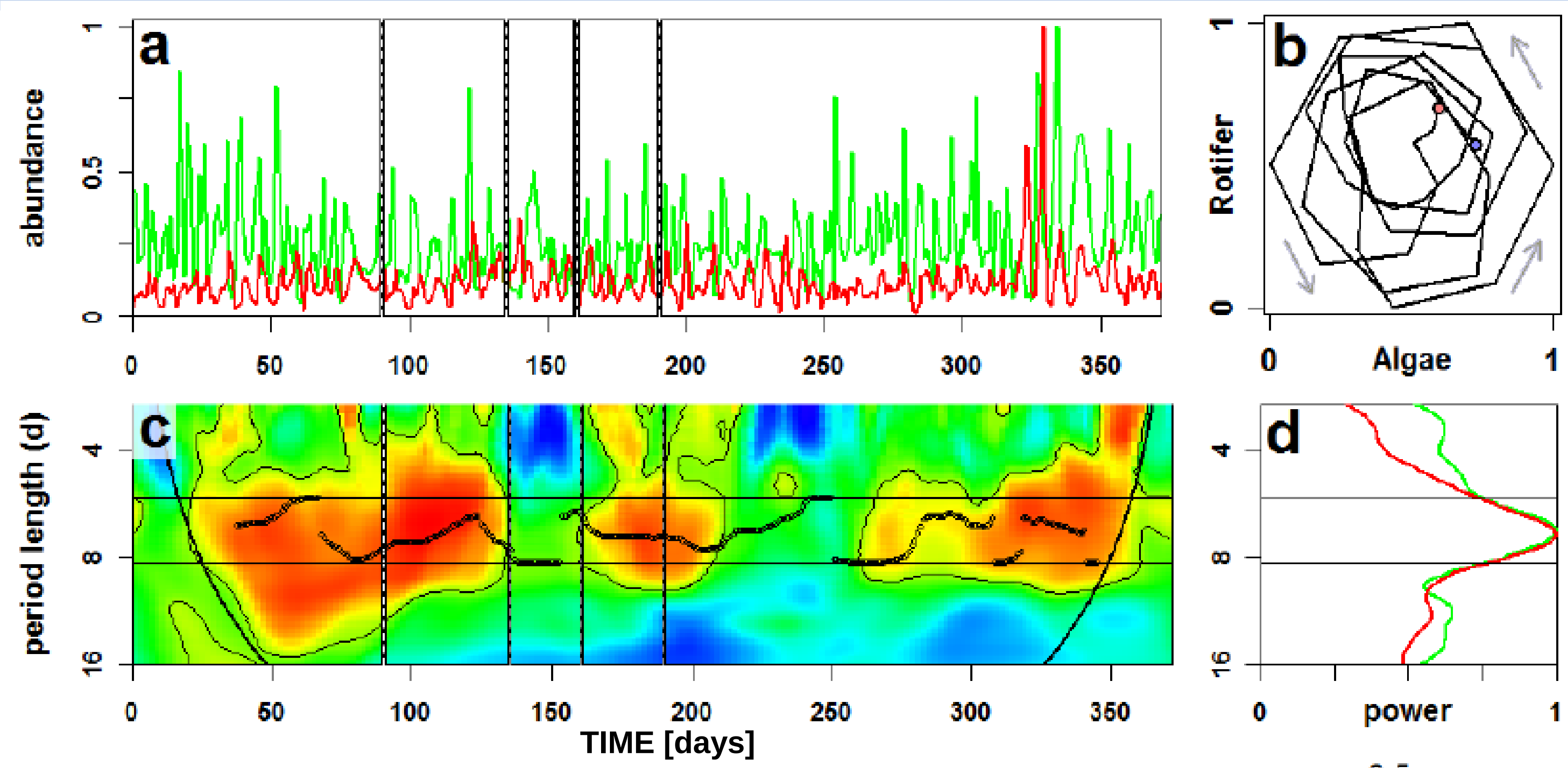


FIG. 5. Increasing oscillations are stabilized and extinction is prevented by prey. Transplants of this system were made on days 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 11.5, 13.5, 15.5, 18.5, 19.5, 22.0, 24.0, 26.0, 28.0, 30.0, and 32.0. The control for this experiment, at upper left, shows the increase in *Paramecium* in the absence of *Didinium*. No transplants of this system were made.

Luckinbill 1973

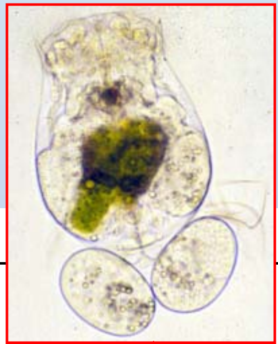
Long-lasting predator-prey cycles – a reality?

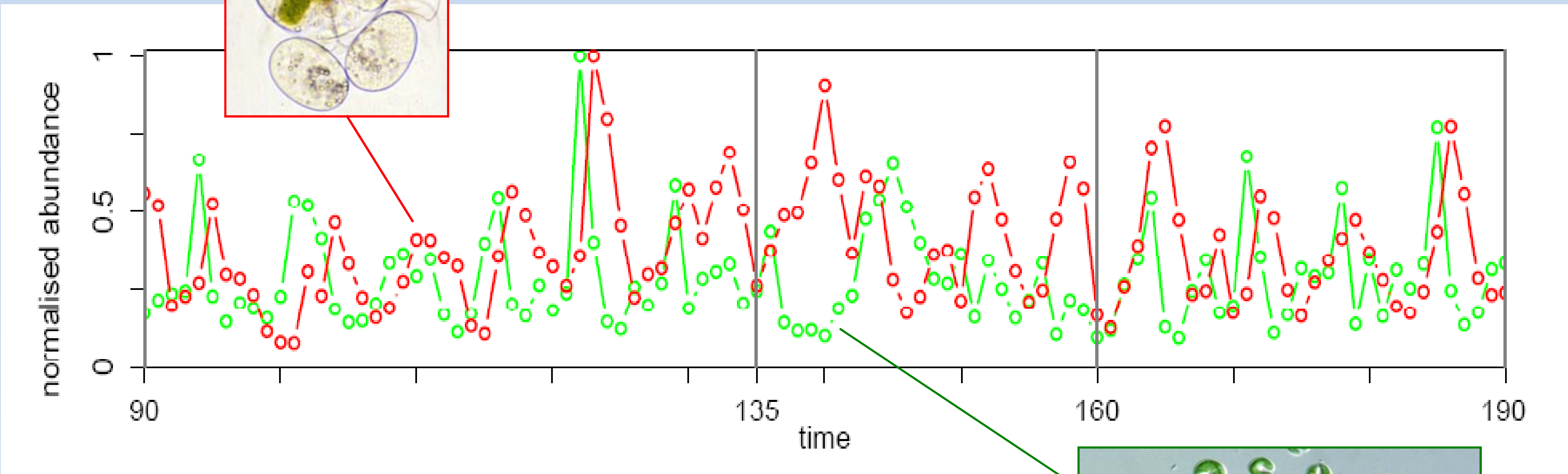
(a) Time Series
(b) Phase Portrait
(c) Wavelet Coherency
(f) Relative phase difference

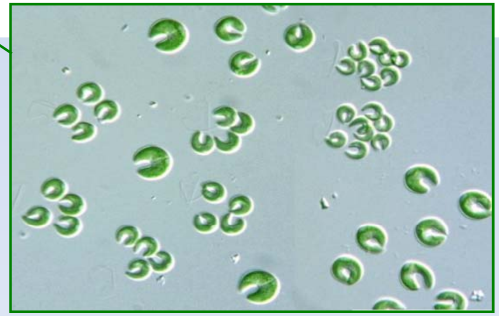


Long-lasting predator-prey cycles – a reality?

The Results

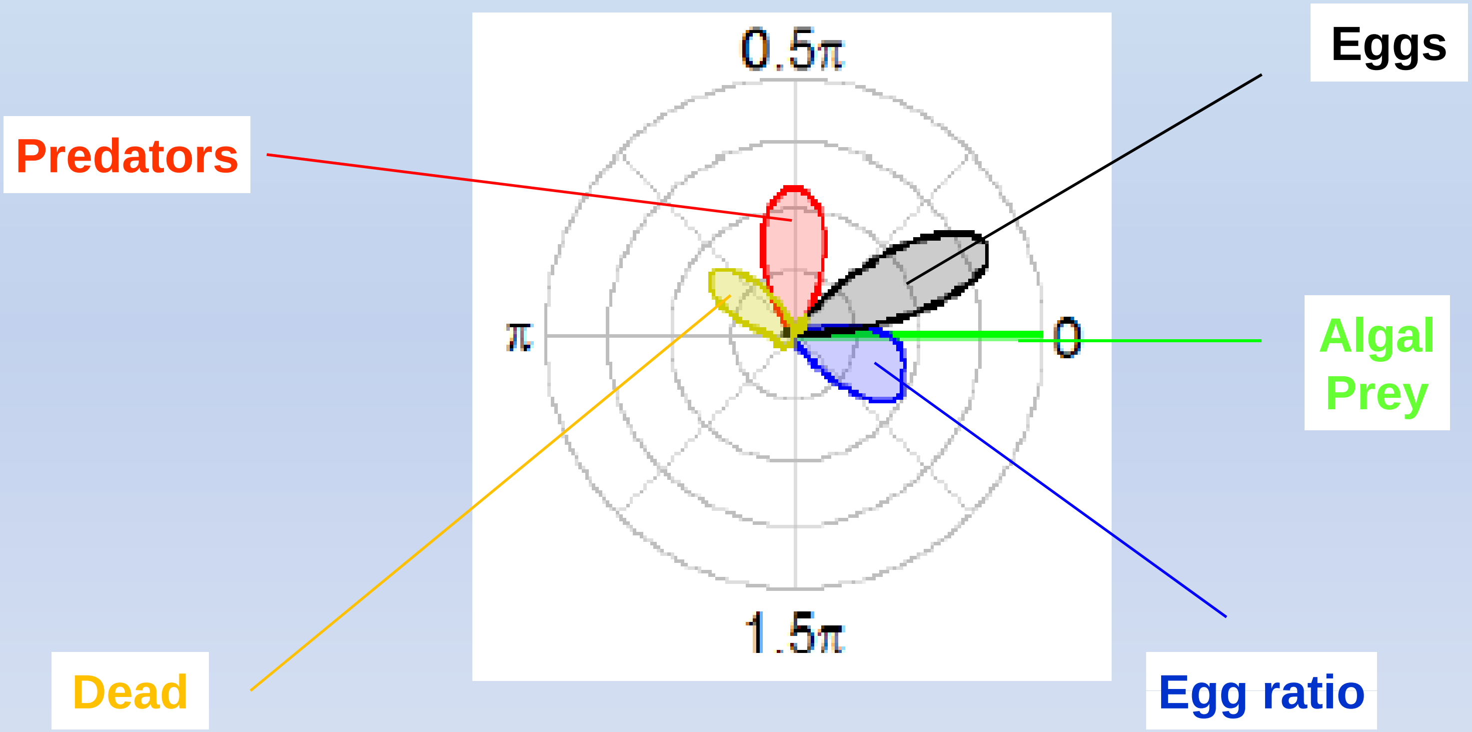




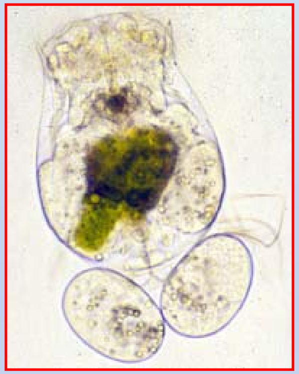


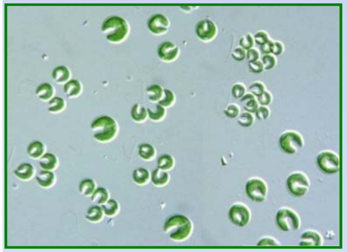
Rudolf et al. (resubmission in prep.)

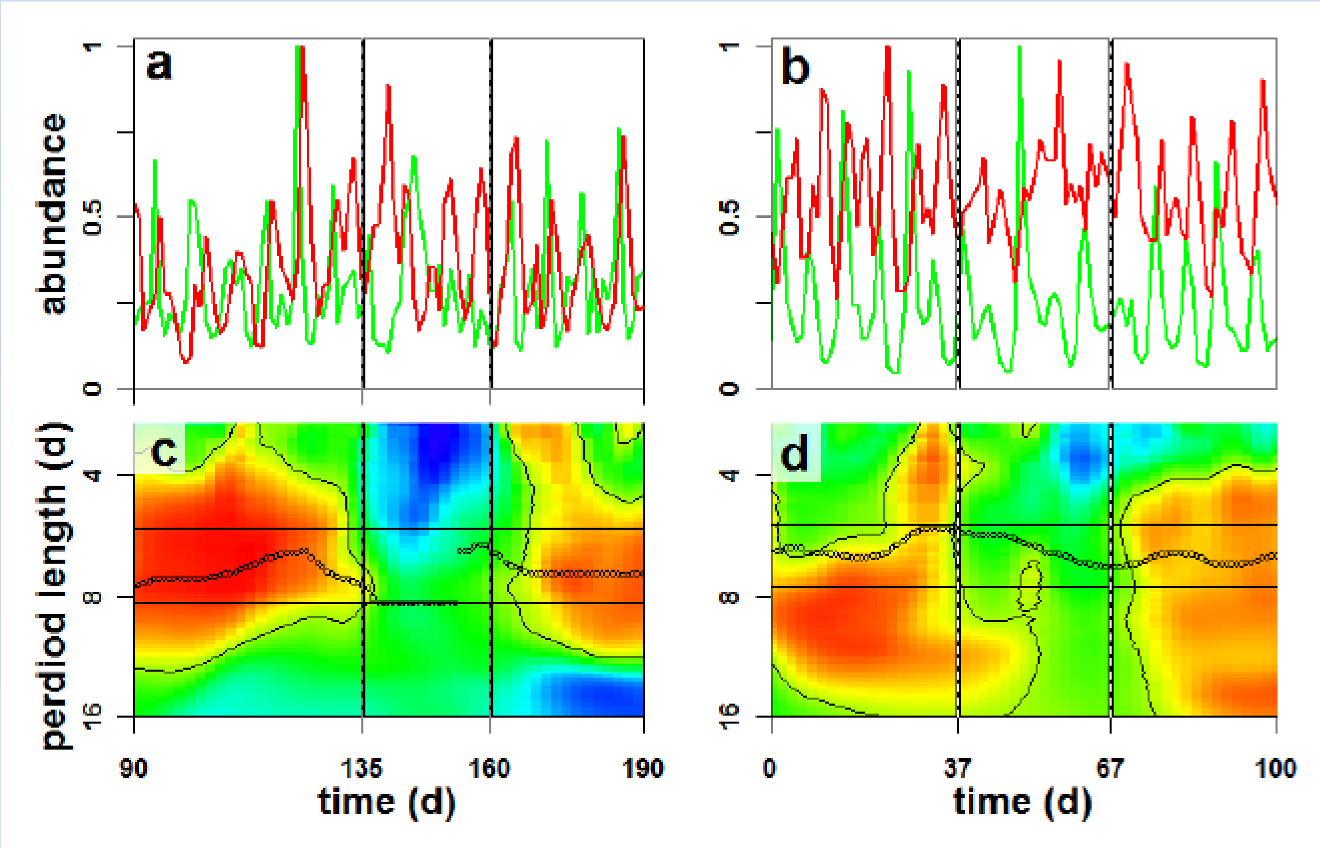
Relative phase difference



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

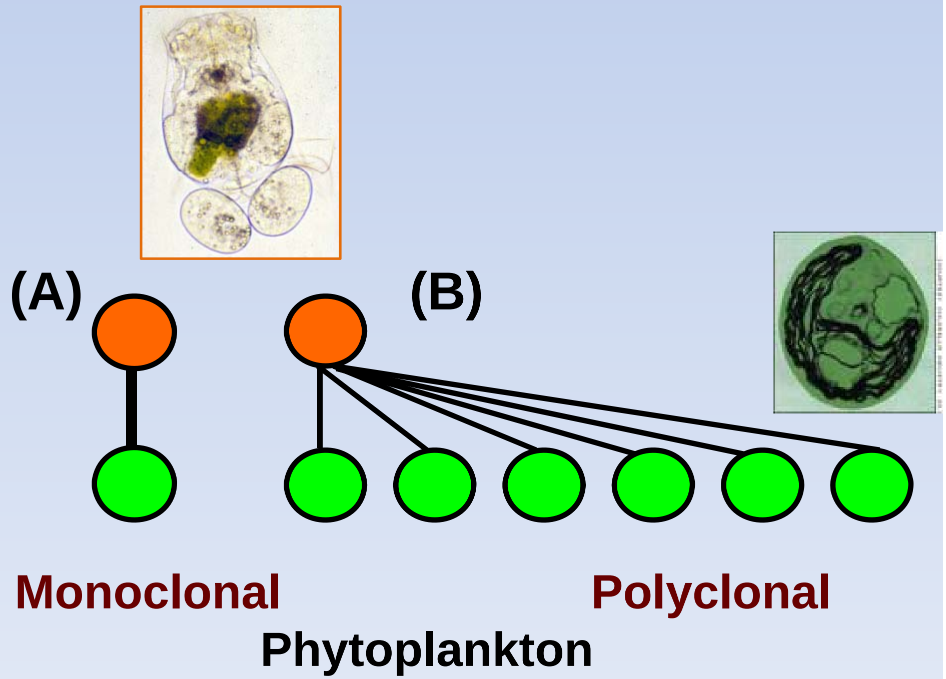
Chapter 3. Genetic diversity and eco-evolutionary dynamics

The Questions

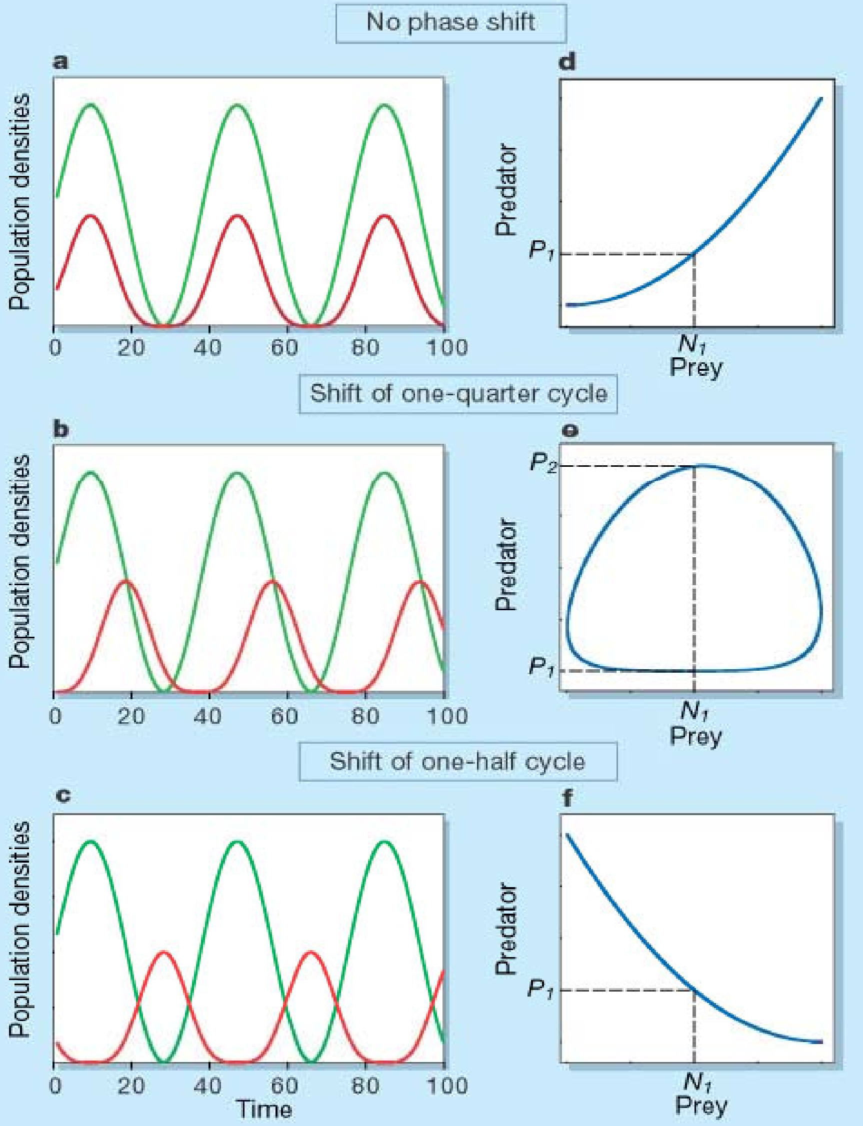
- Do the dynamics of genetically diverse and genetically uniform communities differ?
- Can ecological and evolutionary dynamics happen at the same time scale?

The System

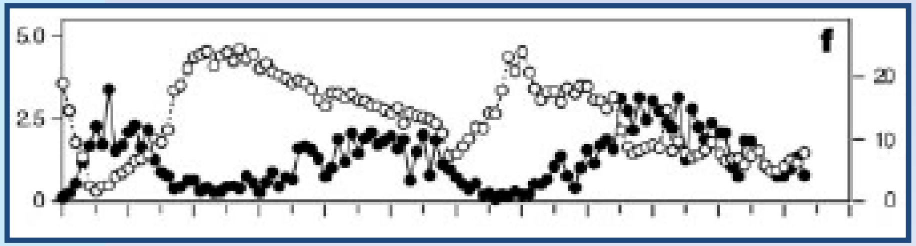
- Rotifer-phytoplankton food chain in chemostats



Phase shifts



„Something is wrong with our predator-prey cycles“

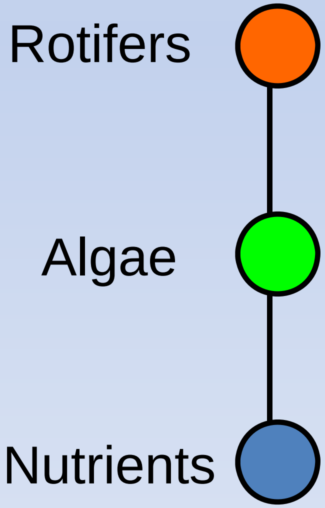


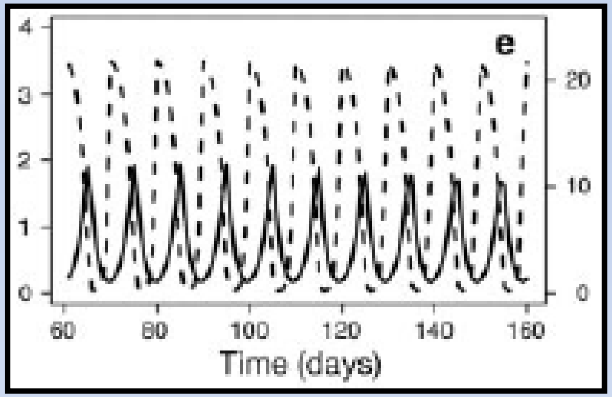
from:Turchin, P. *Nature* (2003)

Dynamics with <u>monoclonal</u> algae

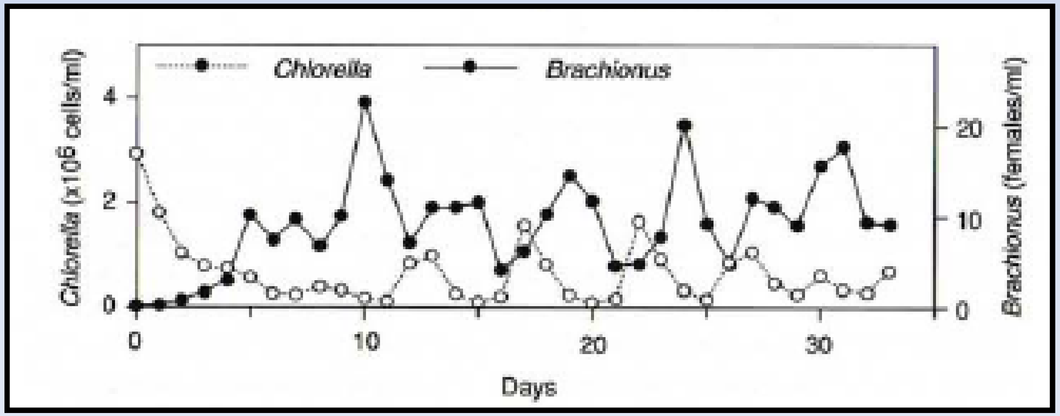
Yoshida et al., *Nature* (2003)

~~PREY EVOLUTION~~





Model
(algae: single variable)

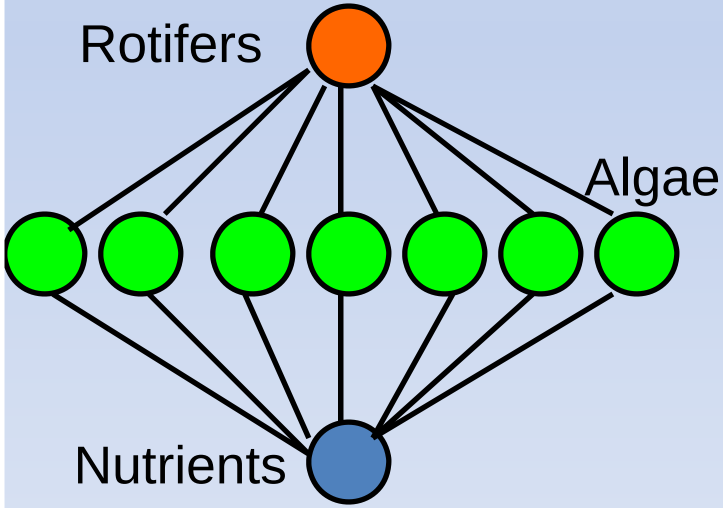


Experiment

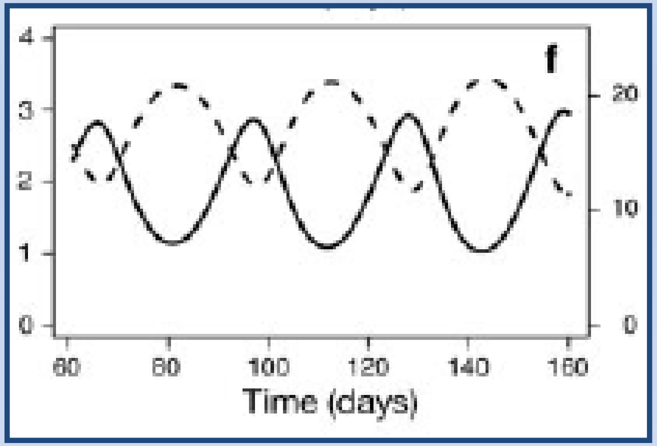
Dynamics with polyclonal algae

Yoshida et al., *Nature* (2003)

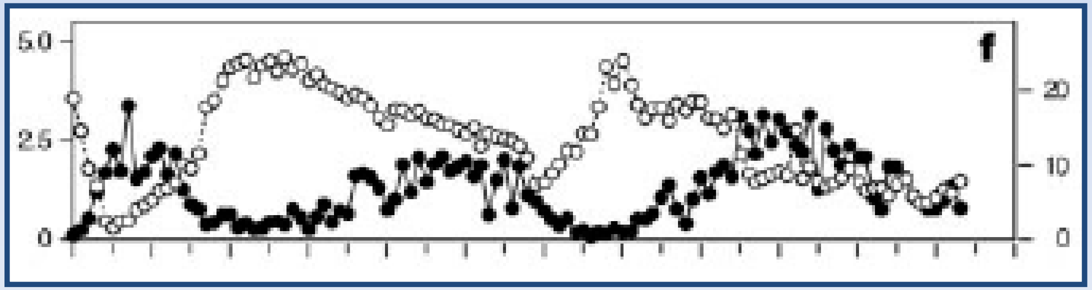
PREY EVOLUTION

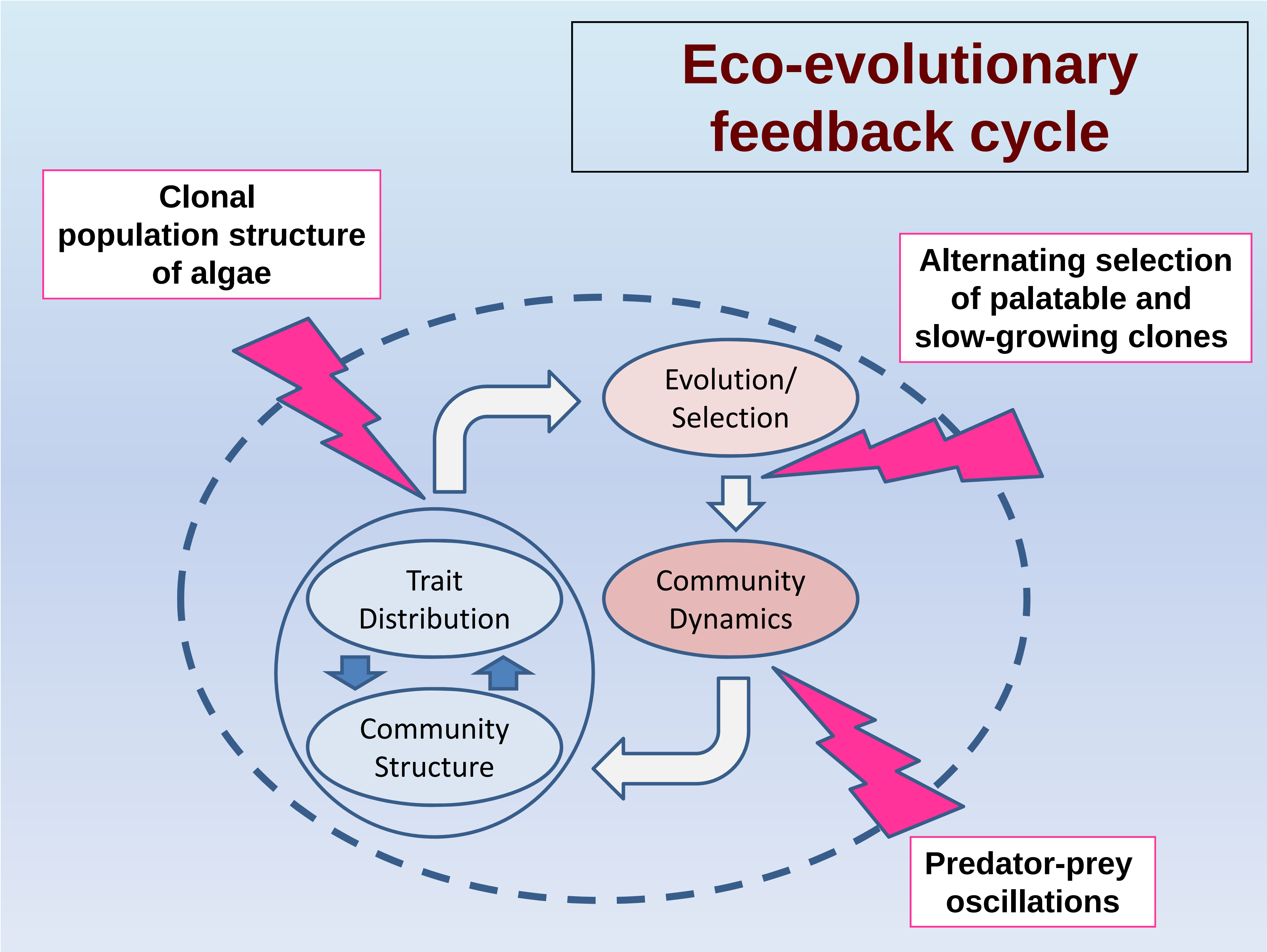


Model
(algae: multiple variables)



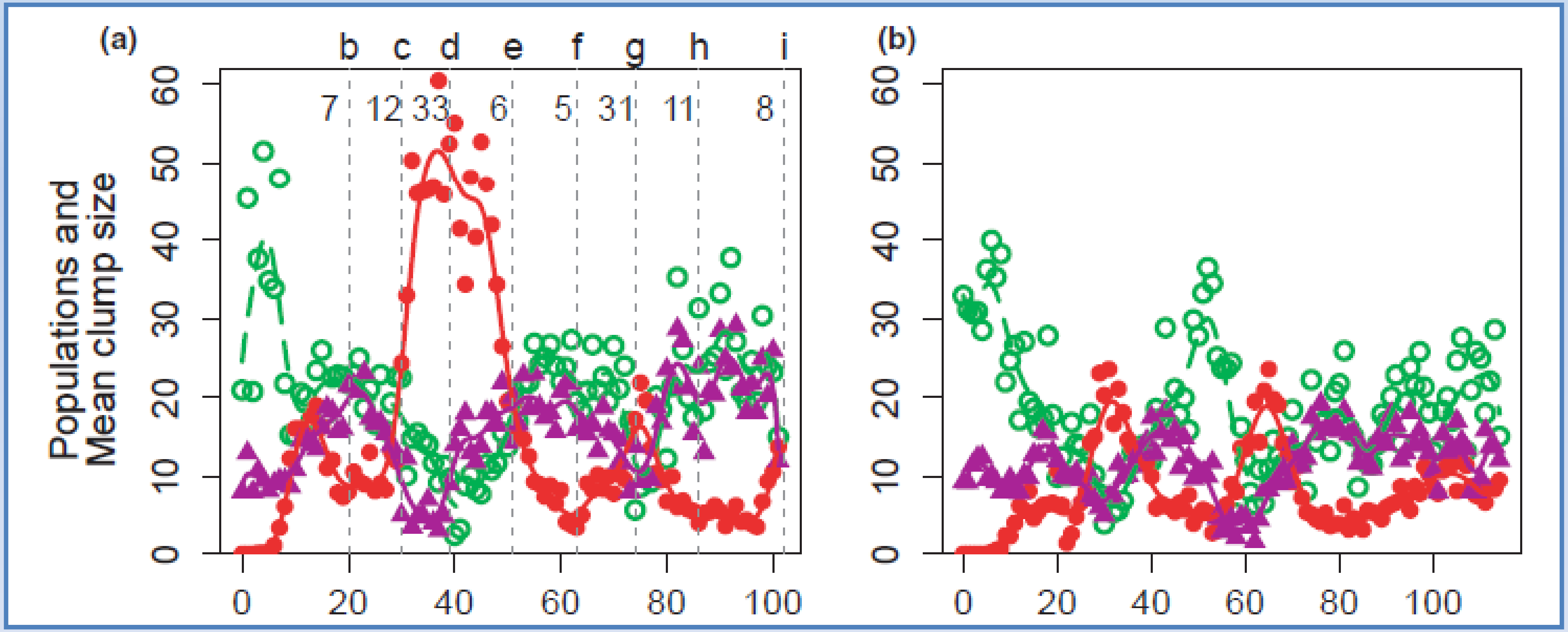
Experiment




Eco-evolutionary feedback cycle
Clonal population structure of algae
Alternating selection of palatable and slow-growing clones
Evolution/ Selection
Trait Distribution
Community Dynamics
Community Structure
Predator-prey oscillations

Trait identified → Clumping of algae

Becks et al. 2012, *Ecology Letters*



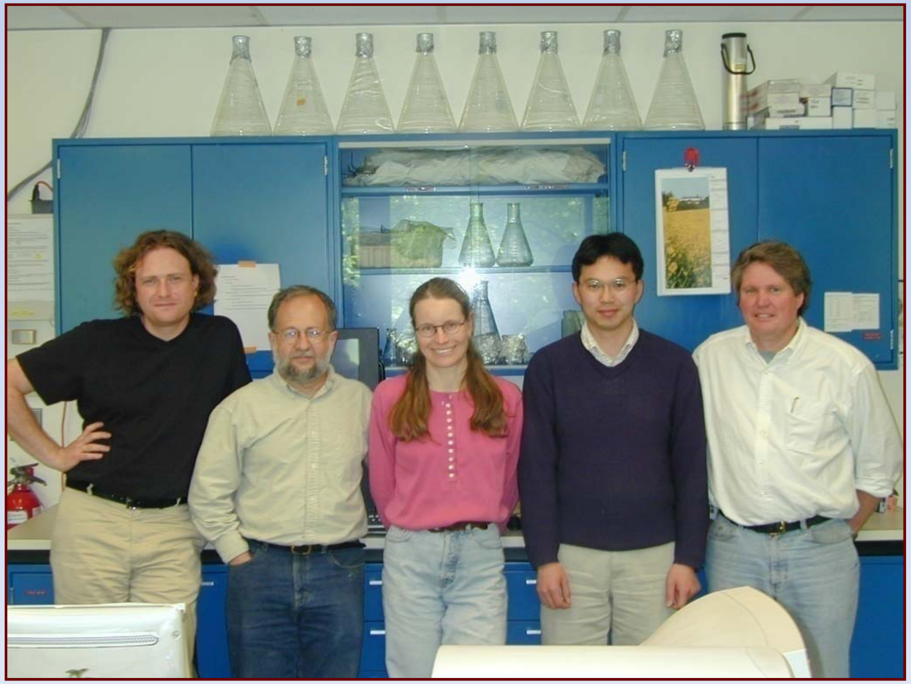
3. Genetic diversity and eco-evolutionary dynamics

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

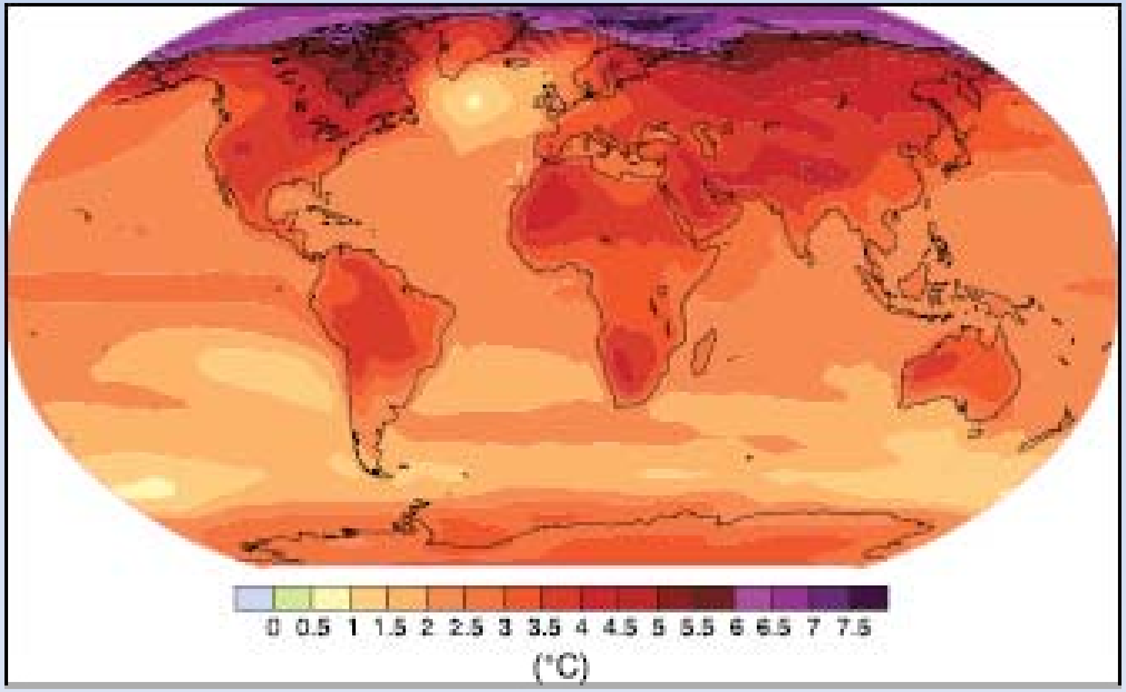


Fussmann   Ellner   Jones   Yoshida   Hairston

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

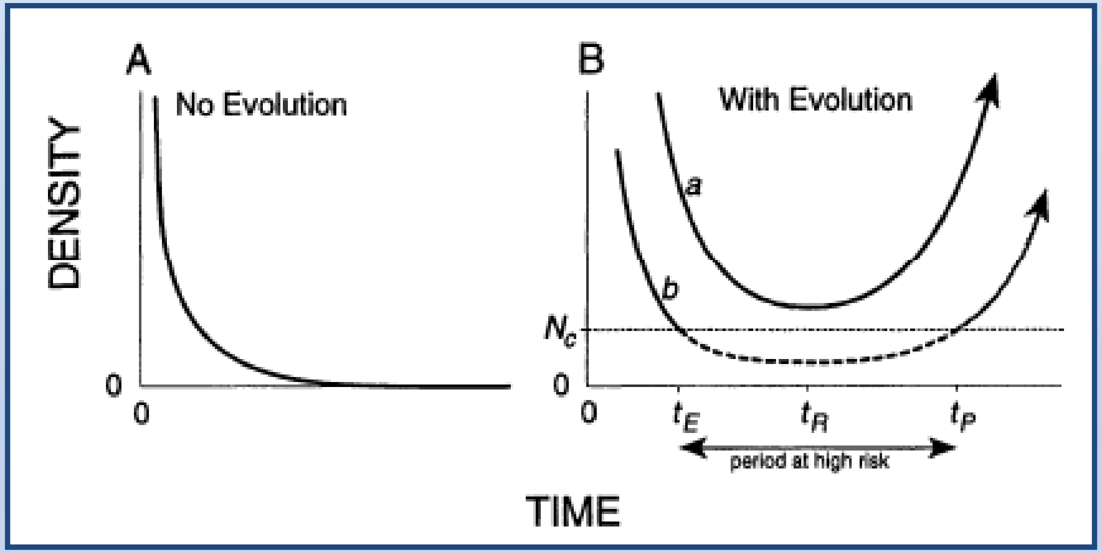
  (in the region where change occurs)

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



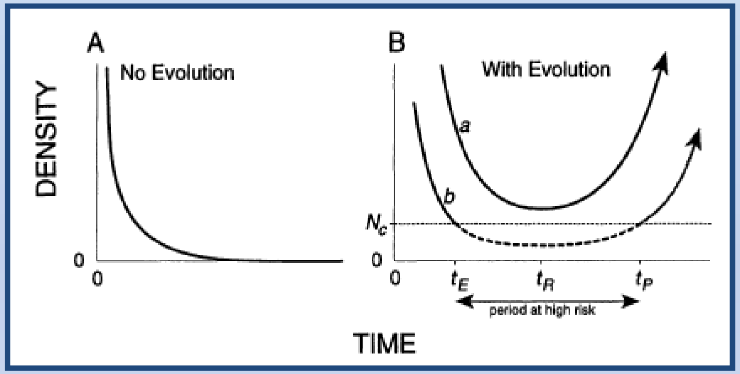
In theory

(Gomulkiewicz & Holt 1995 *Evolution*)

Evolutionary rescue

… and in experimental practice

(Bell & Gonzalez 2009 *Ecol. Lett.*)



In theory …

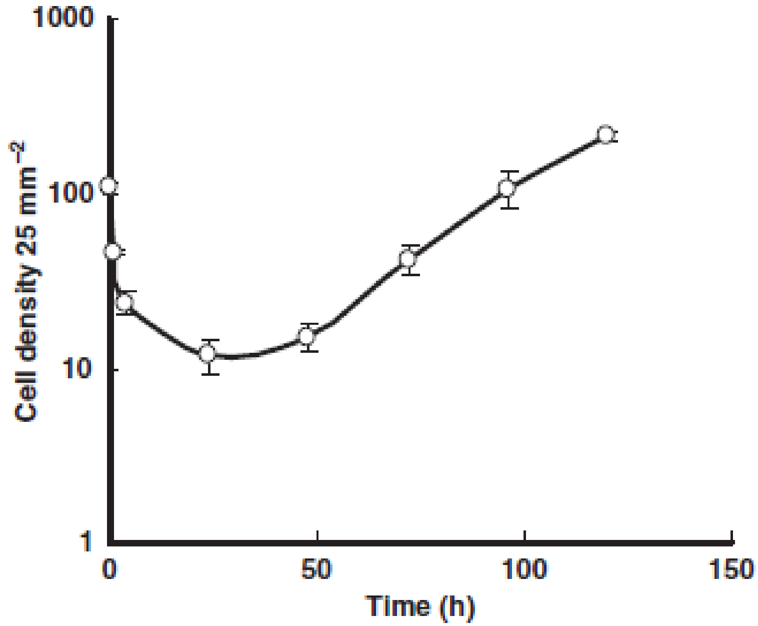
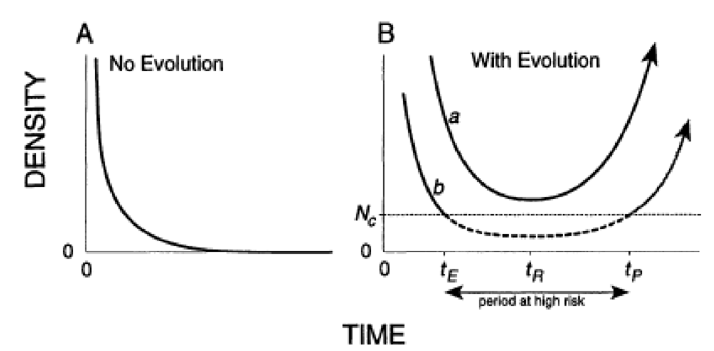


Figure 1 Collapse and recovery of yeast populations (mean ± 1 SE) exposed to high-salt concentration. The concentration used was 125 g L^{-1} of NaCl in yeast–peptone–dextrose medium. The

Evolutionary rescue



In theory …

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

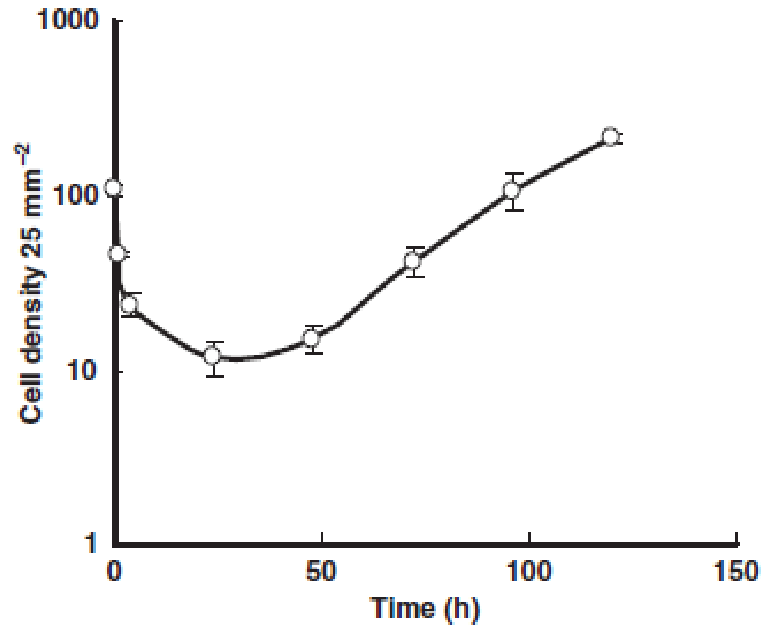


Figure 1 Collapse and recovery of yeast populations (mean ± 1 SE) exposed to high-salt concentration. The concentration used was 125 g L^{-1} of NaCl in yeast–peptone–dextrose medium. The

BUT:
NO THEORY
FOR COMMUNITIES

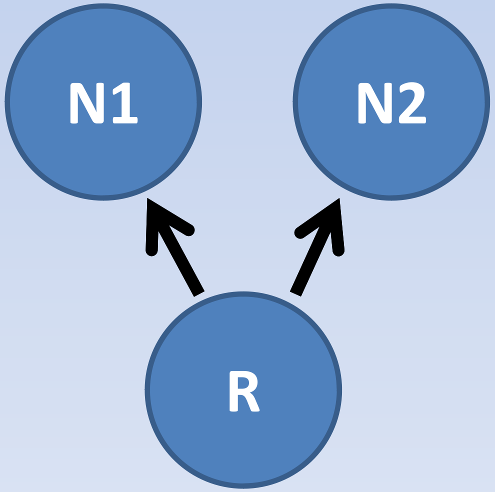
Chapter 4

Community Evolutionary Rescue

The System

An Armstrong-McGehee type competitive system

- Oscillatory dynamics
- External environmental change
- Trait evolution



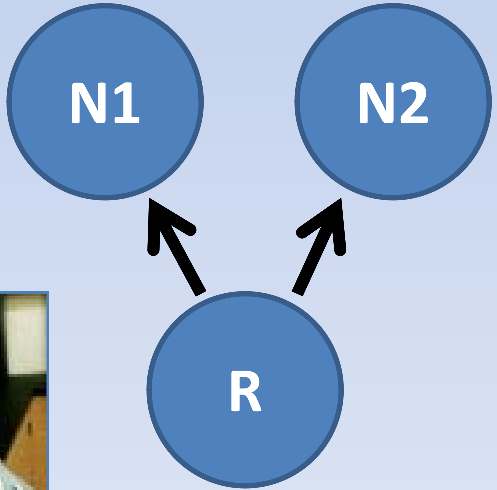
Chapter 4

Community Evolutionary Rescue

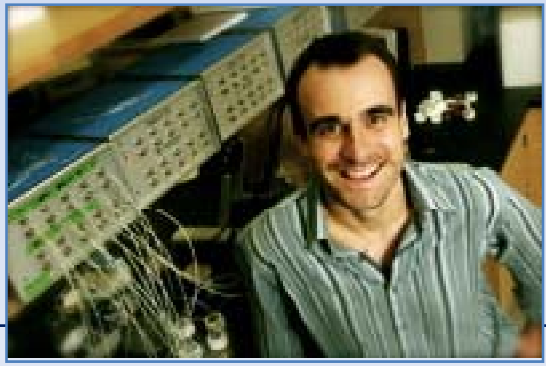
The System

An Armstrong-McGehee type competitive system

- Oscillatory dynamics
- External environmental change
- Trait evolution



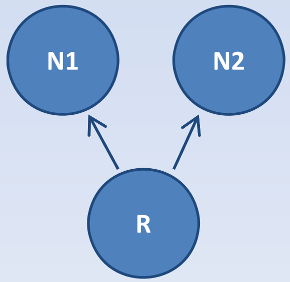
With Andrew Gonzalez, McGill



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?



The Model

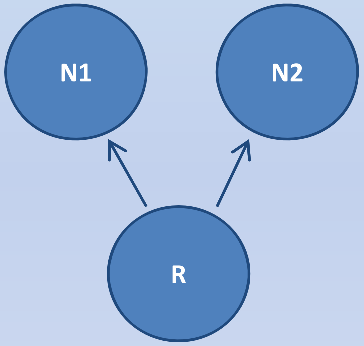
2 × Rosenzweig-MacArthur = Armstrong-McGehee

$$\frac{dR}{dt} = \mu R\left(1 - \frac{R}{K}\right) - f_1(R)N_1 - f_2(R)N_2$$

$$\frac{dN_1}{dt} = \varepsilon_1 f_1(R)N_1 - m_1 N_1$$

$$\frac{dN_2}{dt} = \varepsilon_2 f_2(R)N_2 - m_2 N_2$$

$$\text{with: } f_1(R) = \frac{a_1 R}{1 + b_1 R}; \quad f_2(R) = \frac{a_2 R}{1 + b_2 R}$$

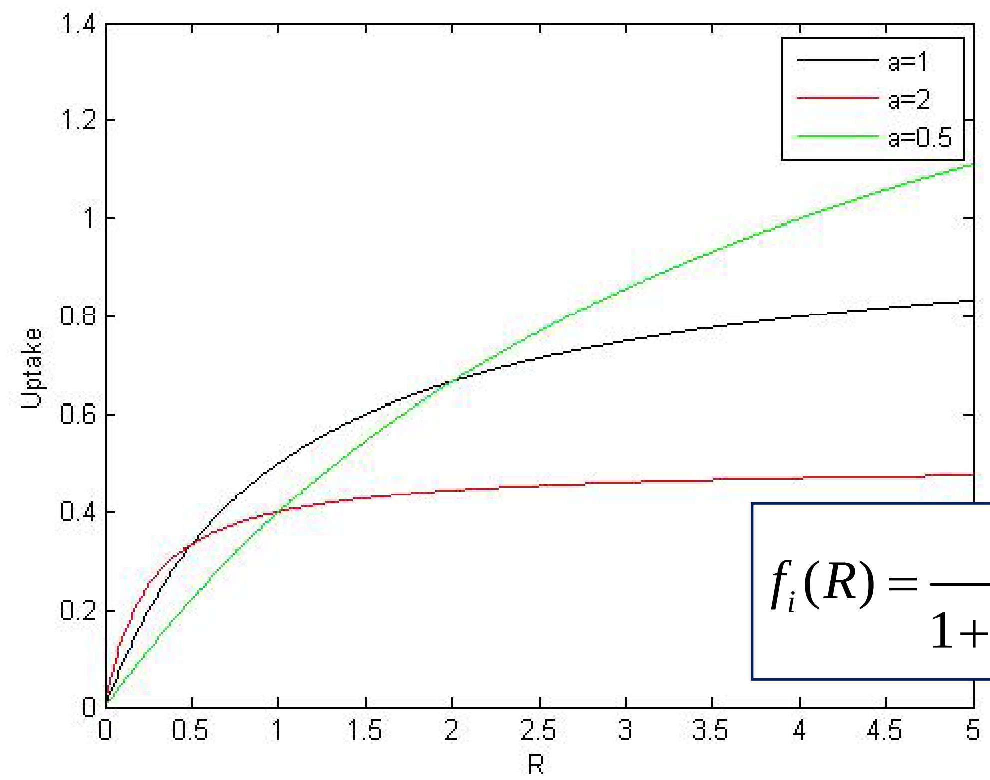


The Model

Linear environmental change

$$\frac{dT}{dt} = p$$

affects curvature of the functional response.



$$f_i(R) = \frac{\left(a_i + z_i T(p)\right) R}{1 + c_i \left(a_i + z_i T(p)\right)^{q_i} R}$$

The Model

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

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

$$= \nu_i \varepsilon_i R \frac{1 + c_i\left(a_i + z_i T(p)\right)^{q_i} R\left(1 - q_i\right)}{\left(1 + c_i\left(a_i + z_i T(p)\right)^{q_i} R\right)^2}$$

The Model

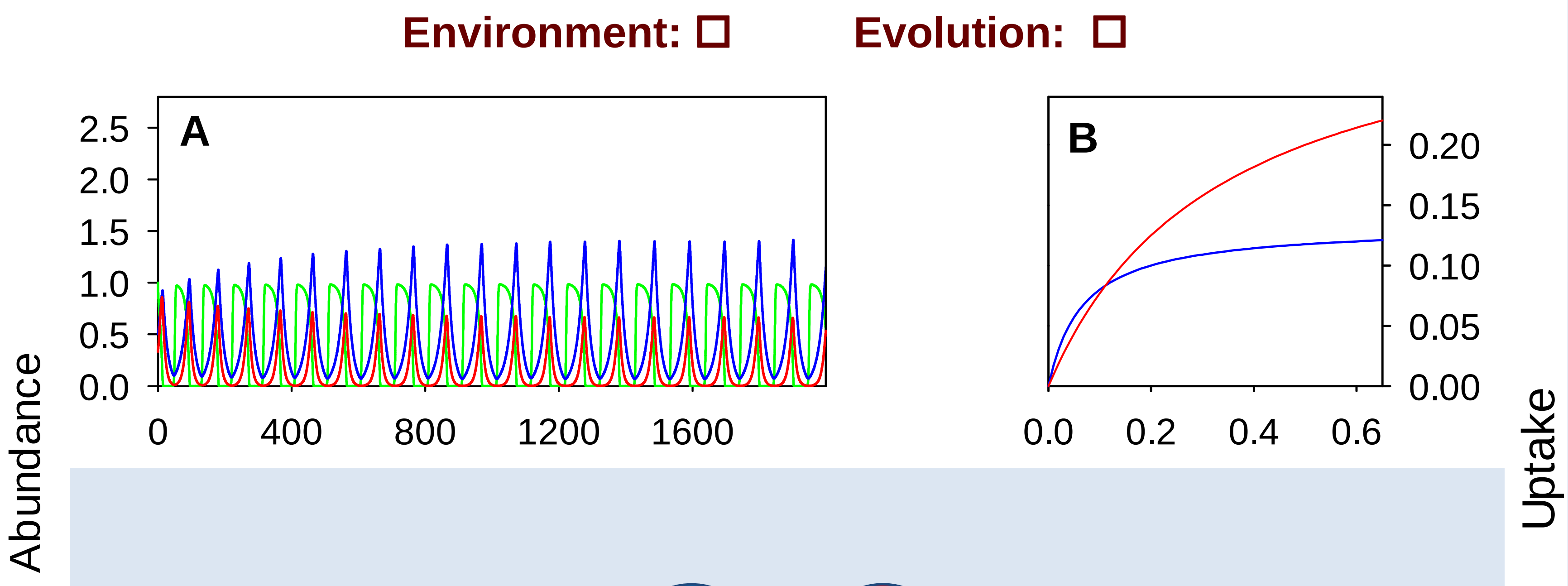
- Manipulate direction and intensity of
  - Environmental change: parameter z_i
  - Evolutionary change: parameter ν_i

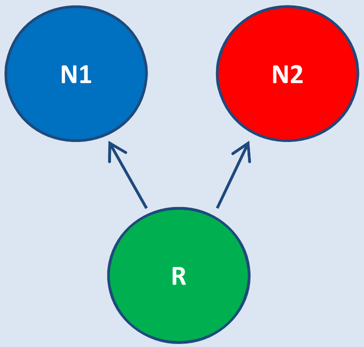
$$\frac{da_i}{dt} = \nu_i \frac{\partial\left(\frac{1}{N_i}\frac{dN_i}{dt}\right)}{\partial a_i} = \nu_i \frac{\partial\left(\varepsilon_i \frac{\left(a_i + z_i T(p)\right)R}{1 + c_i\left(a_i + z_i T(p)\right)^{q_i} R} - m_i\right)}{\partial a_i} =$$

$$= \nu_i \varepsilon_i R \frac{1 + c_i\left(a_i + z_i T(p)\right)^{q_i} R\left(1 - q_i\right)}{\left(1 + c_i\left(a_i + z_i T(p)\right)^{q_i} R\right)^2}$$

Results

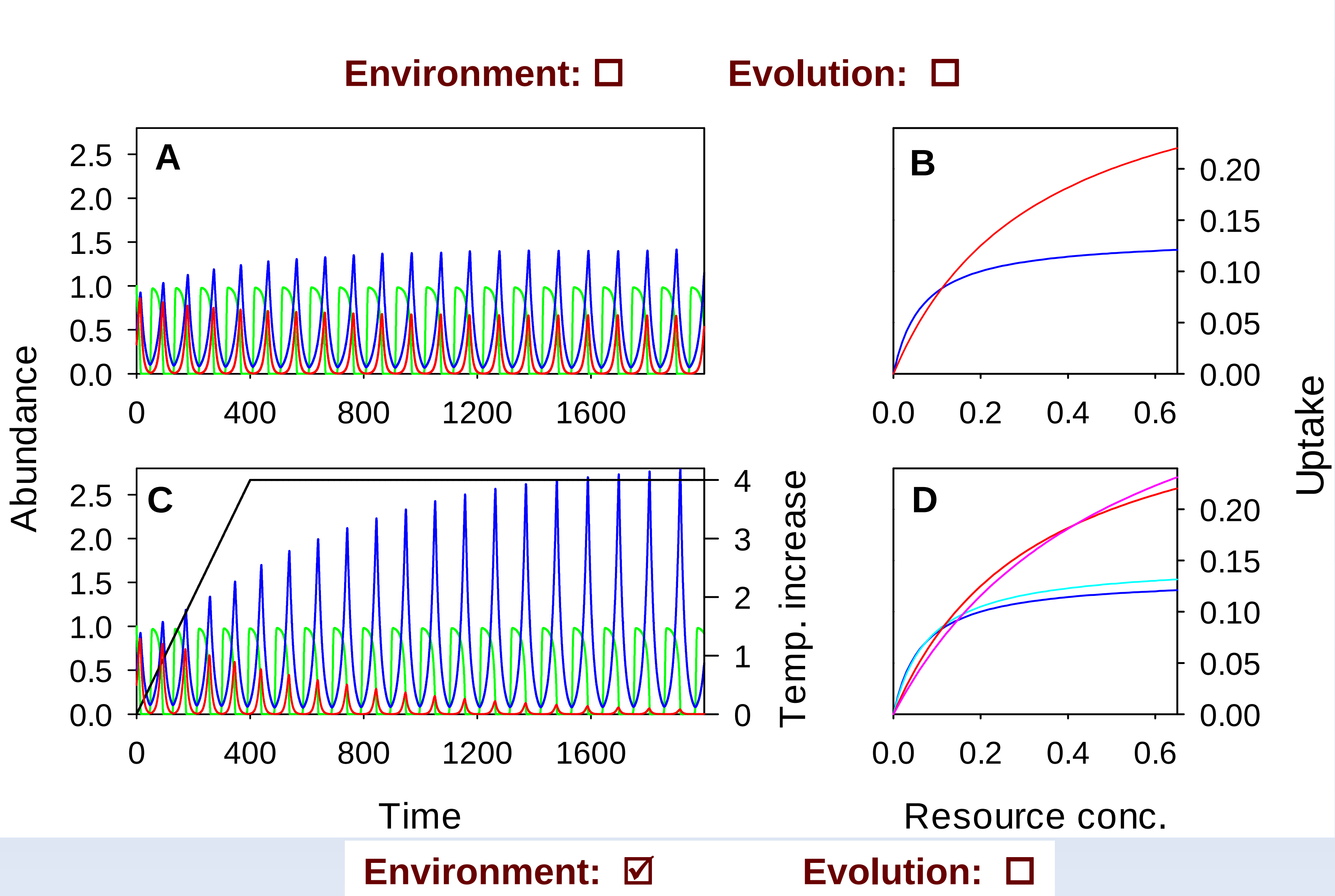
- The baseline Armstrong-McGehee dynamics





Results

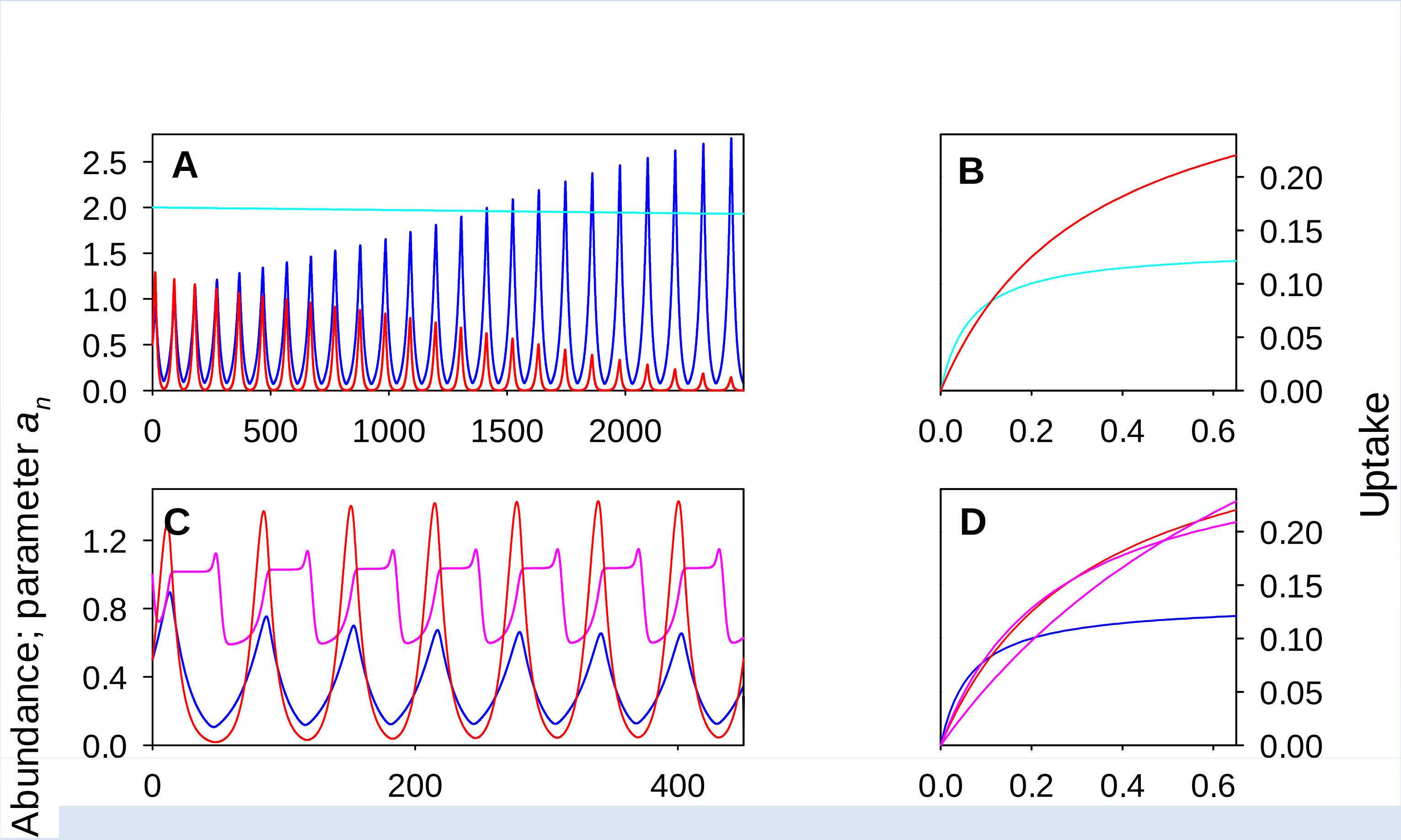
- Environmental change leads to extinction



Results

- Evolution can lead to extinction but doesn't need to

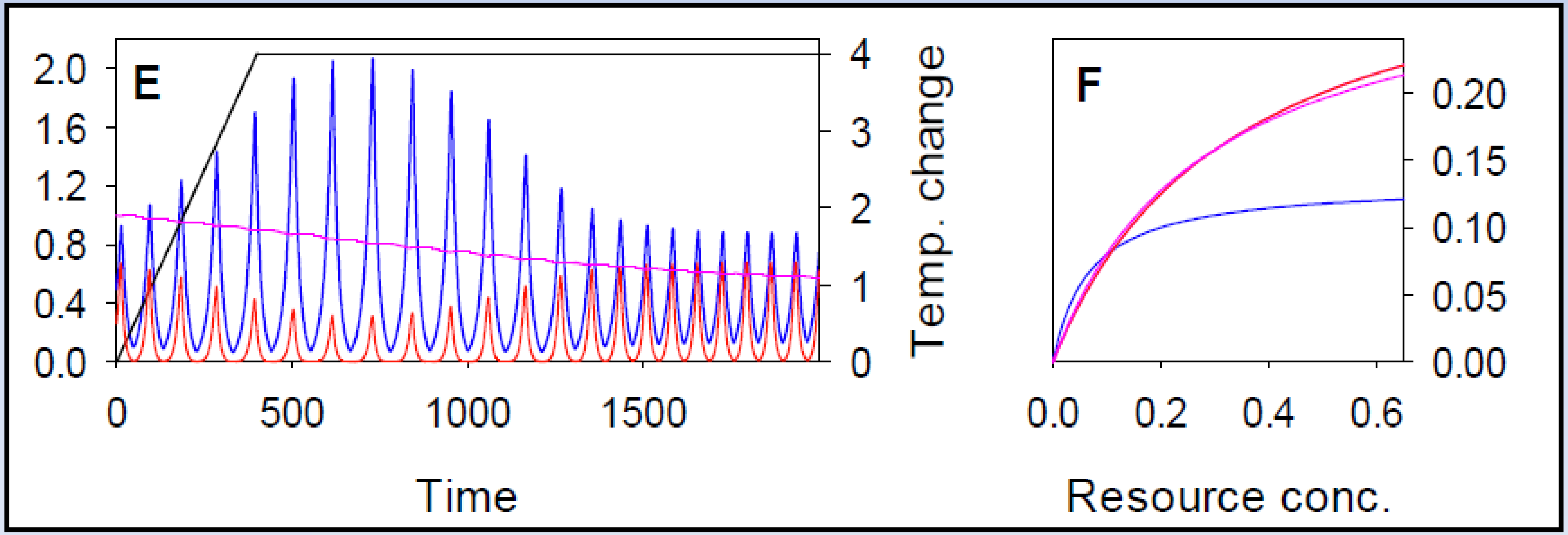
Environment: ☐ Evolution: ☑



Results

- Evolutionary rescue can occur
- Recovery dynamics can be reminiscent of the "U-shaped curve"

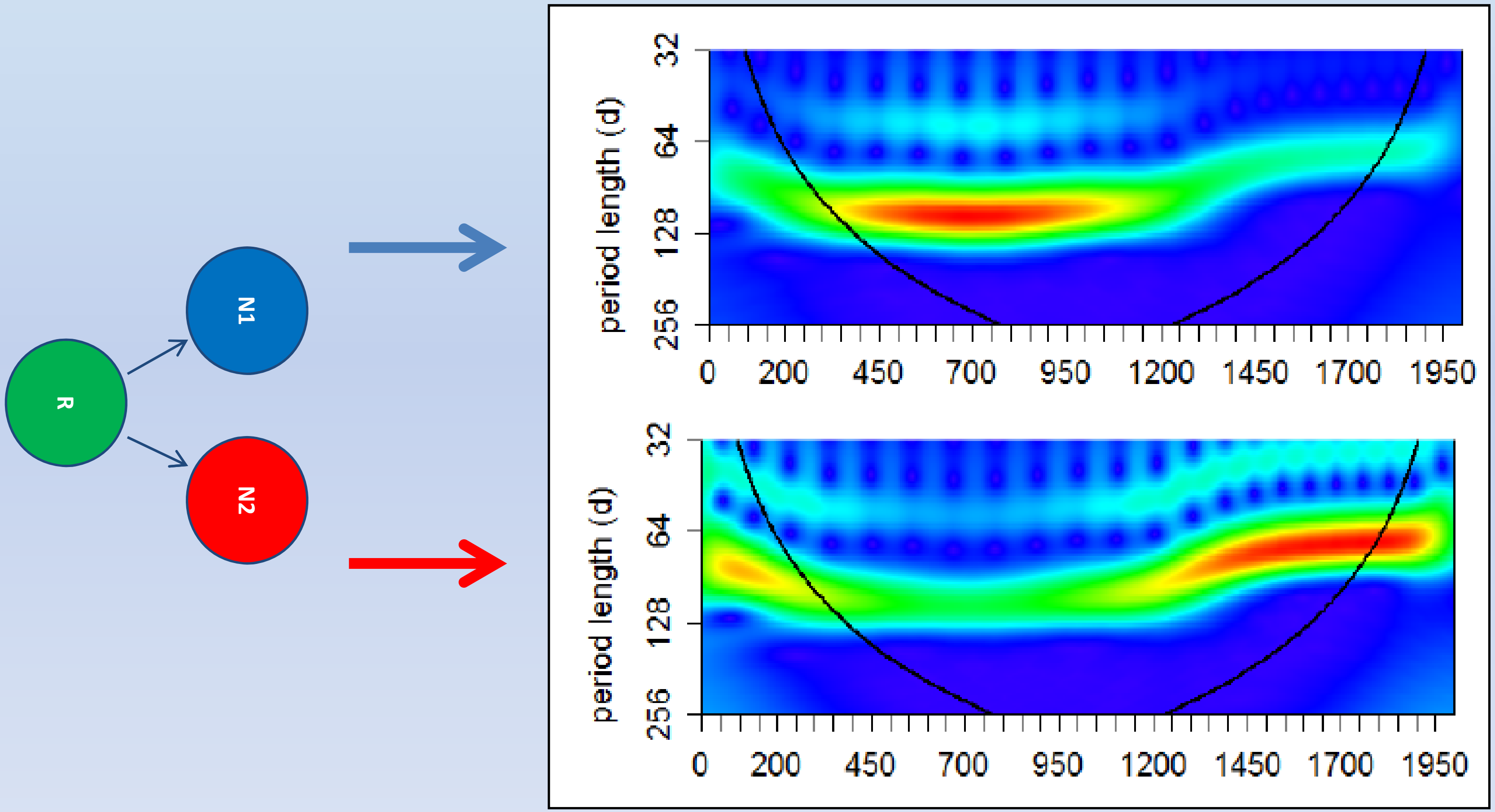
Environment: ☑ Evolution: ☑



Fussmann & Gonzalez, revision submitted, *Roy. Soc. Interface*

Results

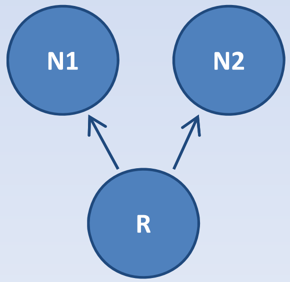
- Dynamic regime pre-, during, and post-rescue differs



Wavelets courtesy of L. Rudolf, B. Blasius

Conclusions

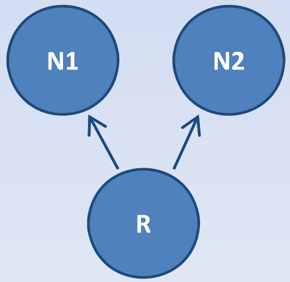
- ER is capable of maintaining an oscillating community experiencing sustained environmental change.
- This is a case study, but ER occurred over a wide range of evolutionary strengths (or genetic variances) and, thus, did not depend on evolution being "just right."



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."