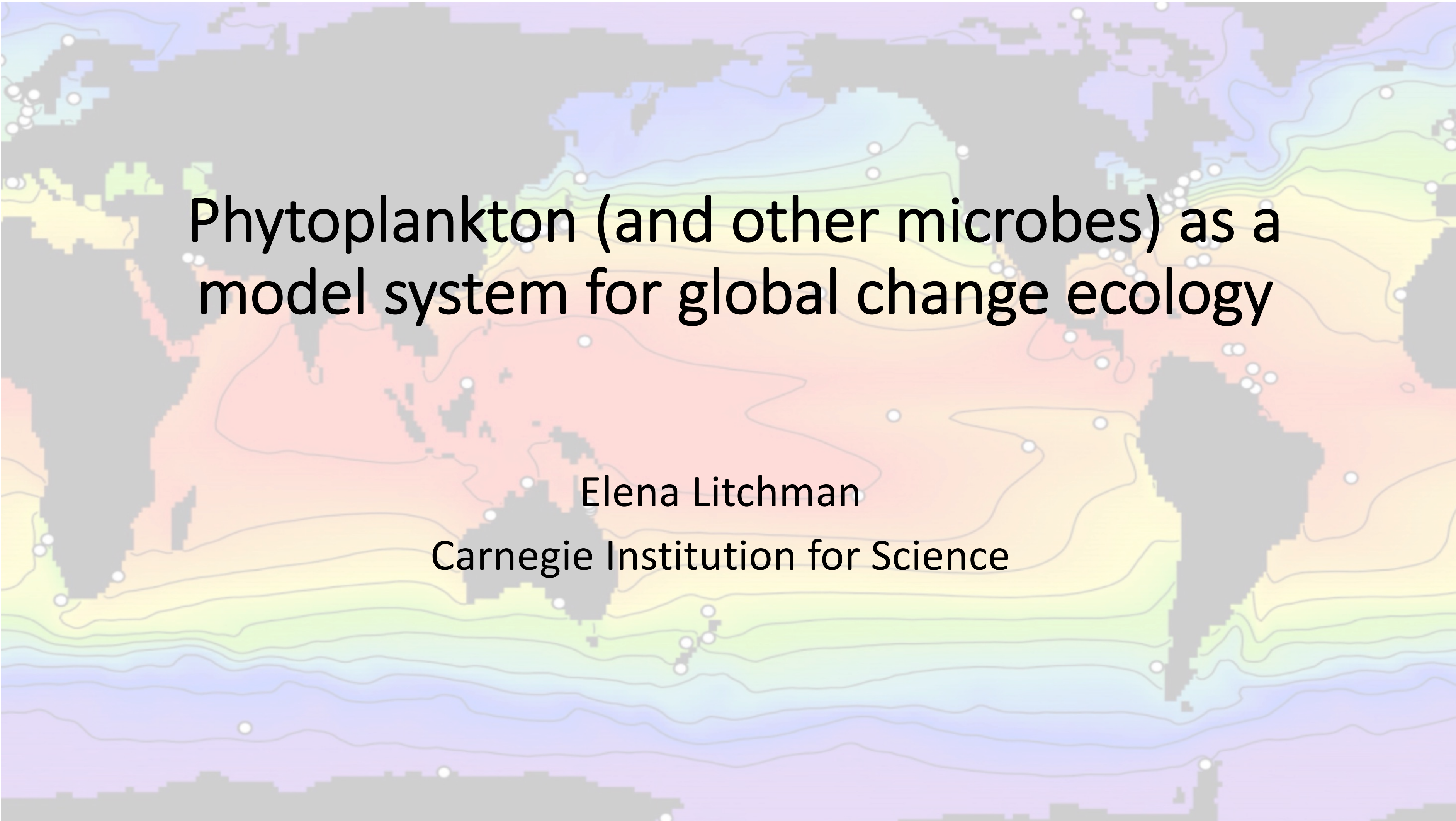
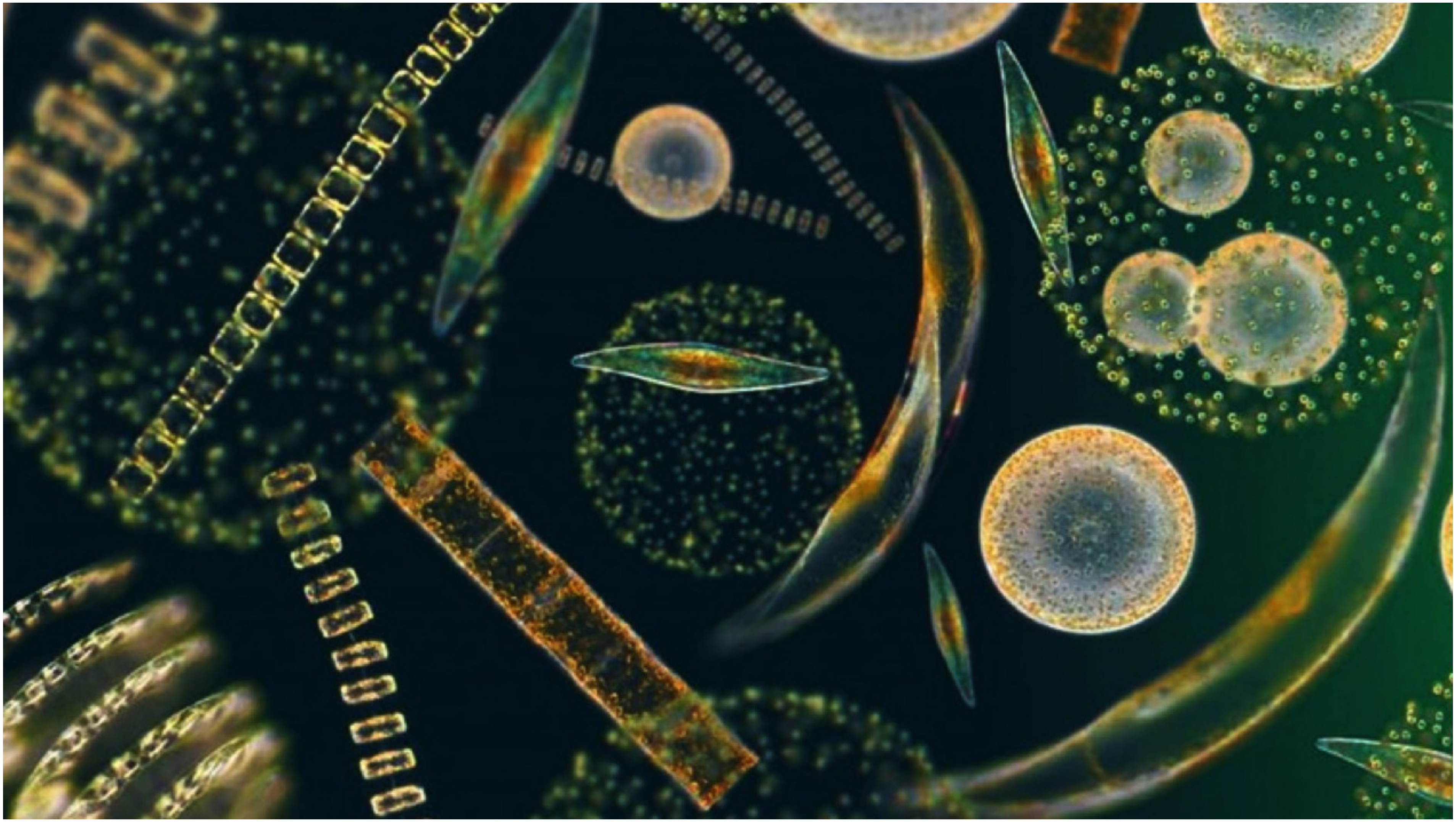


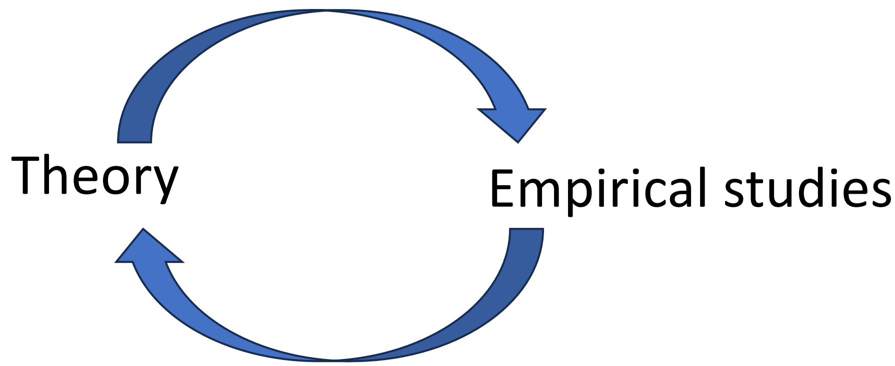
Phytoplankton (and other microbes) as a model system for global change ecology

Elena Litchman

Carnegie Institution for Science

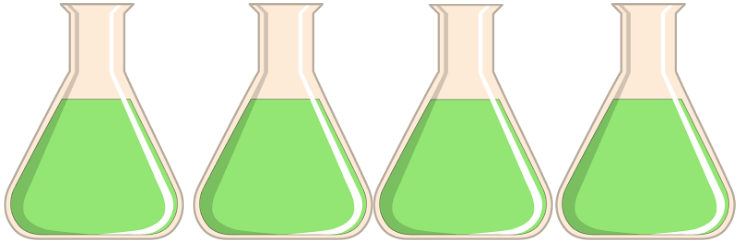


Theory + empirical studies (e.g., experiments) = powerful scientific approach in many disciplines

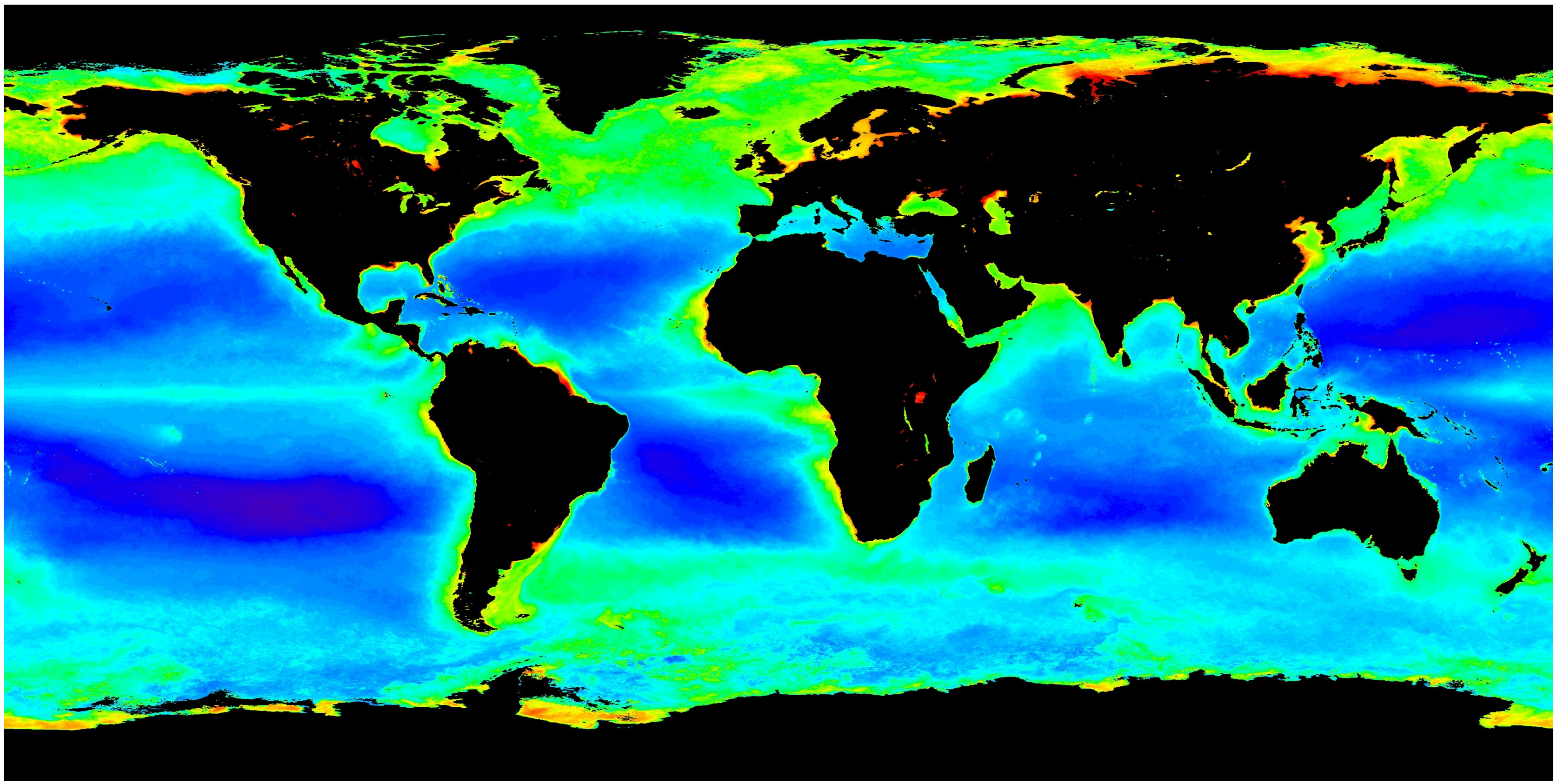


Microbes as a model system

- Phytoplankton and other microbes are an excellent model system in ecology
  - Short generation times (double in a day or less)
  - Large population numbers
  - Easy to manipulate, replicate

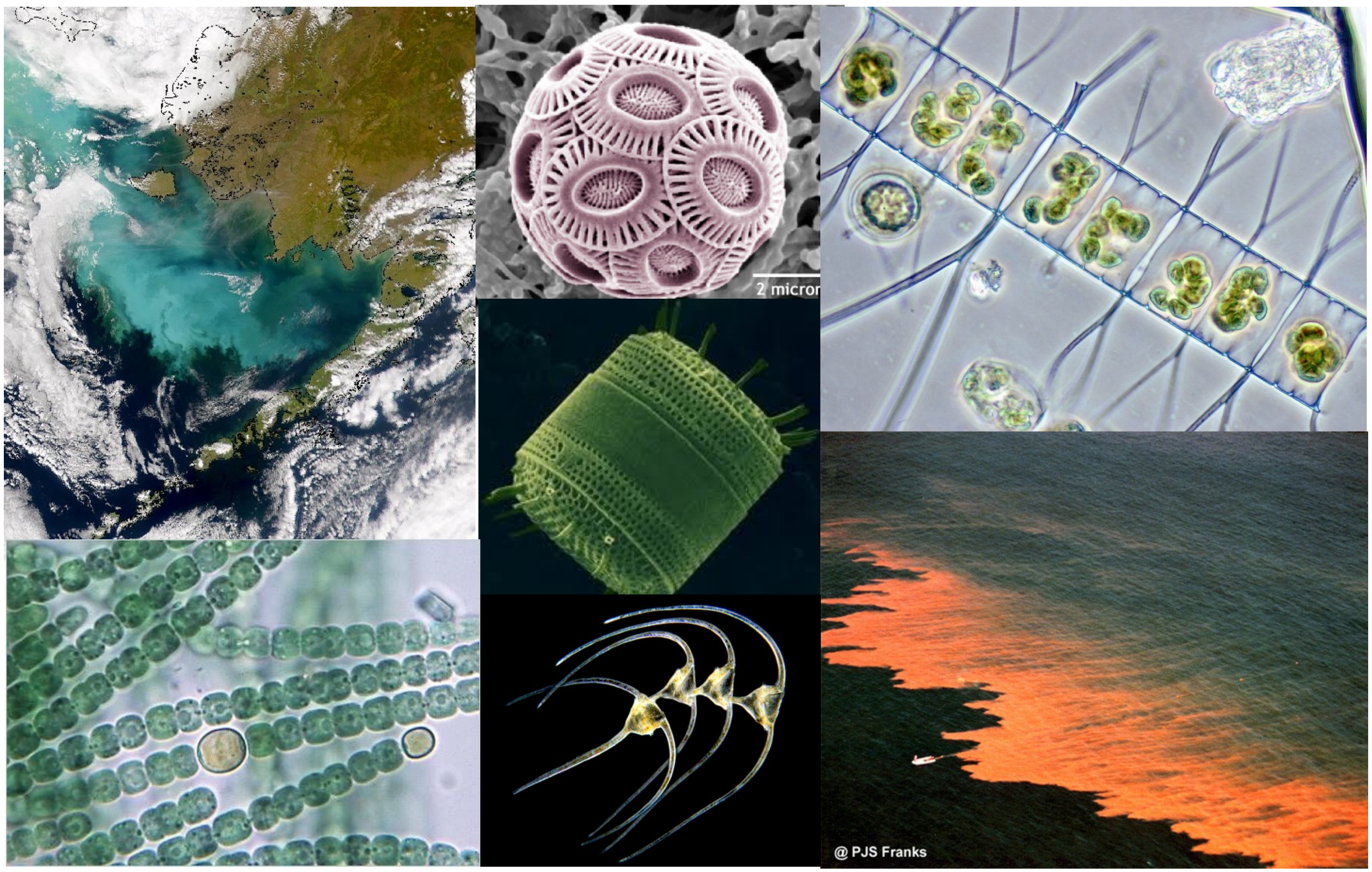


Phytoplankton perform 1/2 of global carbon fixation!



http://oceancolor.gsfc.nasa.gov/SeaWiFS/Gallery_Images/S19972442000244.L3m_CLI_CHLO.jpg

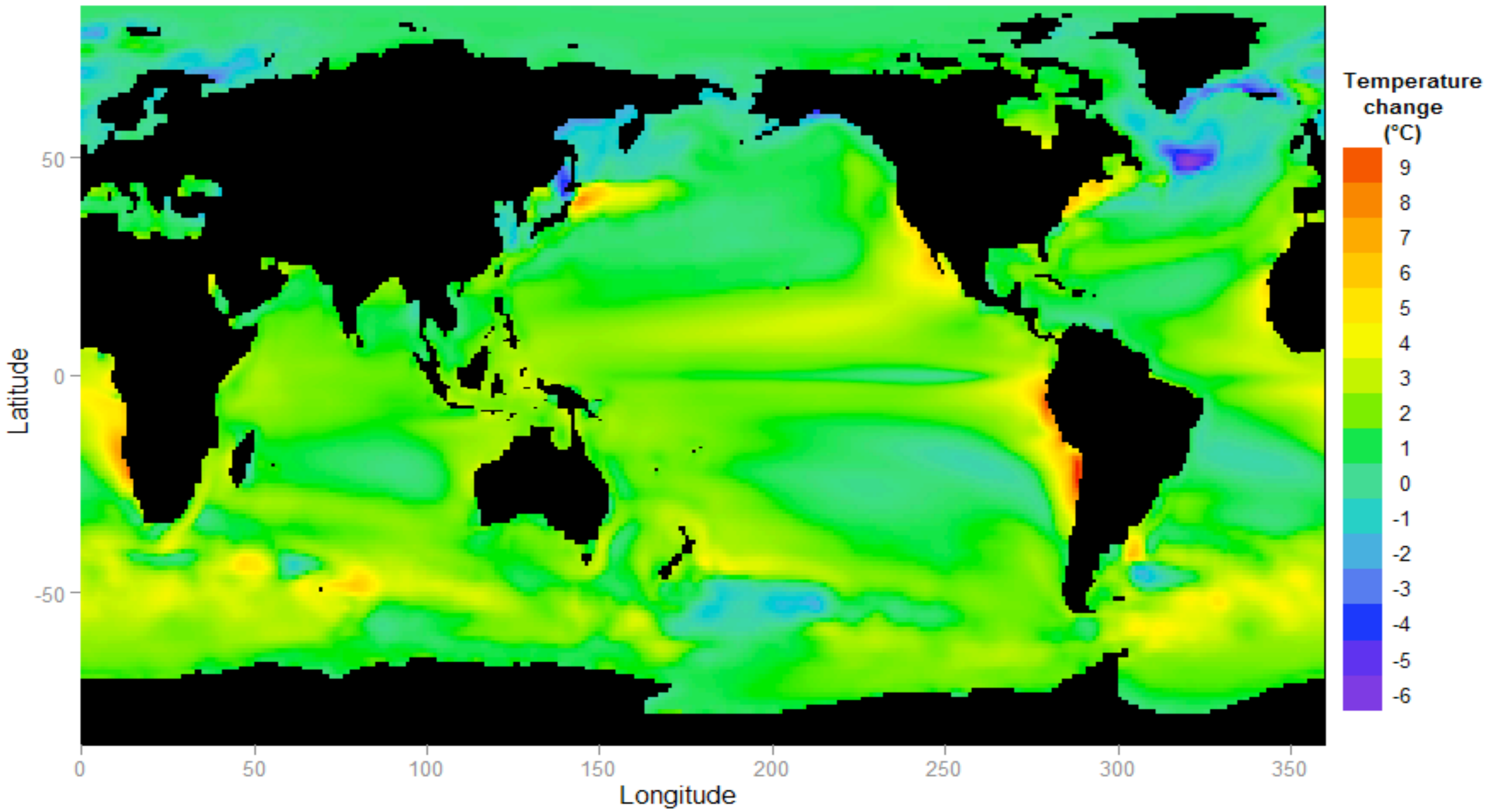
Functional and Biogeochemical Diversity



Complexity-related concepts

- Temperature dependence of growth
- Scaling from low level processes to high level patterns
- Nonlinear stressor interactions
- Importance of evolution
- Environmental change, community resilience and regime shifts (examples from plankton and human gut)
- The role of organismal traits in determining resilience

Predicted Temperature Change
Present-2100



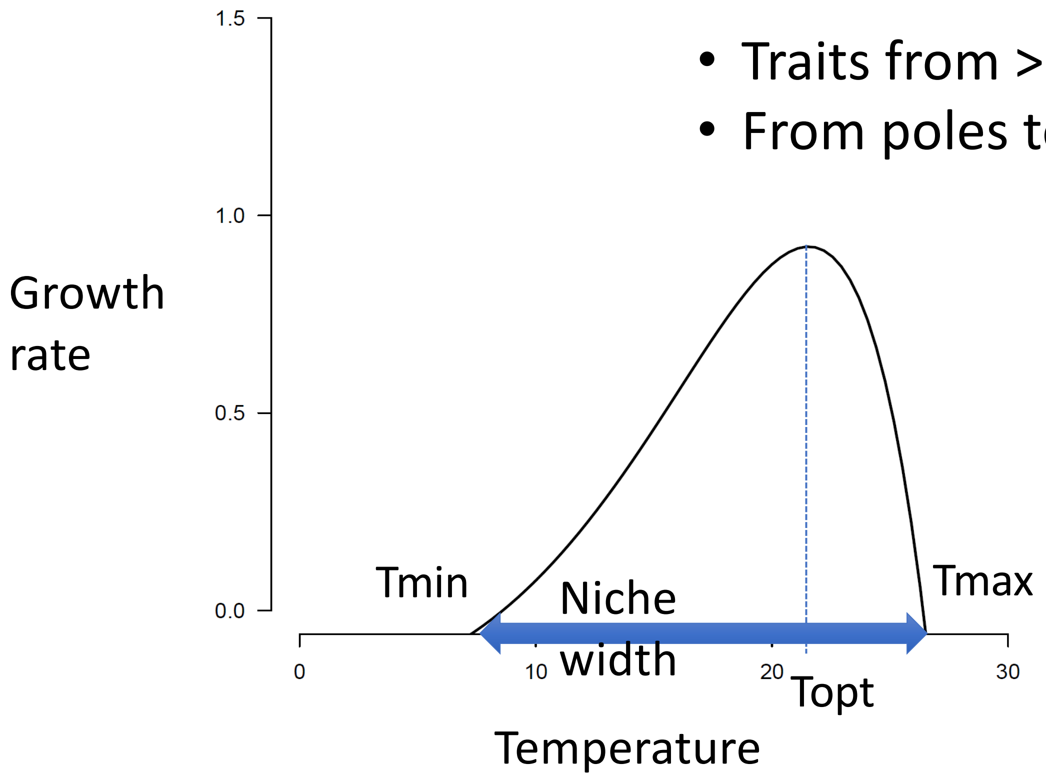
Responses of Species and Communities to Global Change

- Change physiology
- Disperse to more favorable locations
- Selection on genetic variation—evolutionary adaptation
- Species sorting (through competition): winners and losers
- Go extinct

Mechanistic Trait-based Framework

- The focus on ecological traits and trade-offs
- Can reduce complexity while incorporating diversity
- Can help uncover the mechanisms of community assembly
- Can explain and predict patterns of community organization

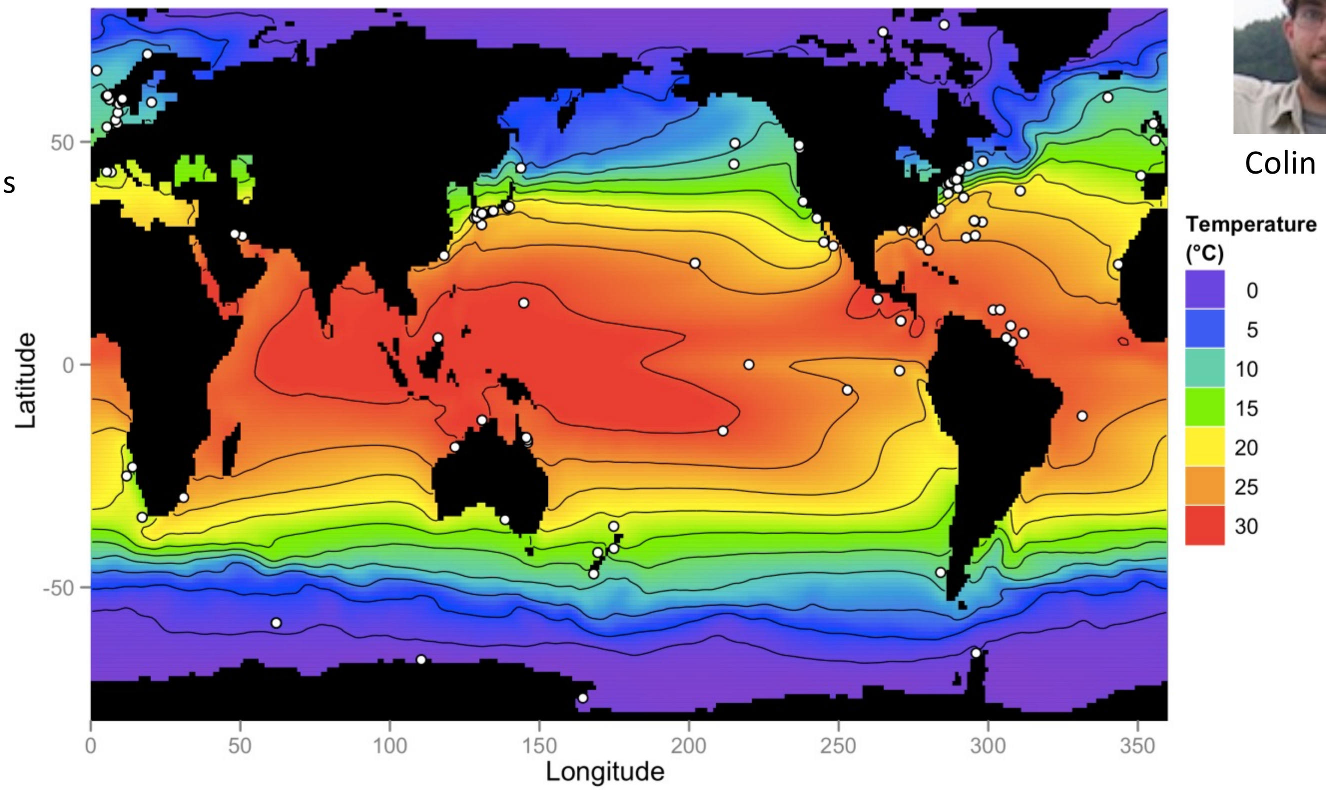
Typical Thermal Tolerance Curve and Relevant Traits



- Traits from >250 species
- From poles to tropics

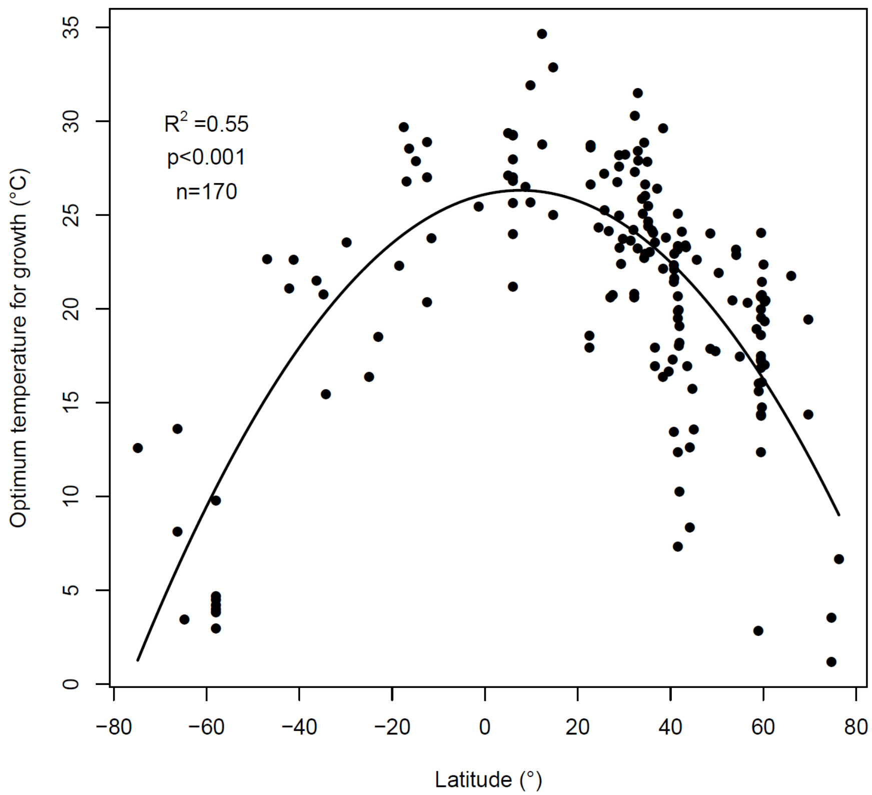
How Do Phytoplankton Respond to Temperature at Present and in the Future?


Mridul Thomas




Colin Kremer

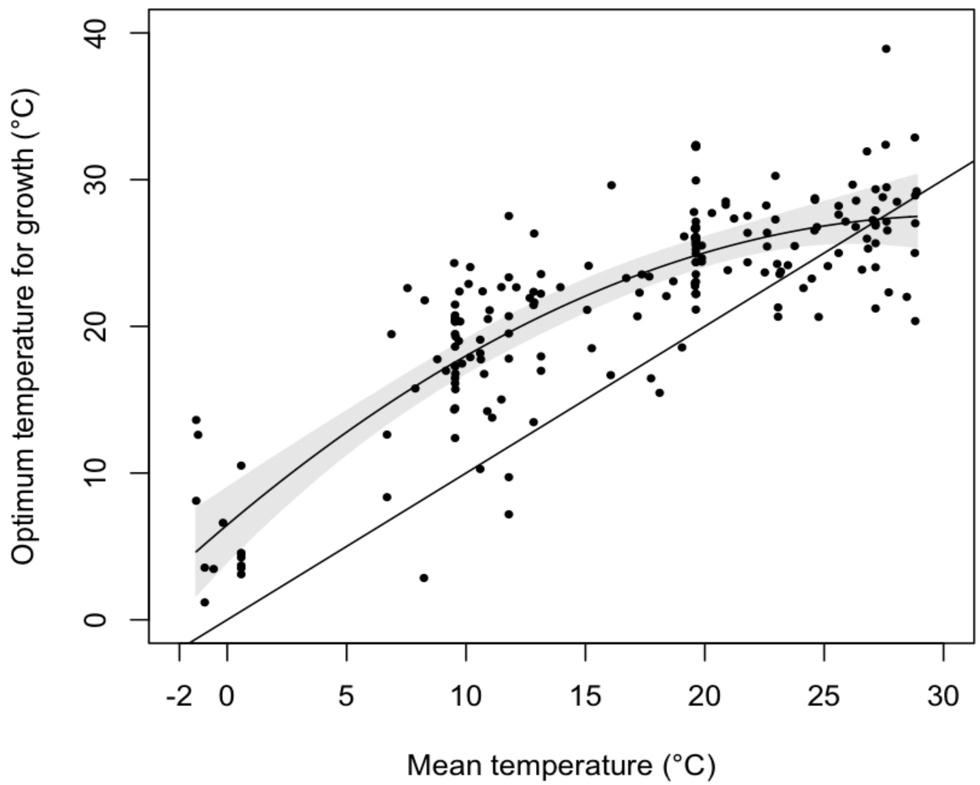
Strong Latitudinal Gradient in Optimal Temperature (Microbial Trait Biogeography)

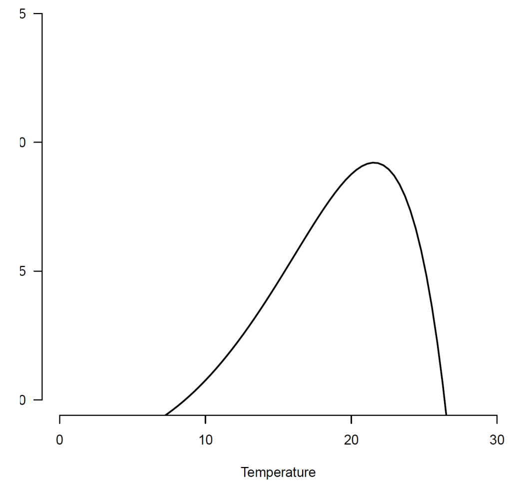


Thomas et al. Science 2012

Adaptation to Ambient Temperature

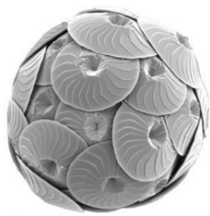
T_{opt}



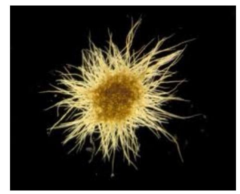


Thomas et al. Science 2012

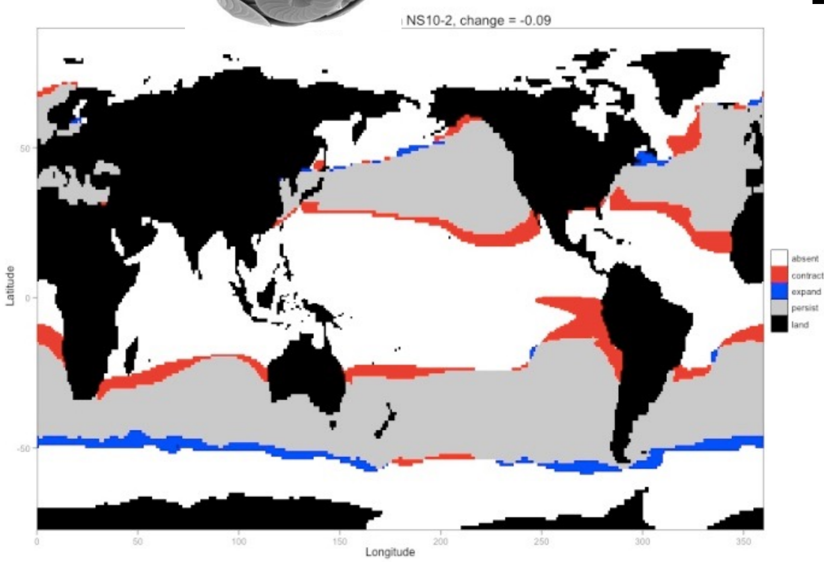
Predicted Range Shifts due to Warming

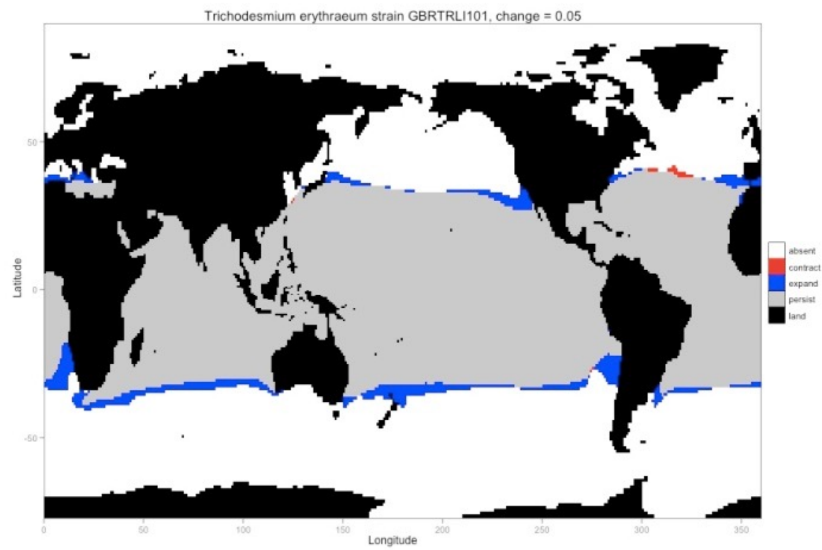


Calcidiscus leptoporus



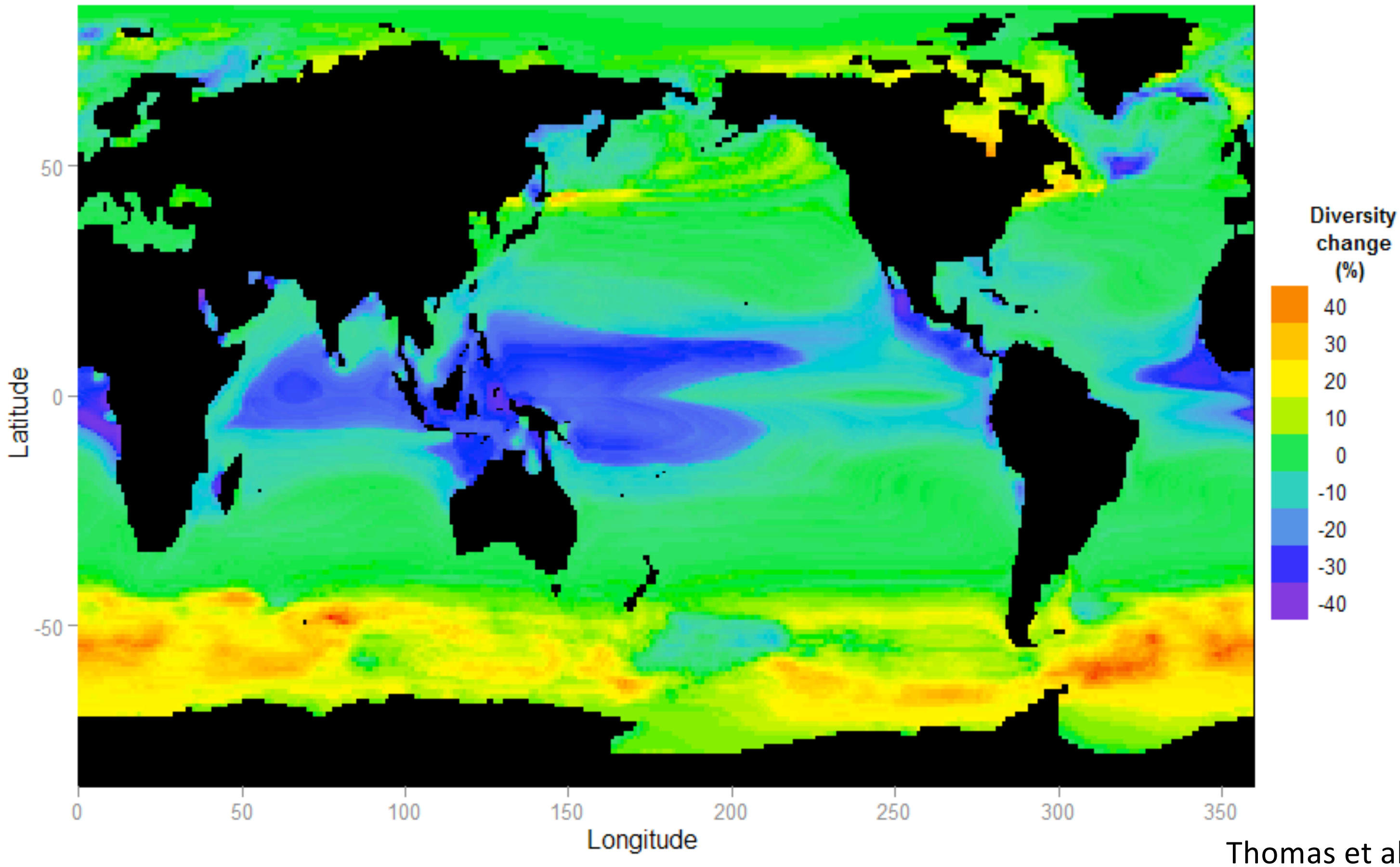
Trichodesmium erythraeum





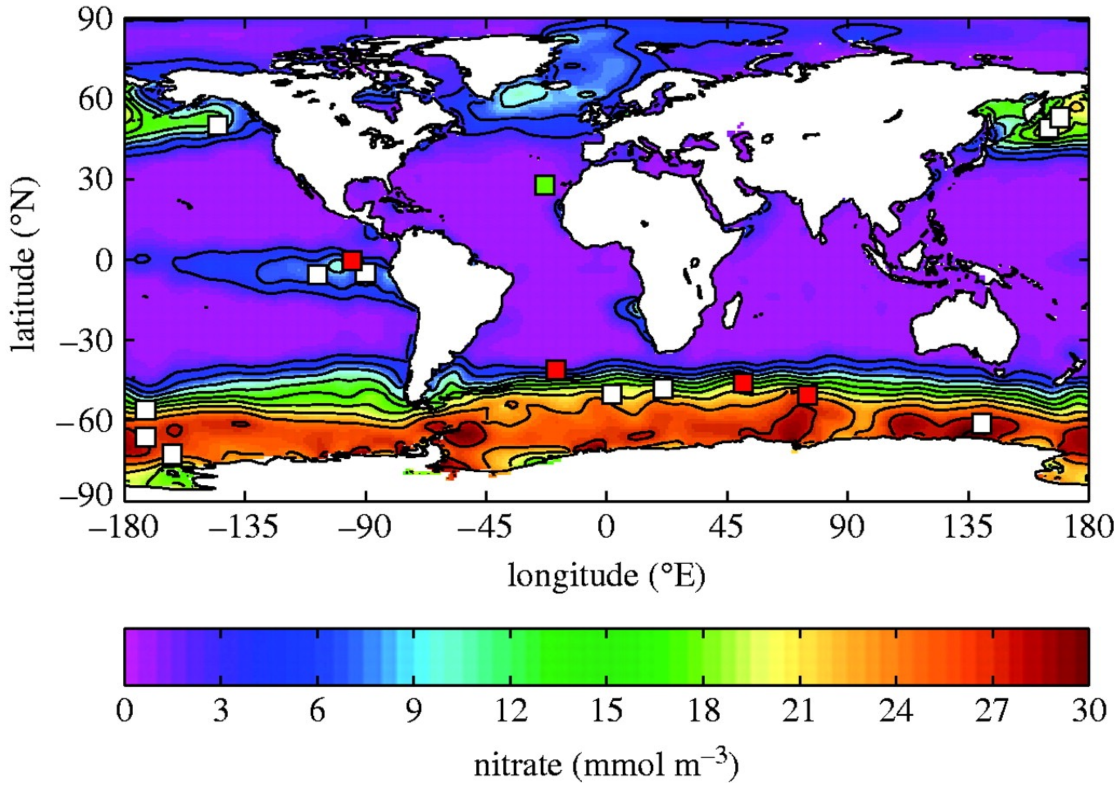
Thomas et al. Science 2012

Potential Diversity Changes due to Range Shifts



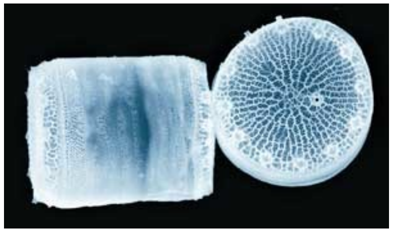
Thomas et al. Science 2012

How Will Nutrient Limitation Affect Temperature Sensitivity?

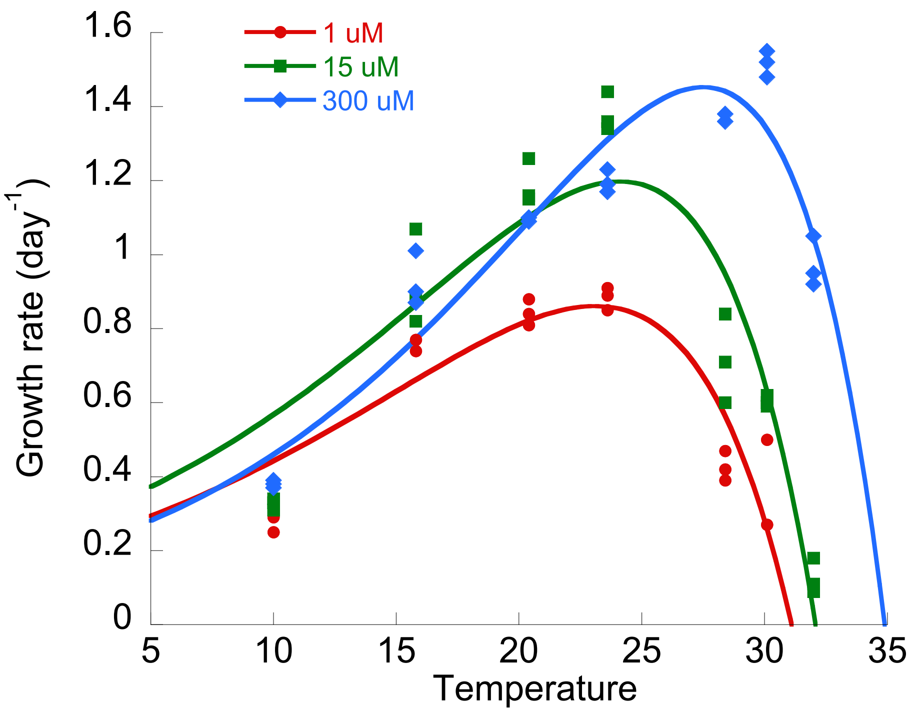


Temperature x Nutrient Interaction

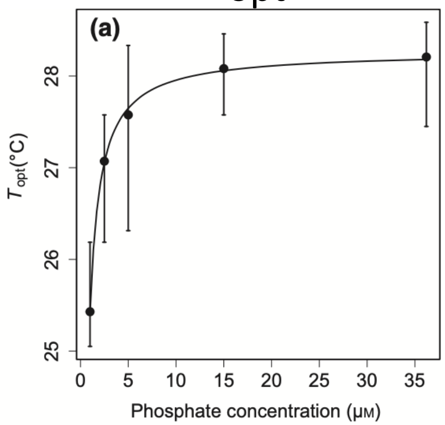
Temperature curves under different N



T. pseudonana



*T*opt

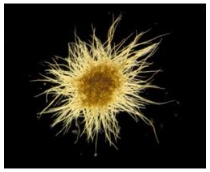


nutrient

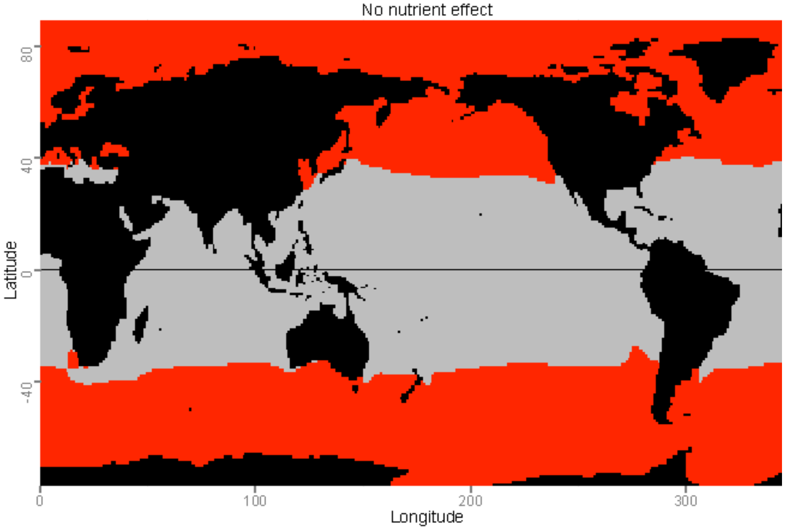
Thomas et al. GCB 2017

How would the predictions on range shifts change if we consider temperature x nutrient interaction?

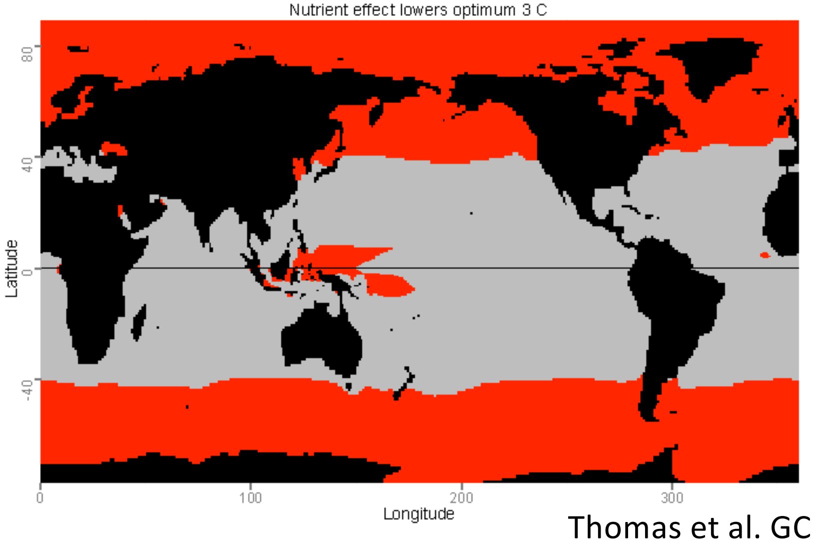
Trichodesmium



No nutrient limitation

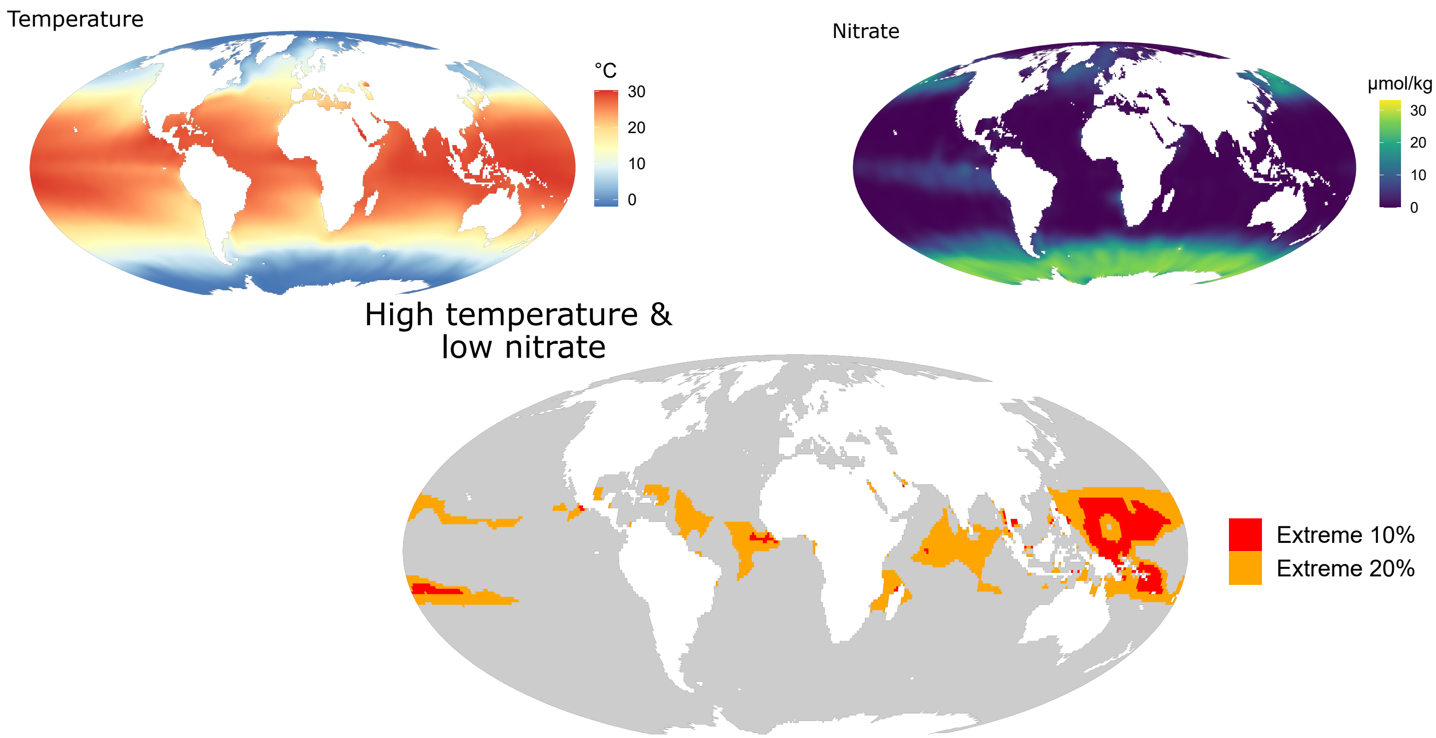


Nutrient limitation

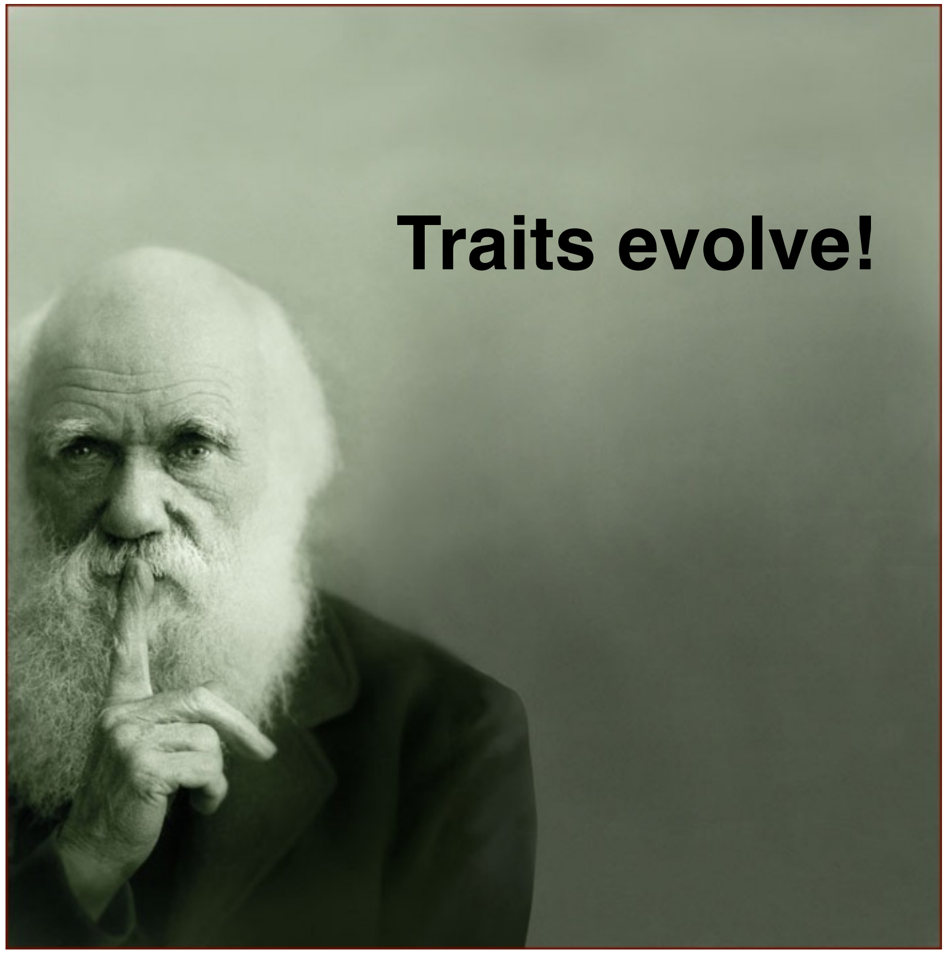


Thomas et al. GCB 2017

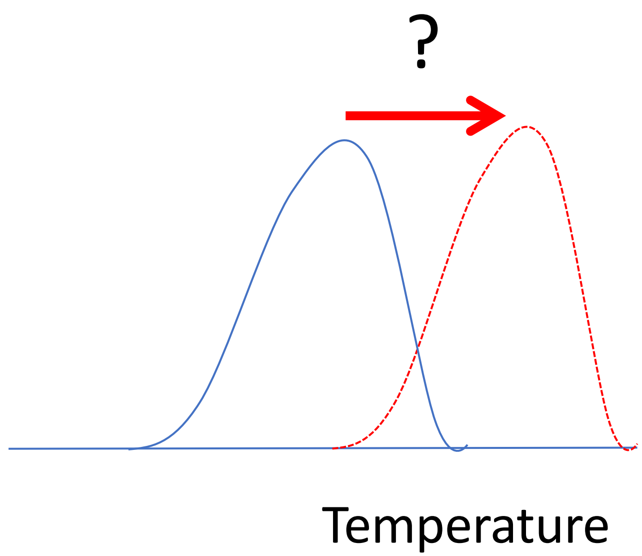
The most vulnerable regions = nutrient limitation and high temperature?



Litchman & Thomas Oikos 2022


Traits evolve!

Can Phytoplankton Adapt to Rising Temperatures?

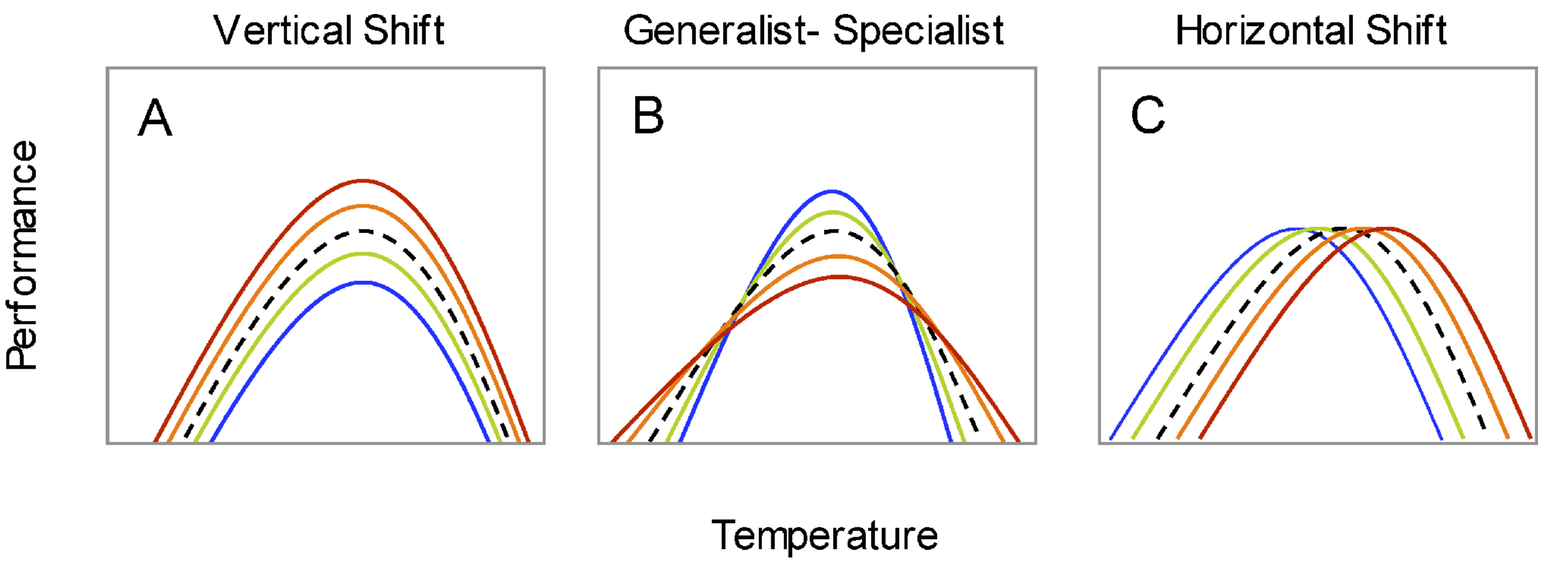


Patterns of adaptation
Temperature Evolution Experiments

Danny O'Donnell

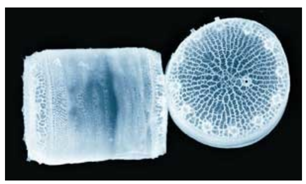
Maria Aranguren

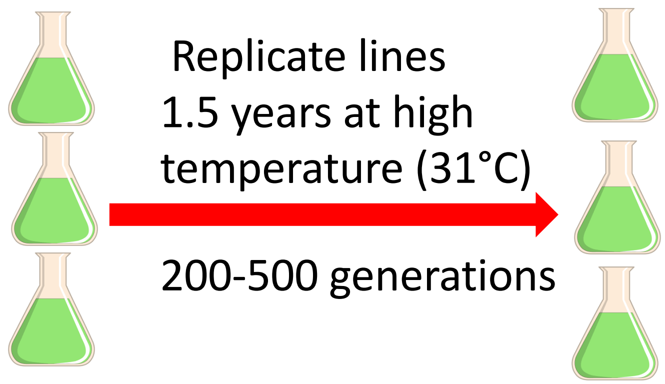
Possible evolutionary changes:



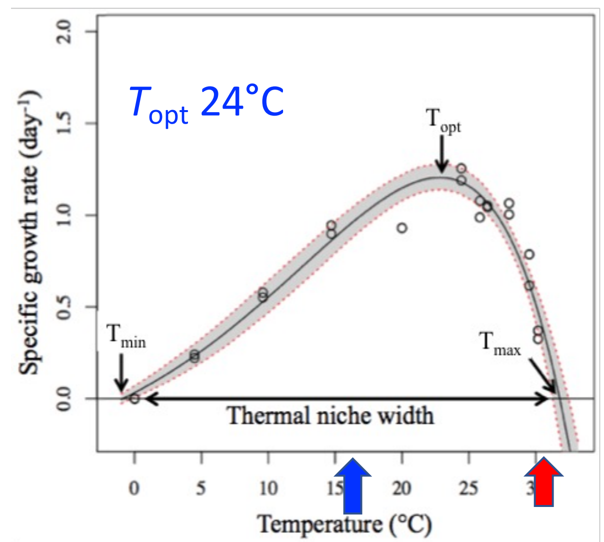
Temperature Evolution Experiments

Model marine diatom *Thalassiosira pseudonana*



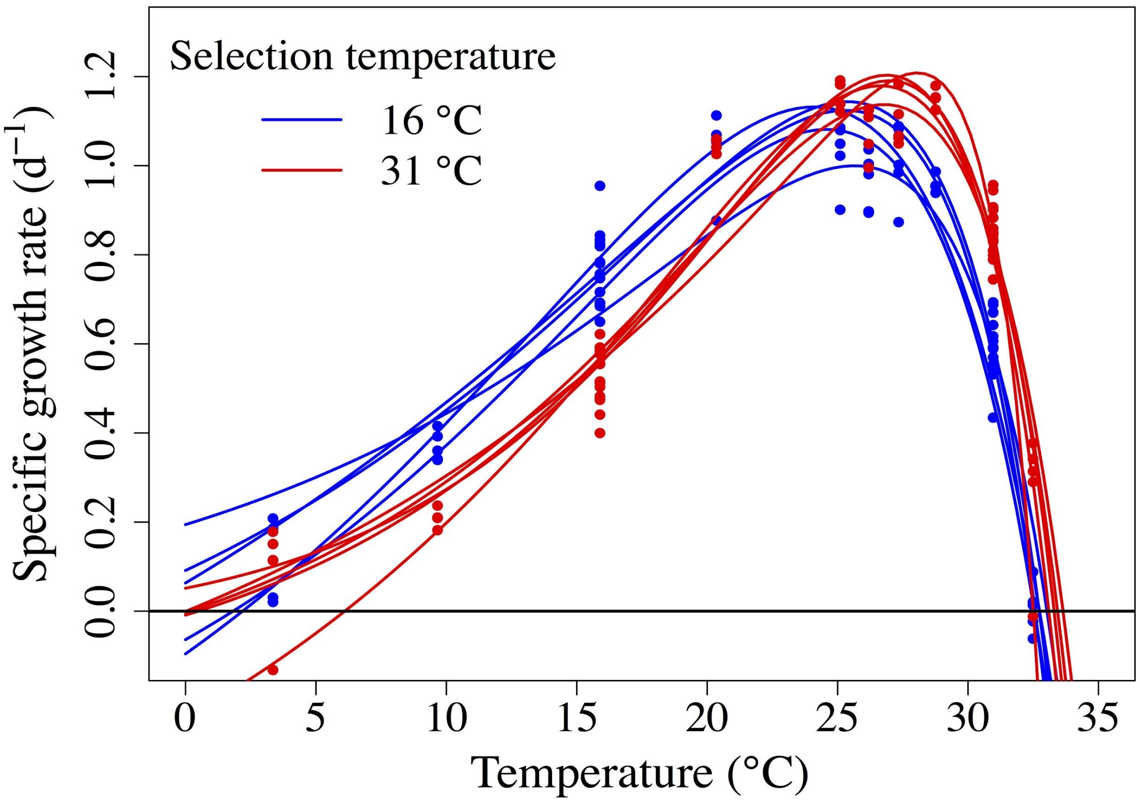


Ancestral strain



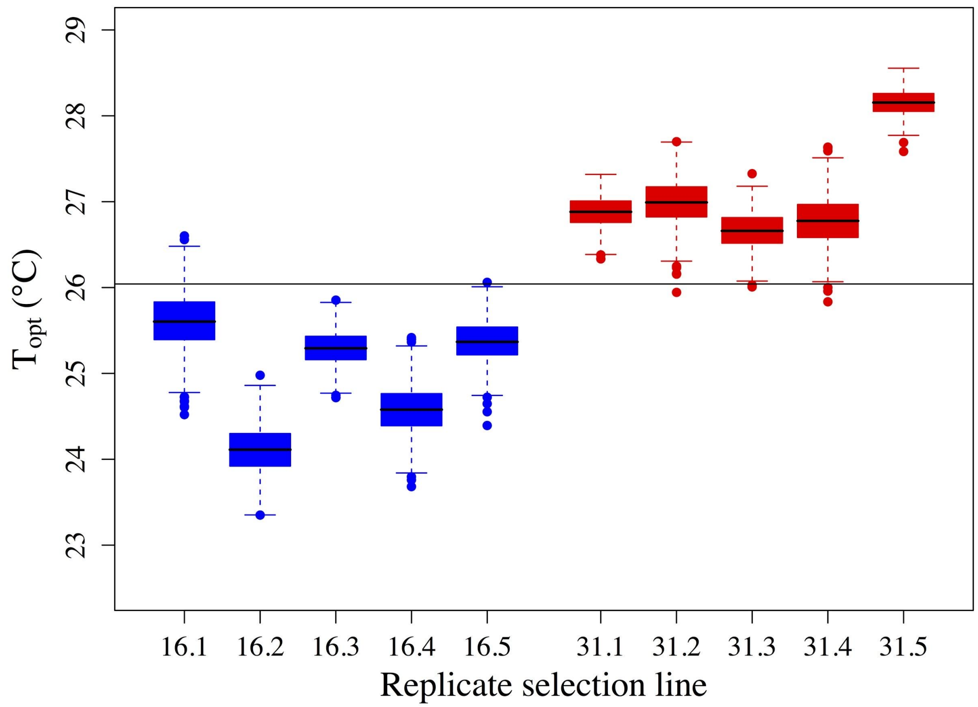
Controls at 16 °C

Response to selection at high temperature (31°C) ca. 350 generations



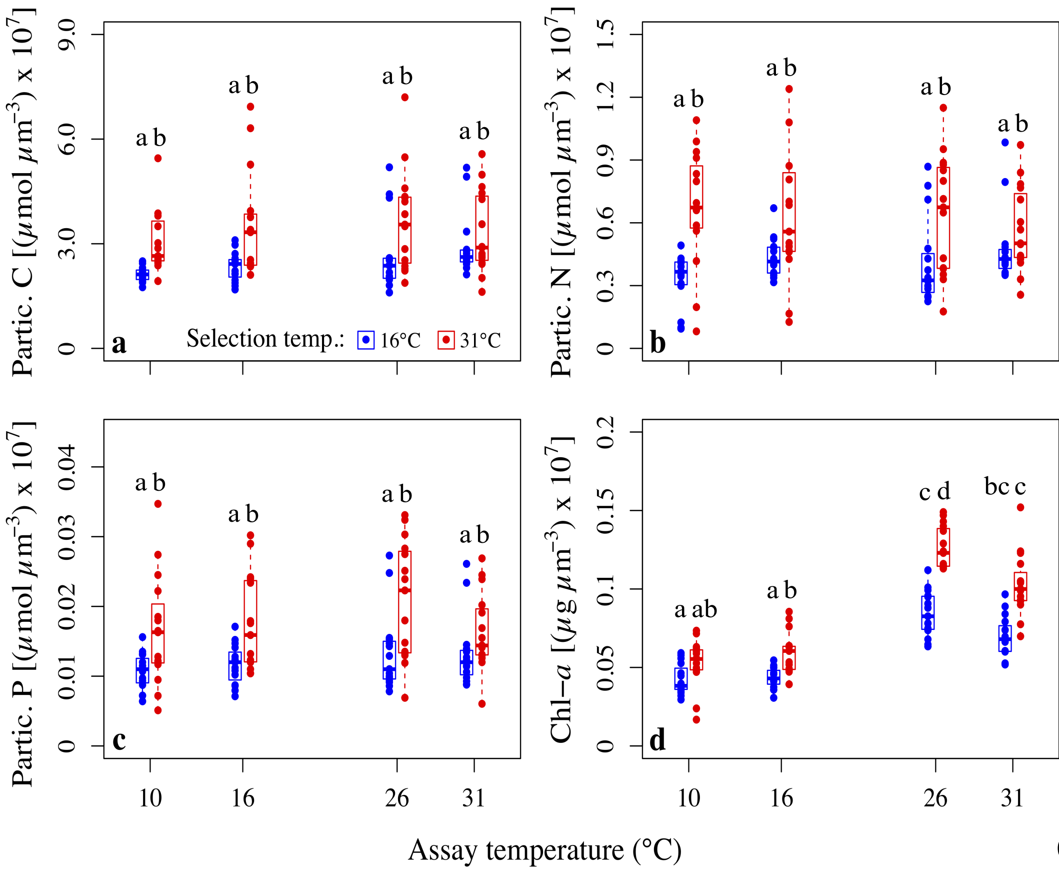
O’Donnell et al. GCB 2018

Evolutionary shift in optimum temperature T_{opt}



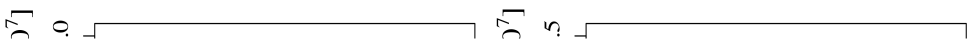
O’Donnell et al. GCB 2018

Differences in C, N, P and Chl *a*

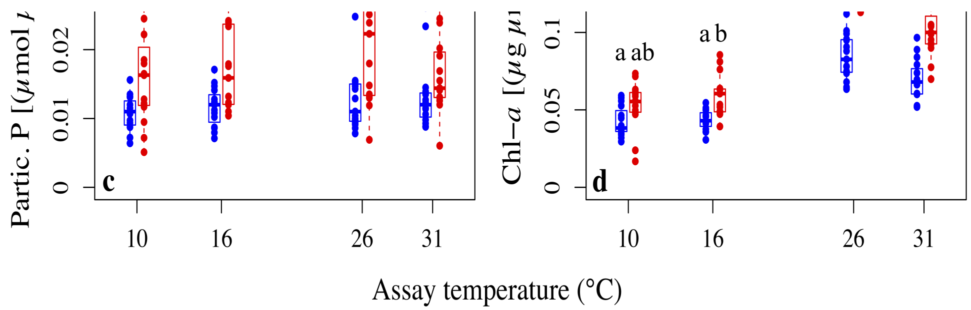


O'Donnell et al. L&O 2021

Differences in C, N, P and Chl *a*



C, N, P and Chl *a* were higher in 31°C-adapted lines
and
C:N and C:P were lower



O'Donnell et al. 2021

Trade-offs in Adaptation to Different Temperatures

Model with costs and benefits can explain the observed trade-off:

$$f(T) = b_1 e^{b_2 T} - d_1 e^{d_2 T} - d_0$$

T-dependent birth

T-dependent death

Cost of protection p (lower birth):

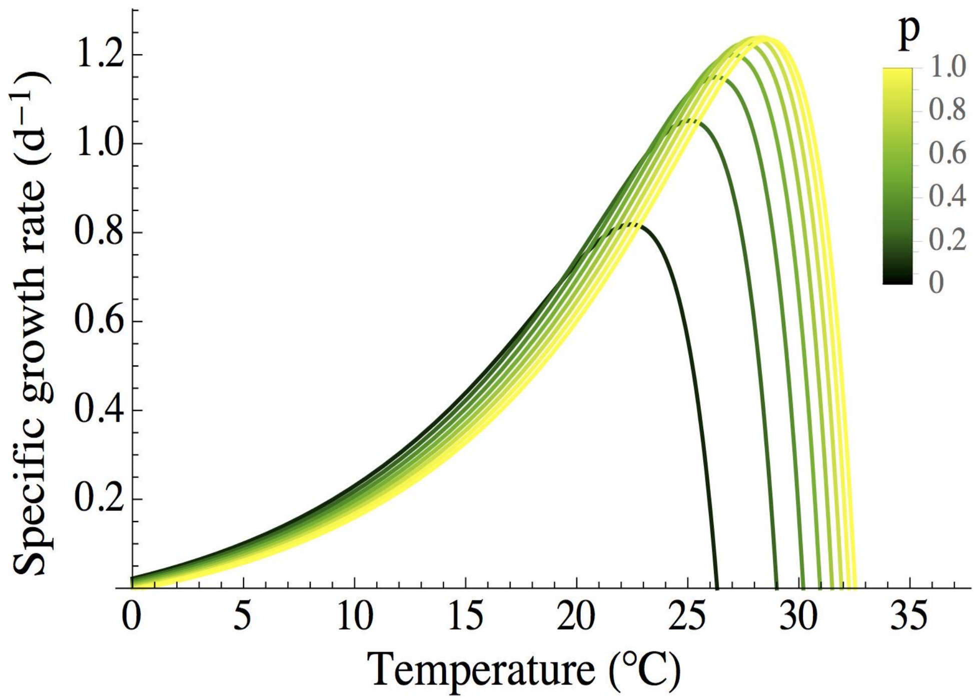
$$q = q_0 + q_1 p \qquad b_1 = \frac{b_1{}'}{q}$$

Benefit of protection p (lower death):

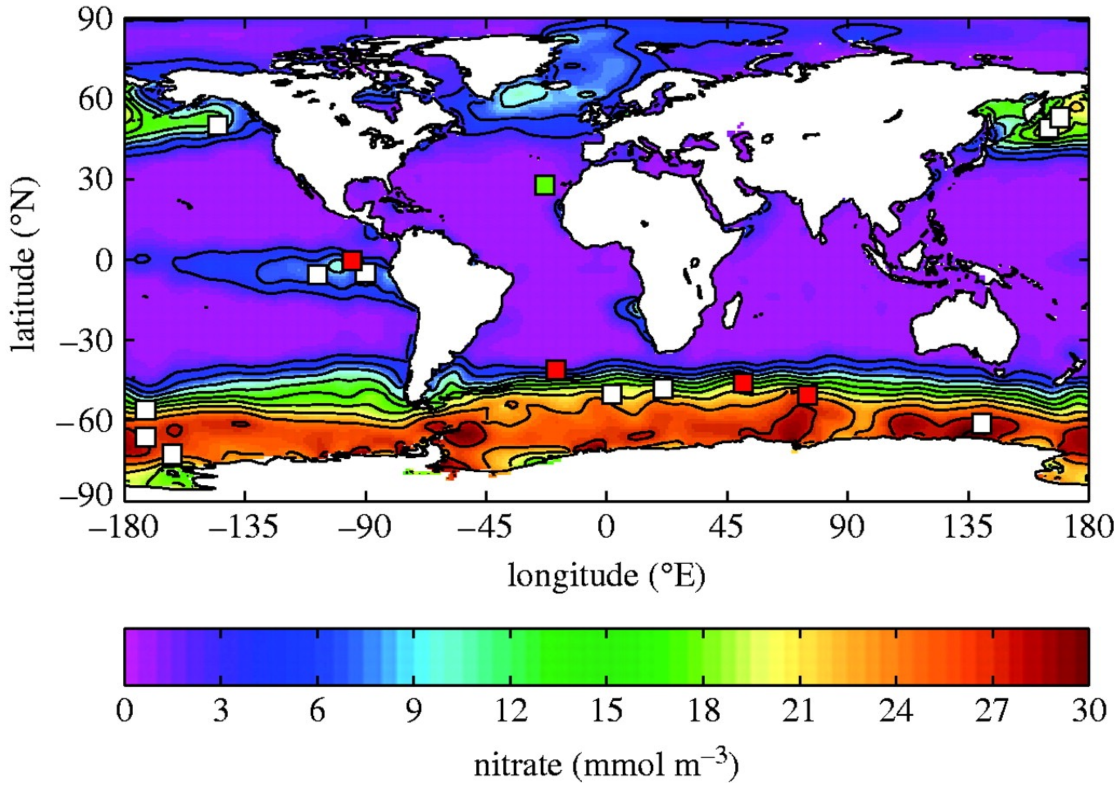
$$d_1 = \frac{d_1{}'}{p}$$

Trade-offs in Adaptation to Different Temperatures

Greater investment in protection and repair (*p*)=>higher nutrient (N) requirements=>cost at low temperatures



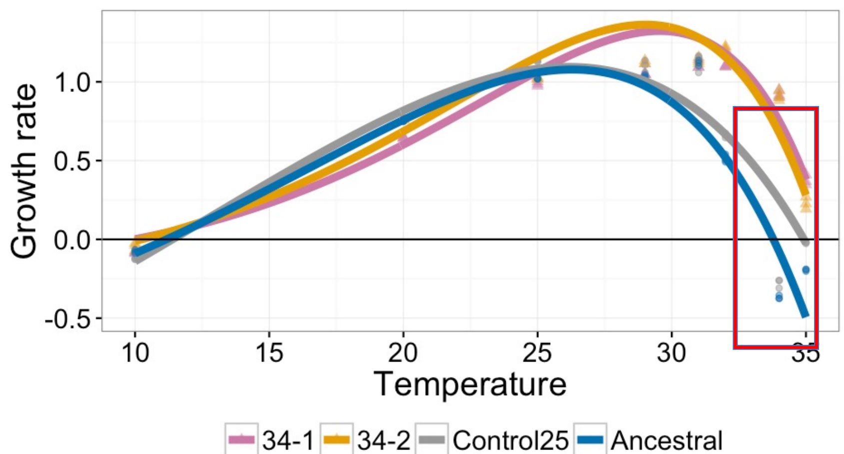
How Will Nutrient Limitation Affect Temperature Adaptation?



Effects of N Limitation on Evolutionary Adaptation to Temperature

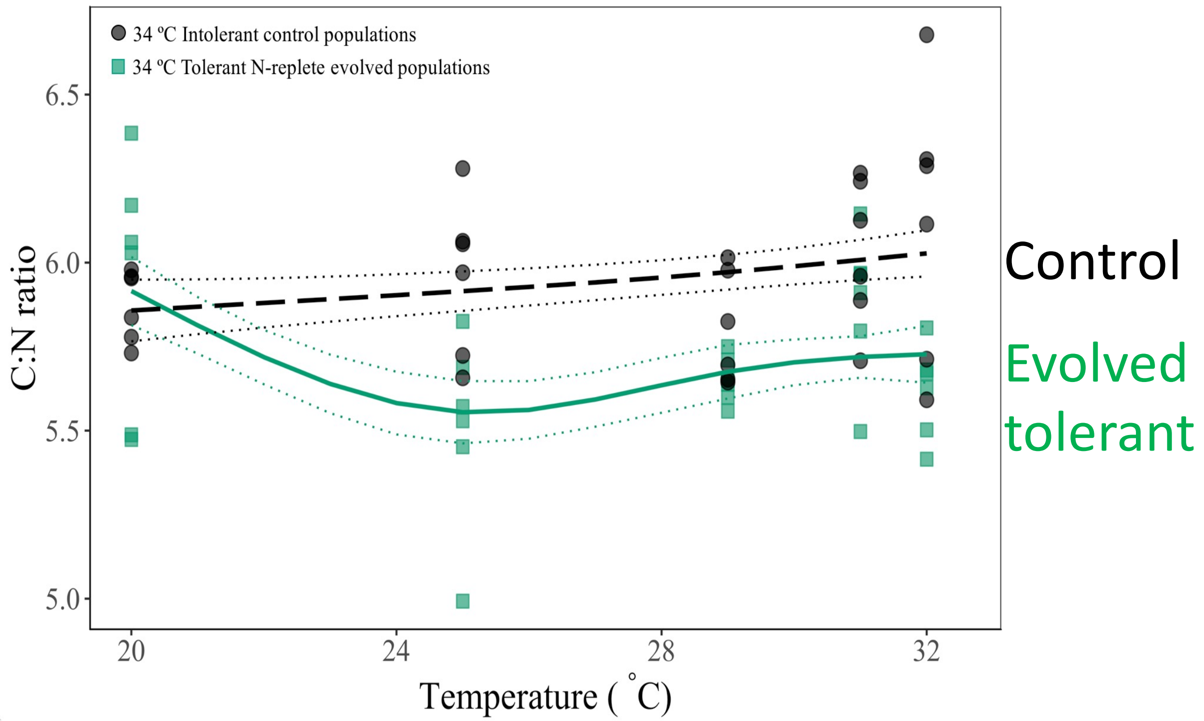
Evolution Experiments Under High and Low N

	+ N	-N
High Temperature	Adapt	Do not adapt



Aranguren-Gassis et al. Eco Lett 2019

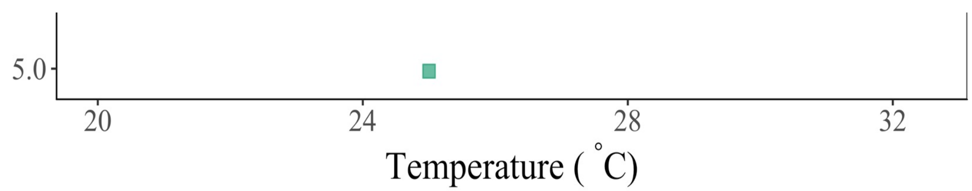
Higher N requirements in high temperature tolerant strains



Aranguren-Gassis et al. Eco Lett 2019

Higher N requirements of high temperature tolerant strains

Tolerant phenotype cannot be selected under N limitation—
NO EVOLUTIONARY RESCUE

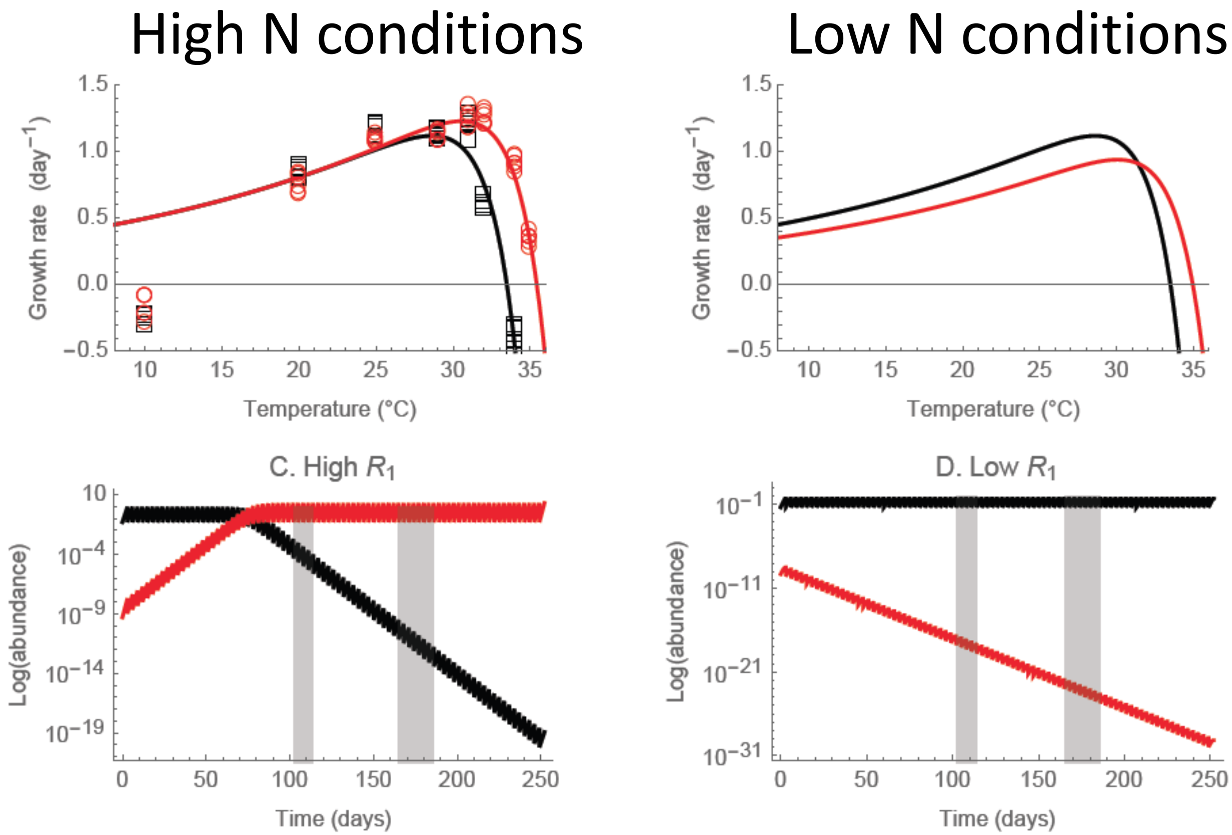


Competition Between Two Phenotypes

Phenotype 1:
High T resistant
High N
requirements

vs

Phenotype 2:
Non resistant
Lower N
requirements



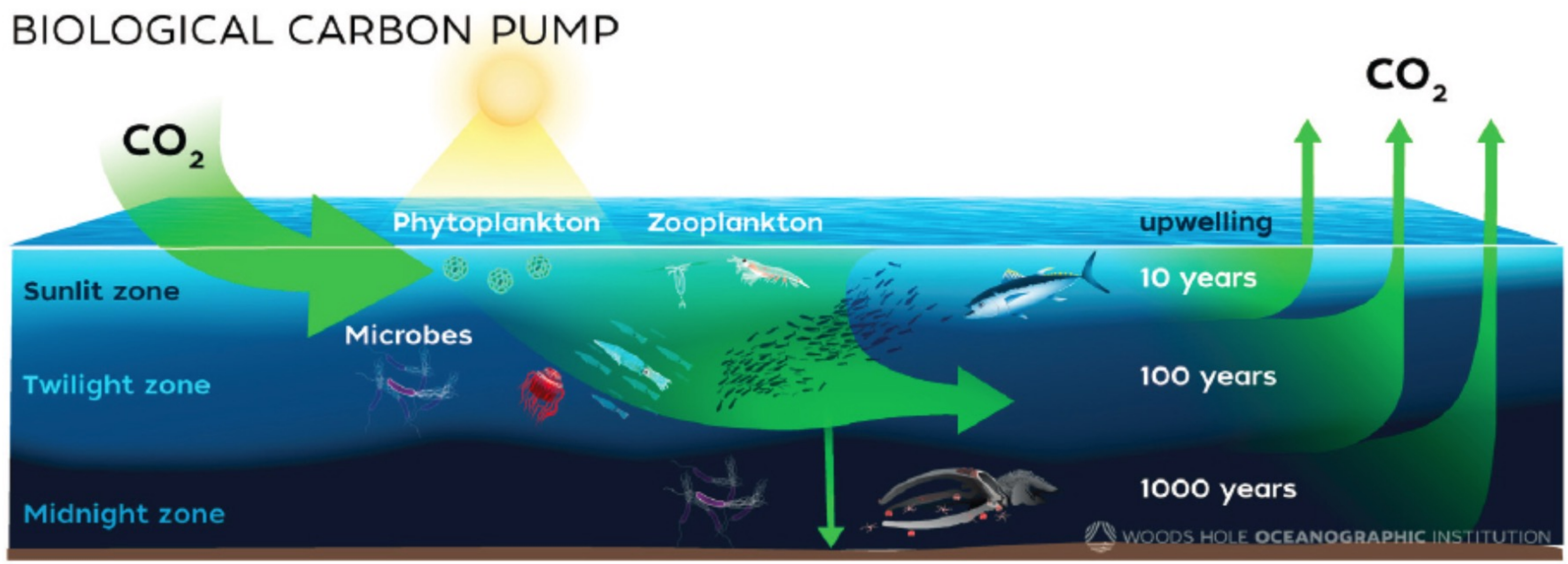
Resource limitation modifies responses to high temperature

- It may be universal: phytoplankton, corals, insects, fish, plants, etc.
- Resource limitation increases sensitivity to high temperatures (lowers T_{opt})
- Various resources (nutrients, water, food, etc.)
- Also: parasites

Litchman & Thomas 2022

Phytoplankton Potential for Climate Change Mitigation: Ocean Nutrient Fertilization for CO_2 Removal (CDR)

Enhancing Biological Carbon Pump
Max theoretical potential: 1 GT C/year



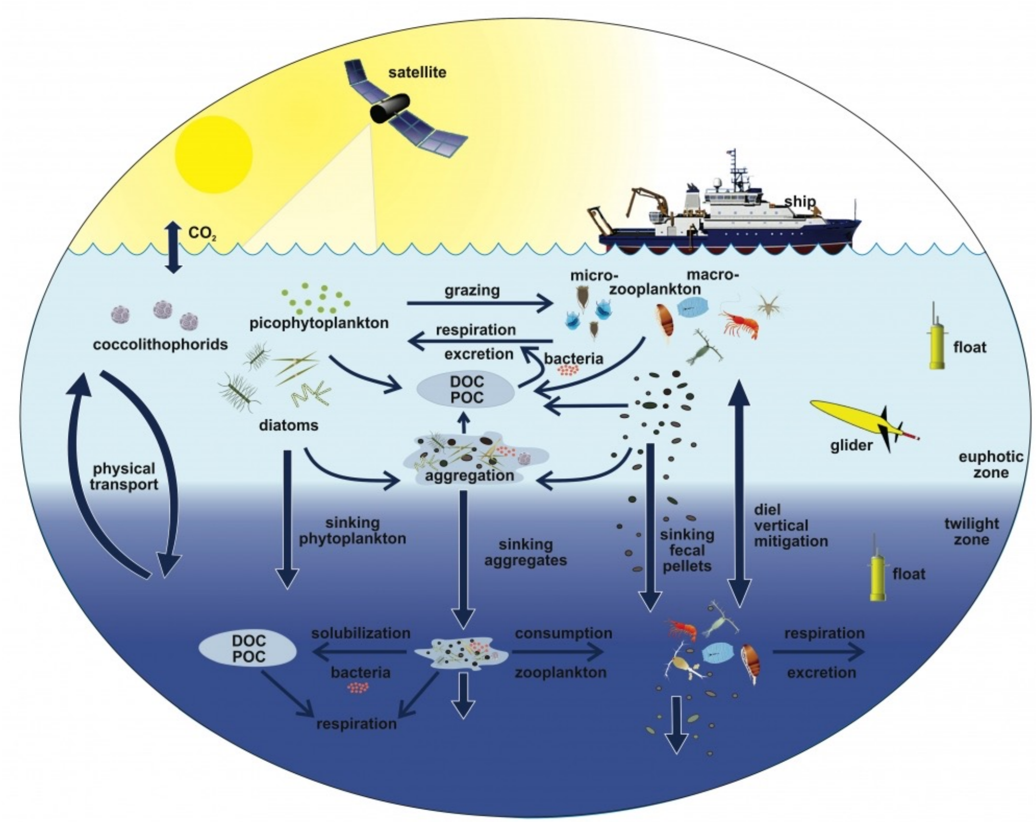
A unique situation: Fundamental research and practical implementation need to happen almost in parallel

- It is critical to identify most urgent questions and the effective ways to guide applications
- The problem of a shifting baseline—e.g., warming is changing community structure
- OIF approaches need to be adjusted as conditions change

➡ **adaptive** OF

- Use **ecological principles** to maximize efficiency and avoid/minimize negative ecological consequences

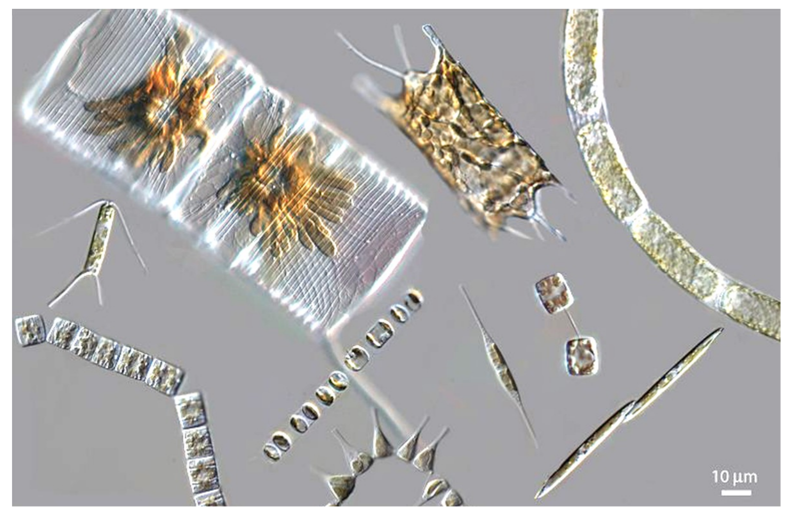
Ecology Informs Adaptive Ocean Fertilization For CO_2 removal



Pulsed nutrient additions

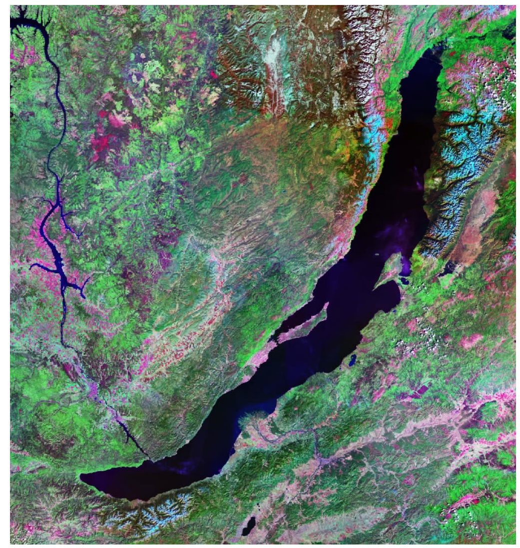
Large diatoms

Efficient carbon sequestration!



Climate change and regime shifts

Lake Baikal, Siberia under Climate Change

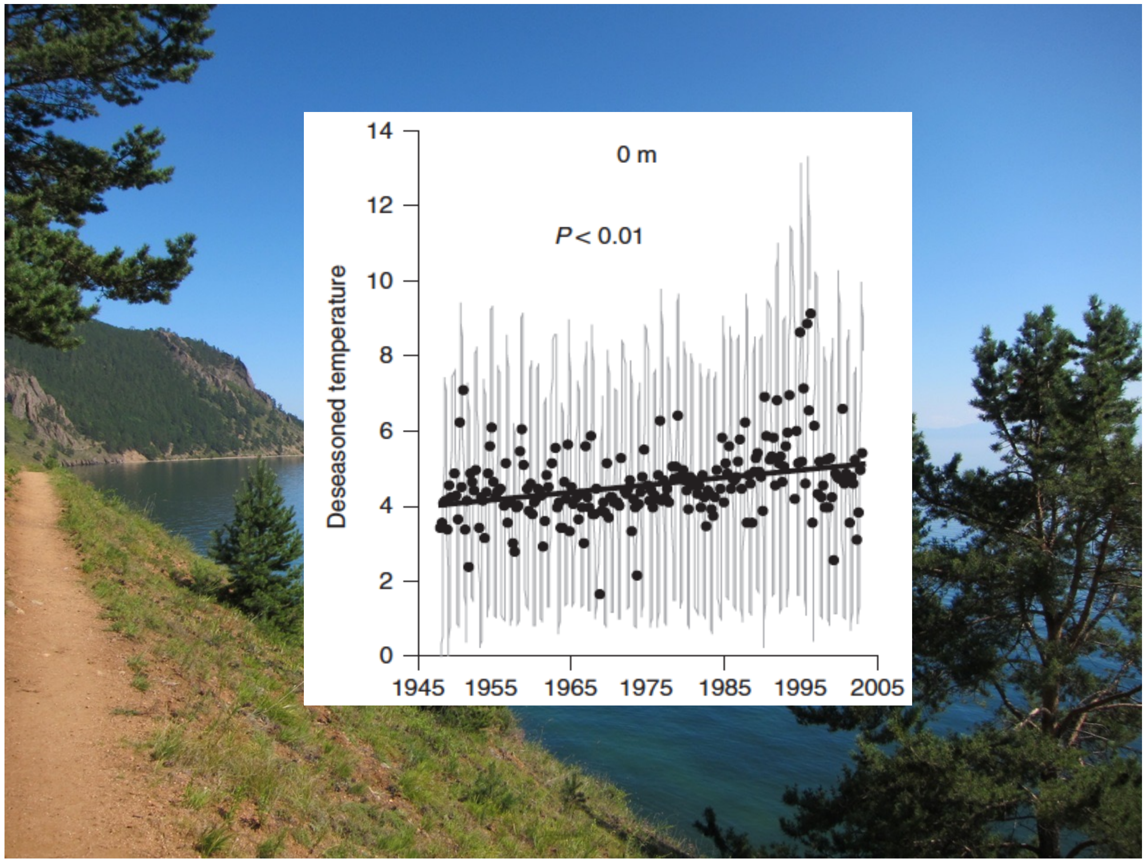


- World's oldest (25 MY), deepest lake (>1 mile deep), holds 20% of all unfrozen freshwater in the world
- UNESCO World Heritage Site

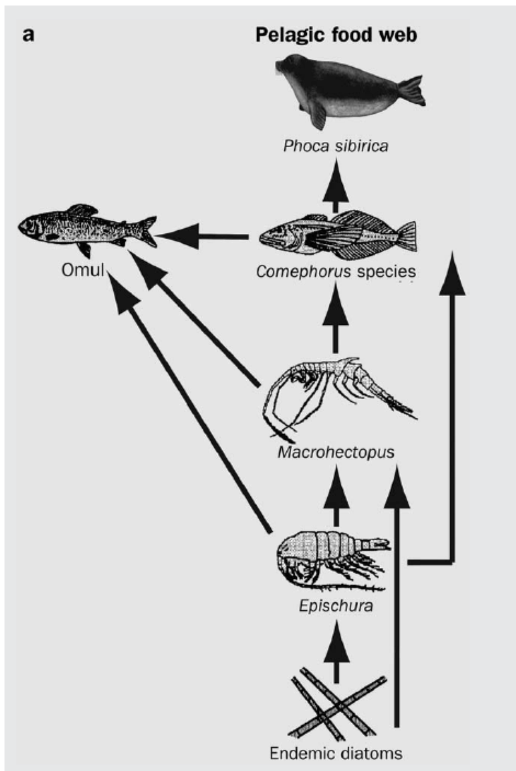
Lake spans > 3° latitude

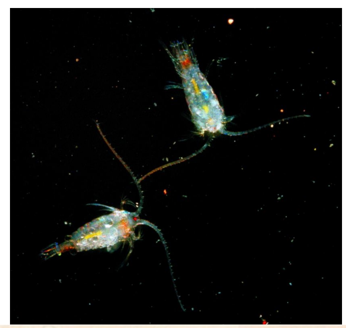
Lake Baikal, Siberia under Climate Change

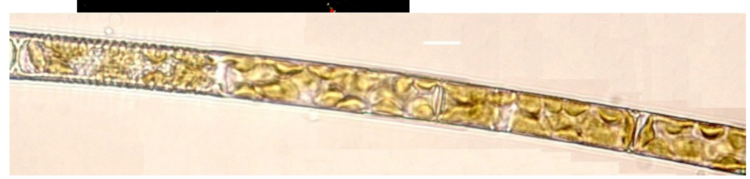
Lake Baikal, Siberia under Climate Change



Plankton Food Web in Lake Baikal



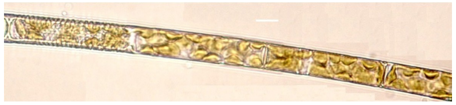




Endemic diatoms bloom under ice

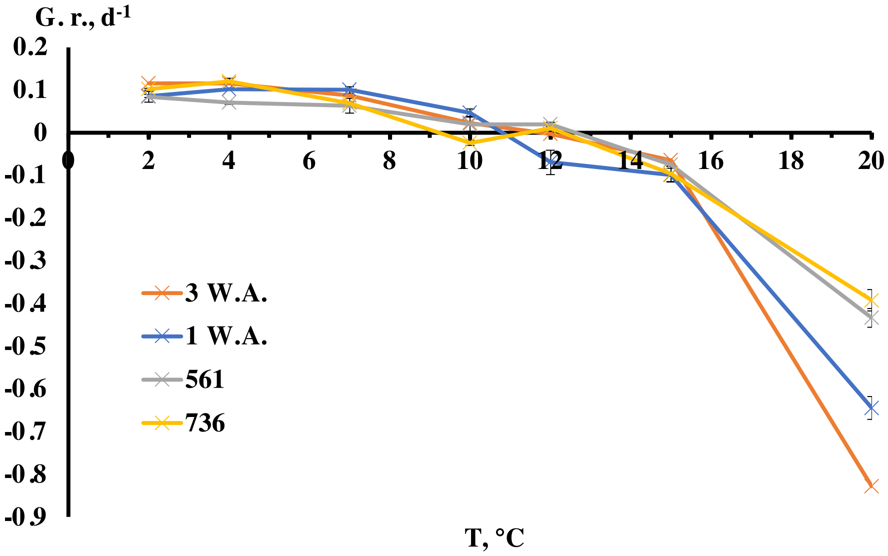
Temperature Responses

Endemic diatoms

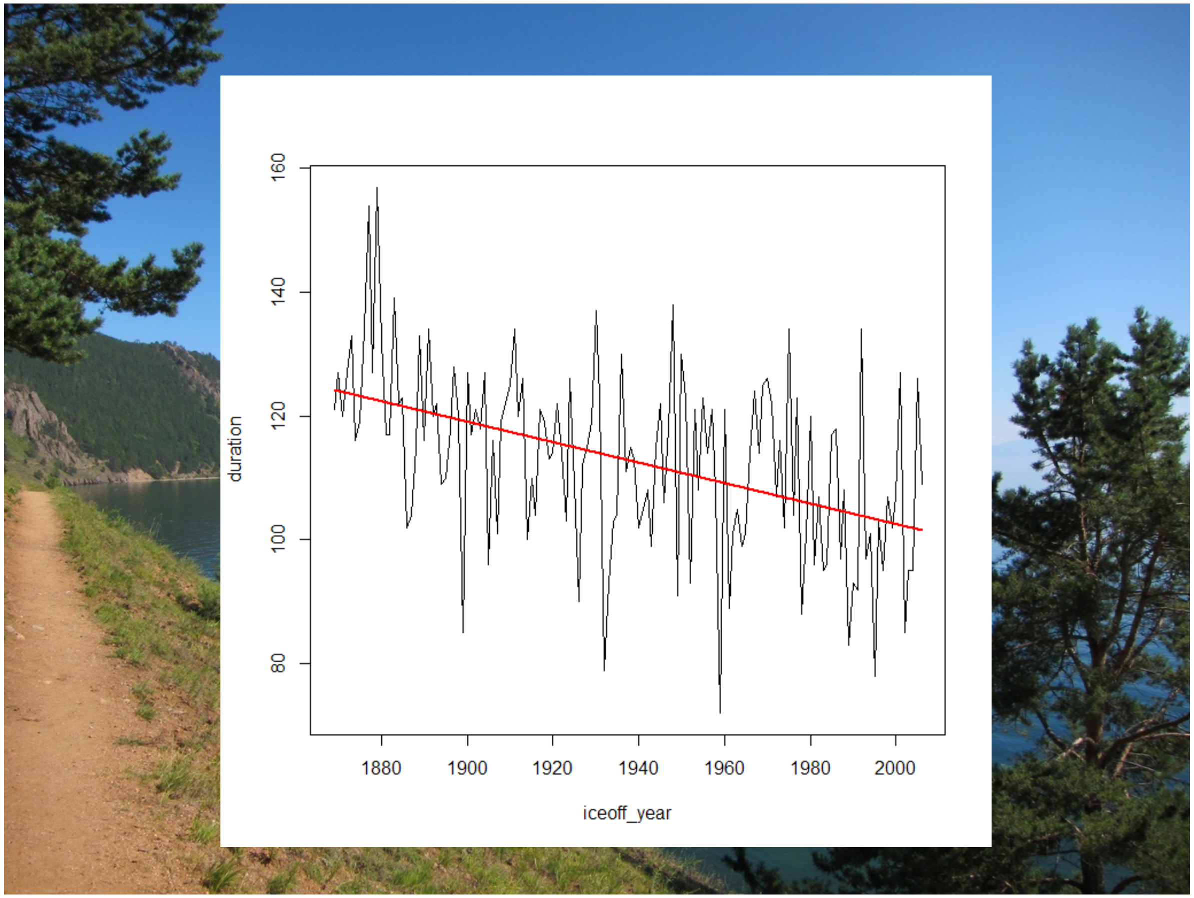


Aulacoseira baikalensis

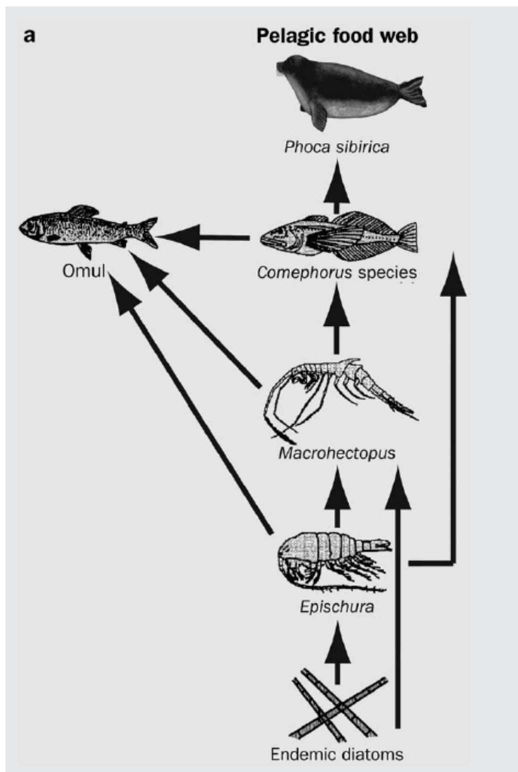
Cannot grow above 10-12°C, T_{opt} 4°C

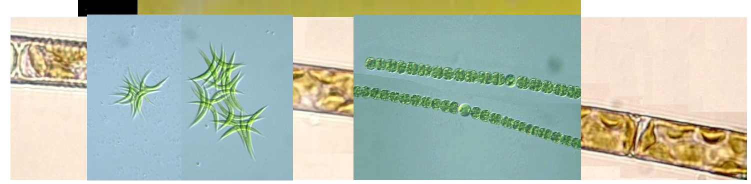


Lake Baikal Ice Cover Duration



Plankton Food Web in Lake Baikal

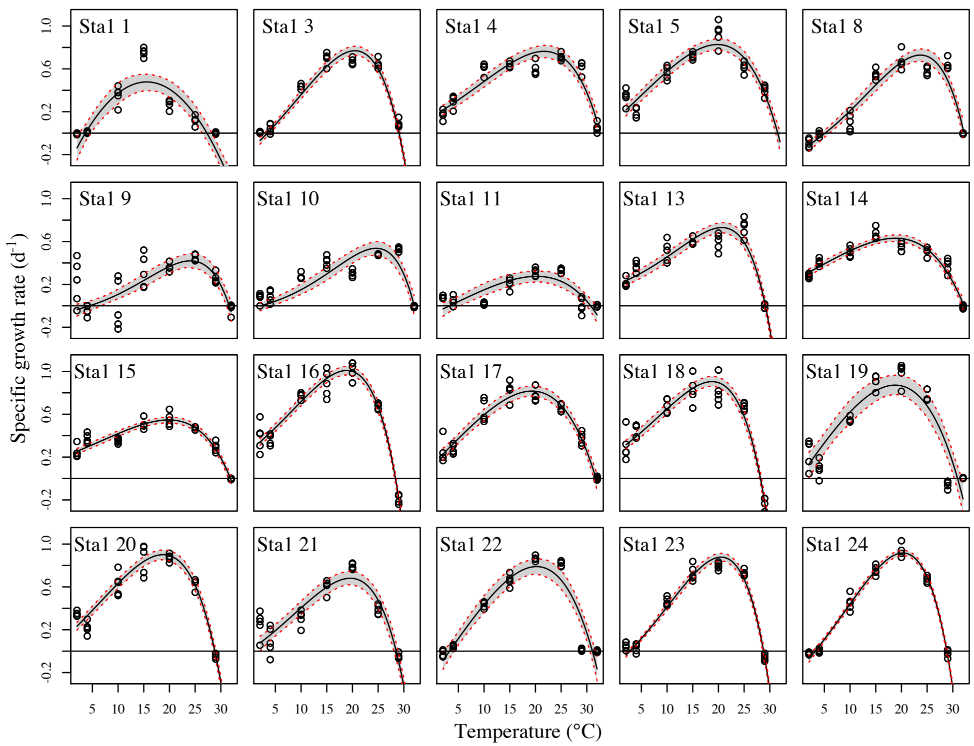




Temperature Responses

Cosmopolitan diatom (*Synedra*)

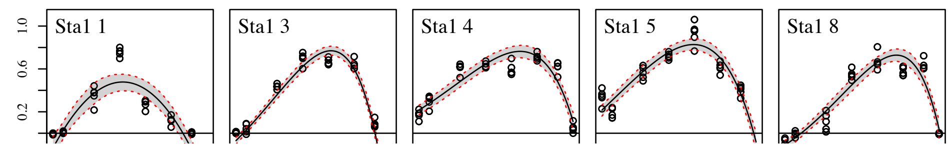
Growth rate



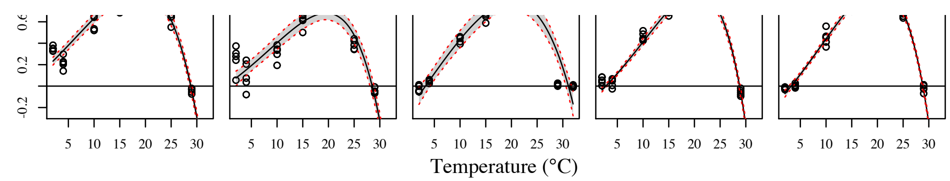
Temperature

Temperature Responses
Cosmopolitan diatom

Growth rate

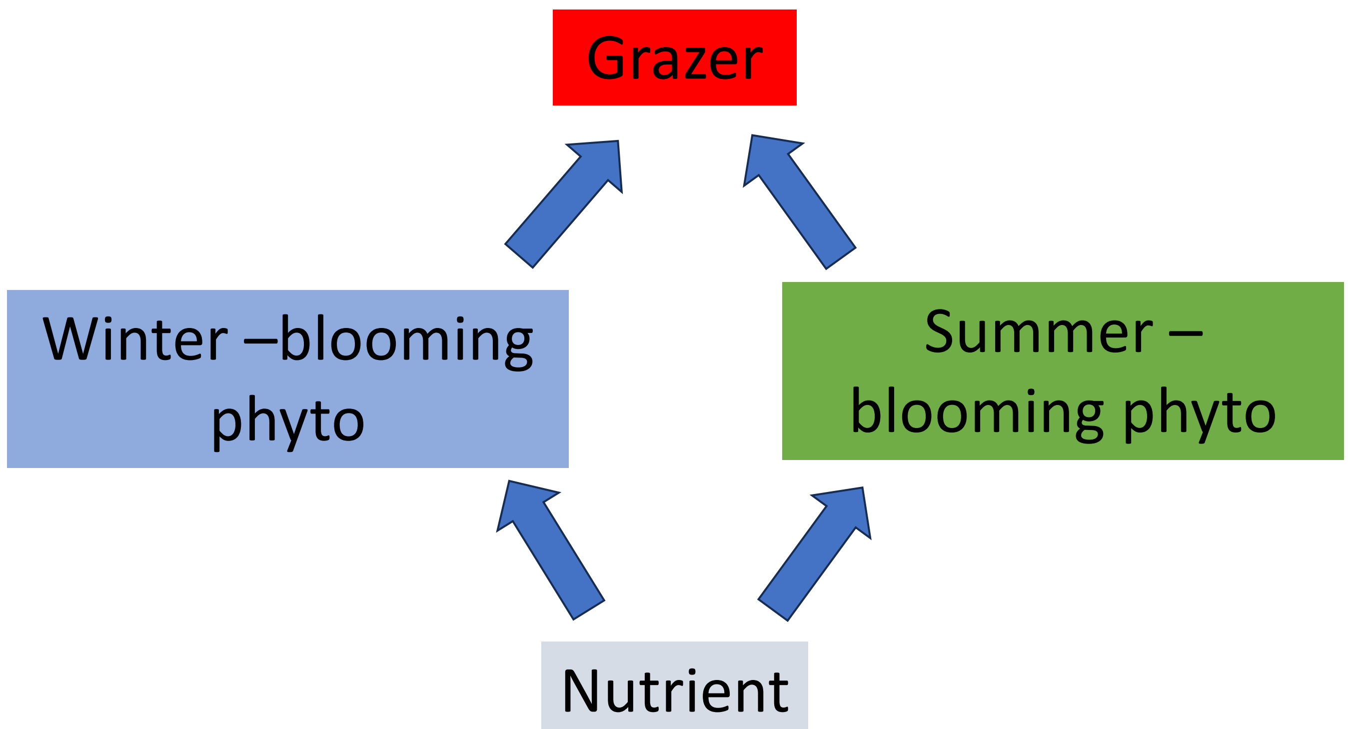


- Grows well up to 25°C!
- T_{opt} above 20°C
- Wide thermal niche (ca. 30°C)
- Present for most of the year

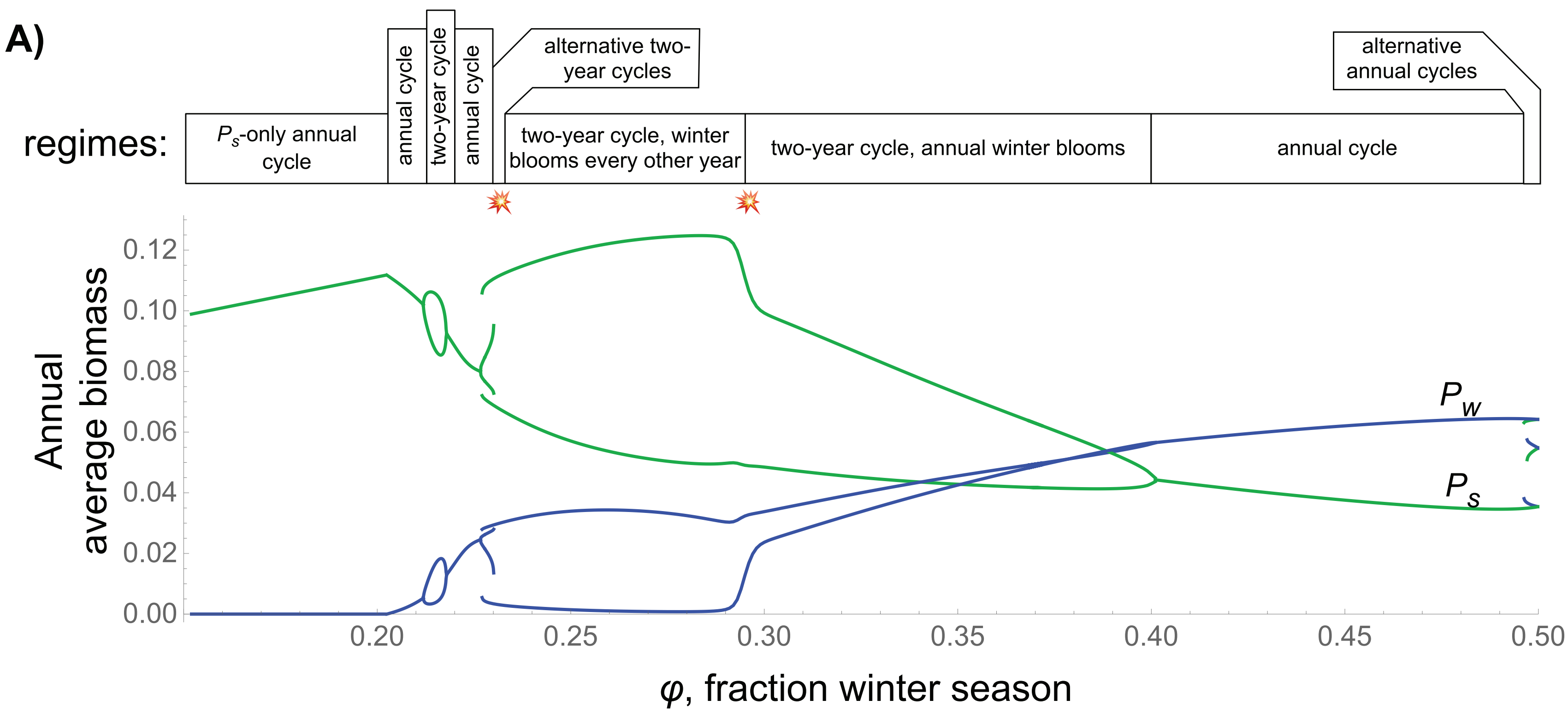


Temperature

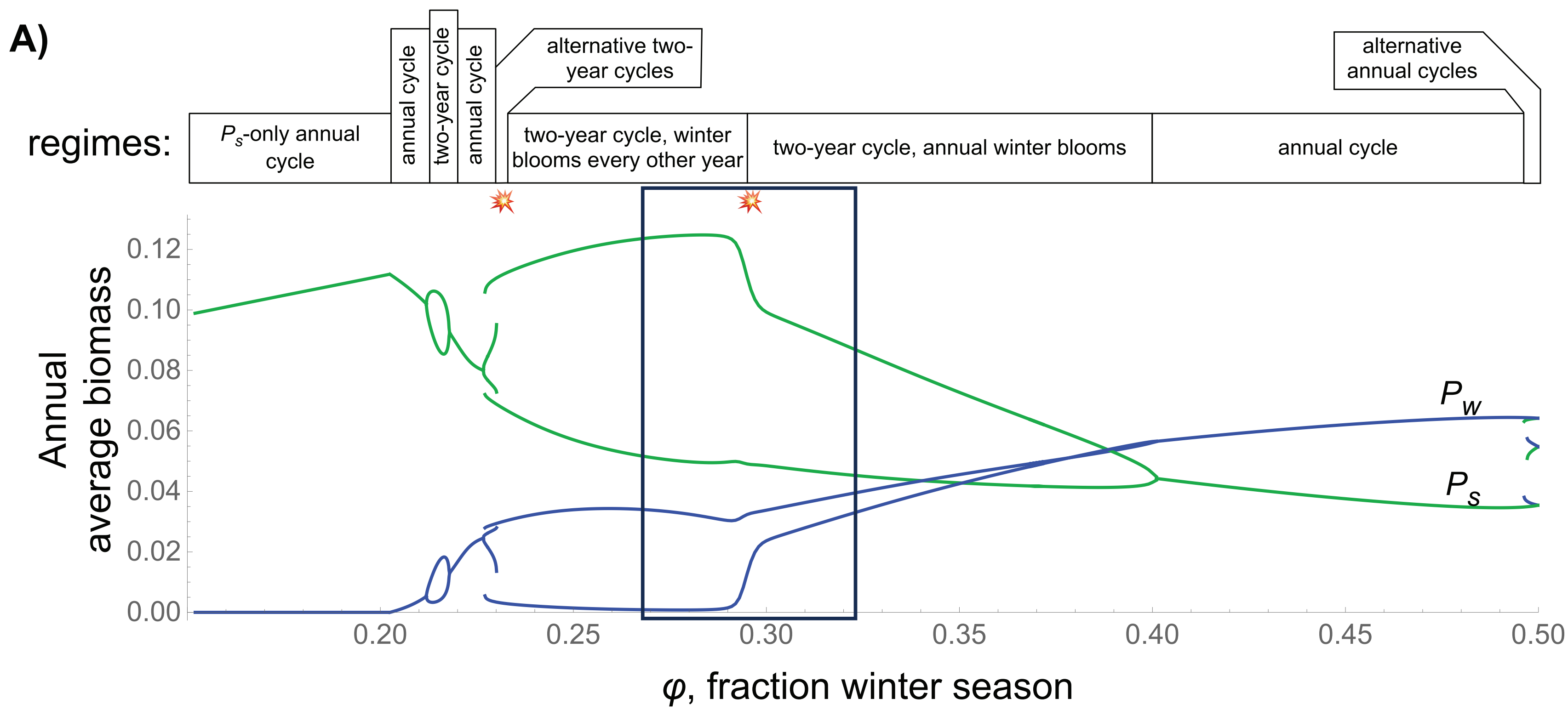
Lake Baikal food web model



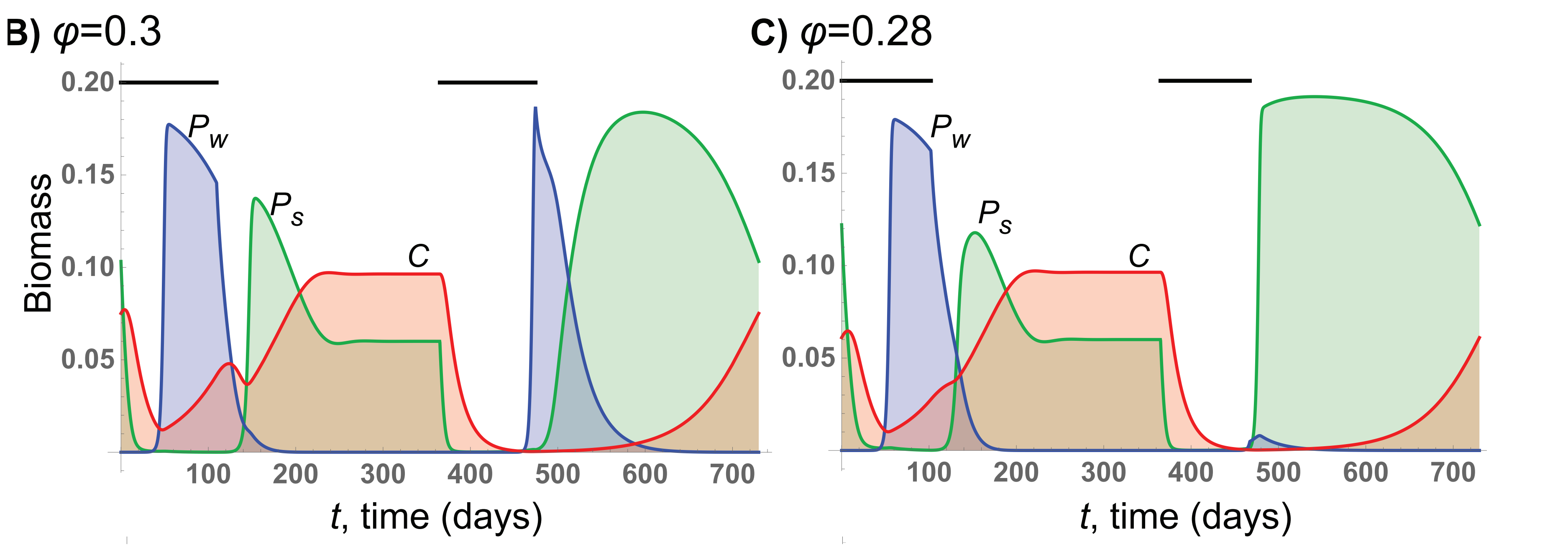
Regime shifts with changing ice cover duration



Regime shifts with changing ice cover duration



Community dynamics under different ice cover duration

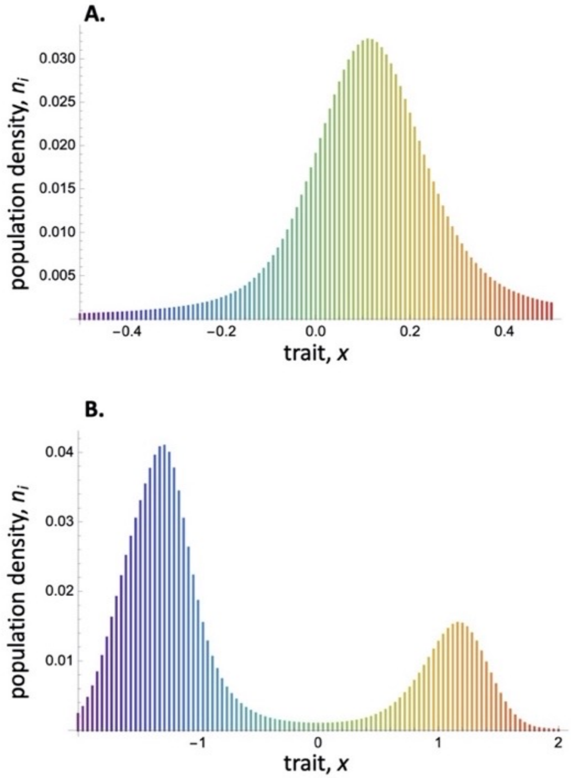


Necessary conditions for abrupt regime shifts

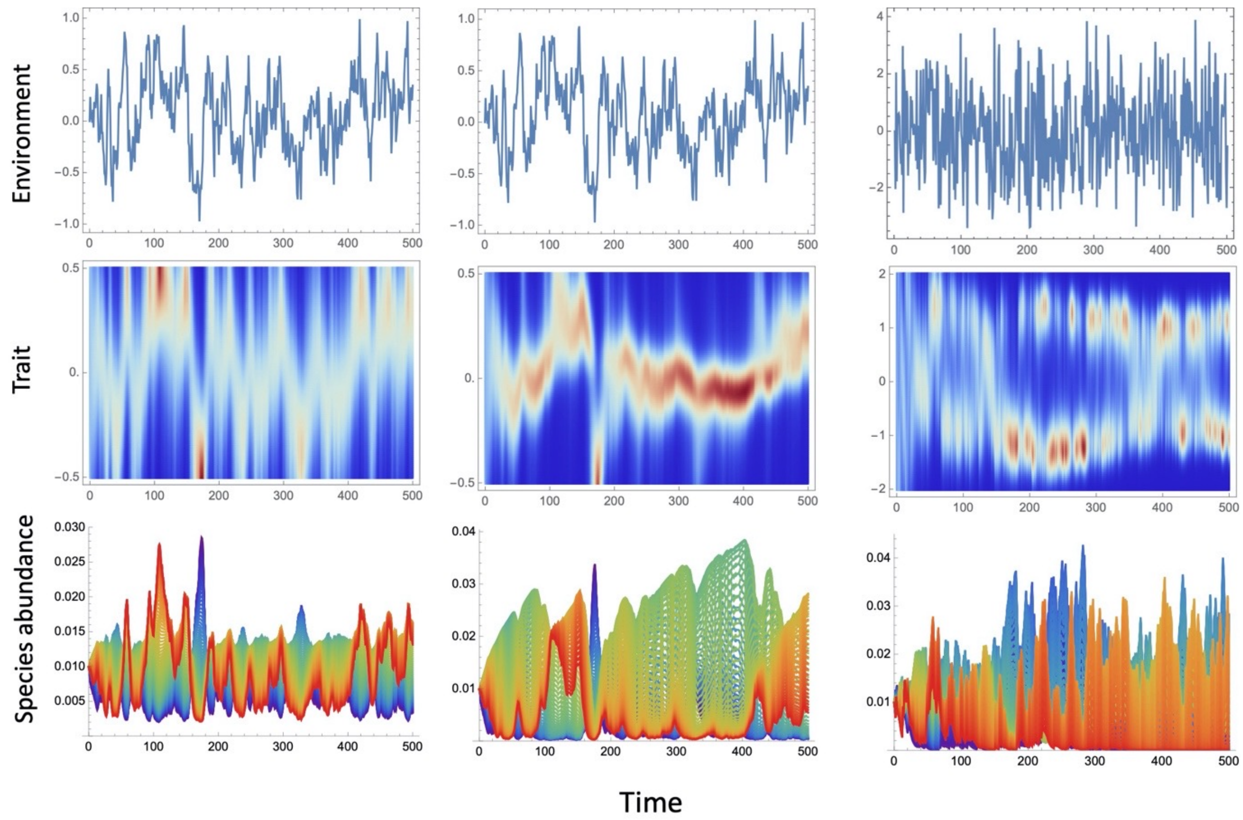
- nonlinear functional responses
- presence of predator-prey interactions

Trait distributions and ecosystem resilience

- Do some trait distributions result in communities and ecosystem functions more resilient to perturbations, including extreme events?



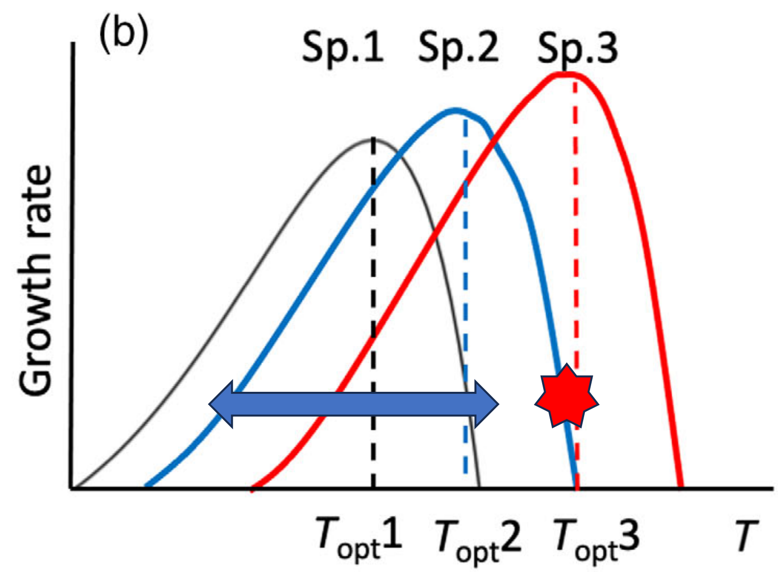
High amplitude fluctuations may lead to bimodal trait distributions



Trait distributions and ecosystem resilience

- When do extreme events lead to extreme responses?

Extreme event: in the 10 or 90 percentile of density distribution

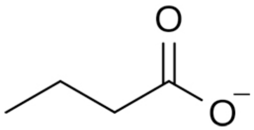


Regime shifts in host-associated microbiota

Gut microbiota effects on:

- Host metabolism
- Immunity
- Chronic diseases
- Longevity
- Mental health

Main mechanism: through microbial metabolites
E.g., SCFA butyrate (diet, community composition)



Structure and function of gut microbiota

- > 1000 species (bacteria, archaea, fungi, protists, viruses)
- Common ecological interactions
  - Competition
  - Mutualism (cross feeding)
  - Predation
  - Parasitism
- Host-mediated

Structure and function of gut microbiota

- > 1000 species (bacteria, archaea, fungi, protists, viruses)
- Common ecological interactions
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  - Predation
  - Parasitism

  (Competition and Mutualism: Lotka-Volterra)
- Host-mediated

Structure and function of gut microbiota

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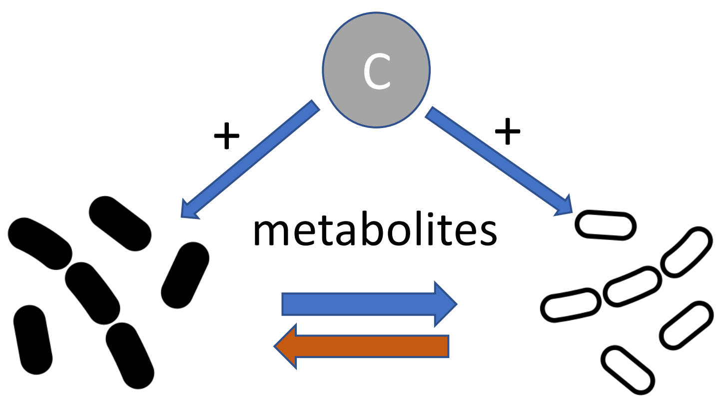
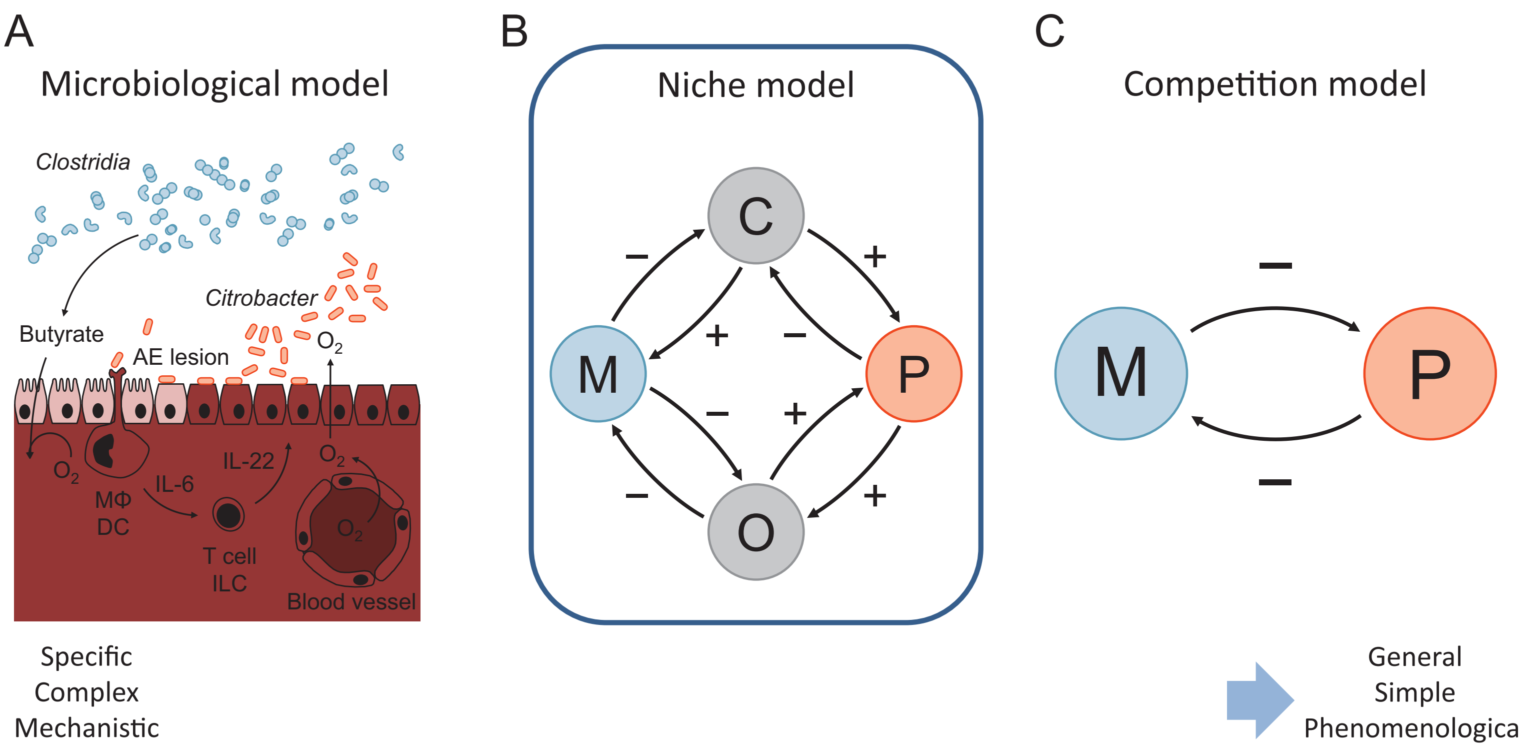
Lotka-Volterra

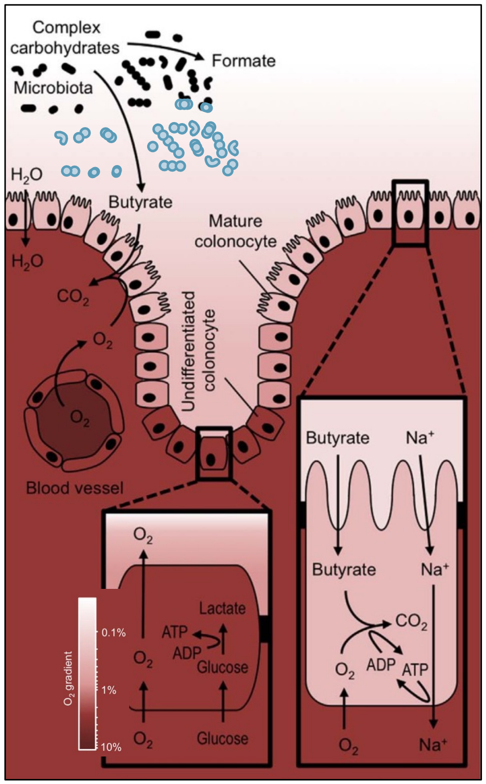


Resource-based interactions

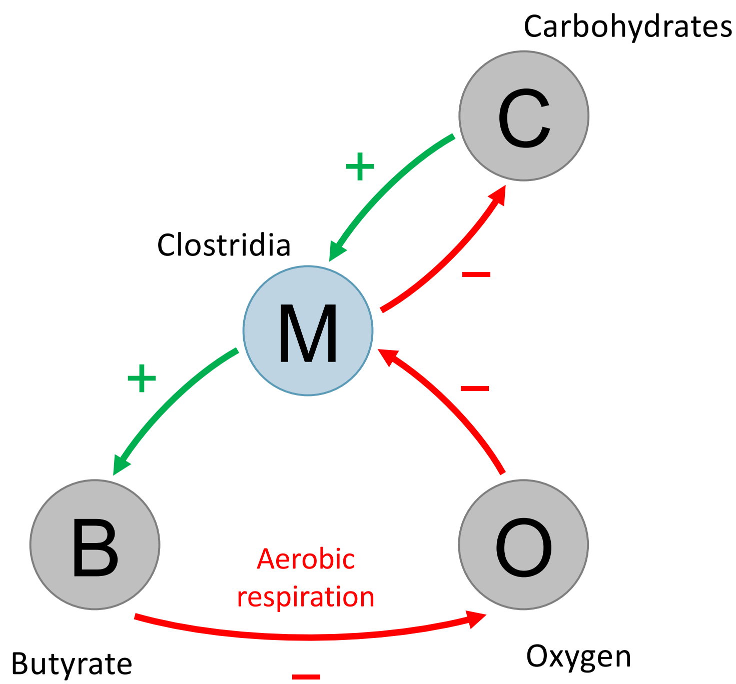
Continuum of modeling approaches



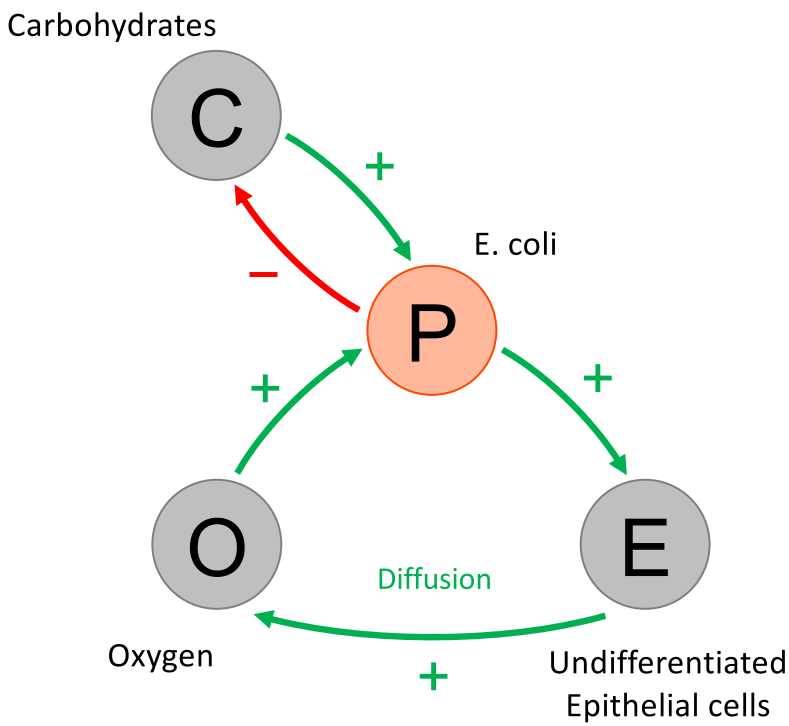
Beneficial bacteria in a healthy gut

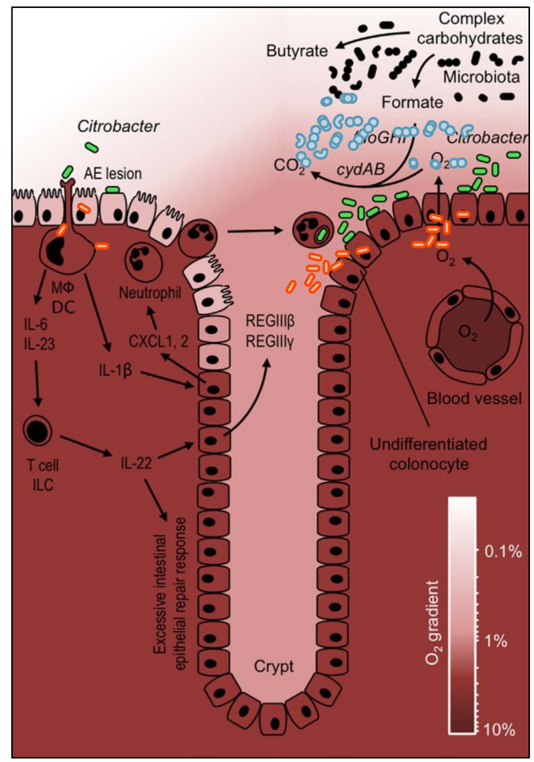


Rivera-Chávez et al. 2016



Pathogen initiates its (disruptive) feedback





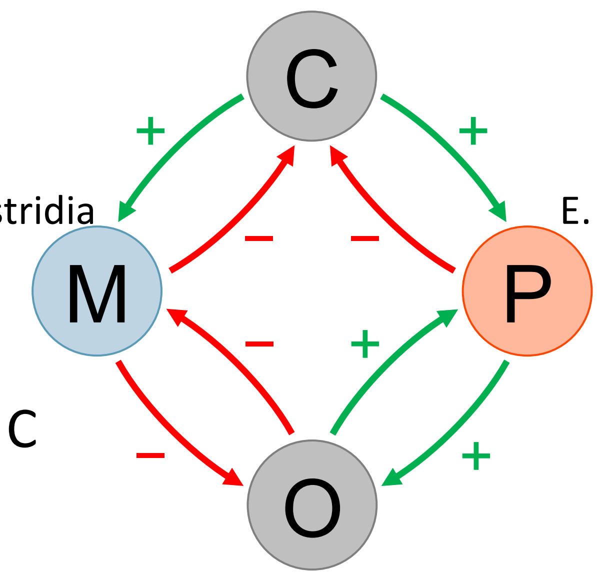
Rivera-Chávez et al. 2016

Reduced model:

Thomas Koffel

John Guittar

- Mutualist and pathogen compete for C
- Both controlled by O_2
- Hence, C:O_2 ratio is important



Guittar et al. Am Nat 2021

The model

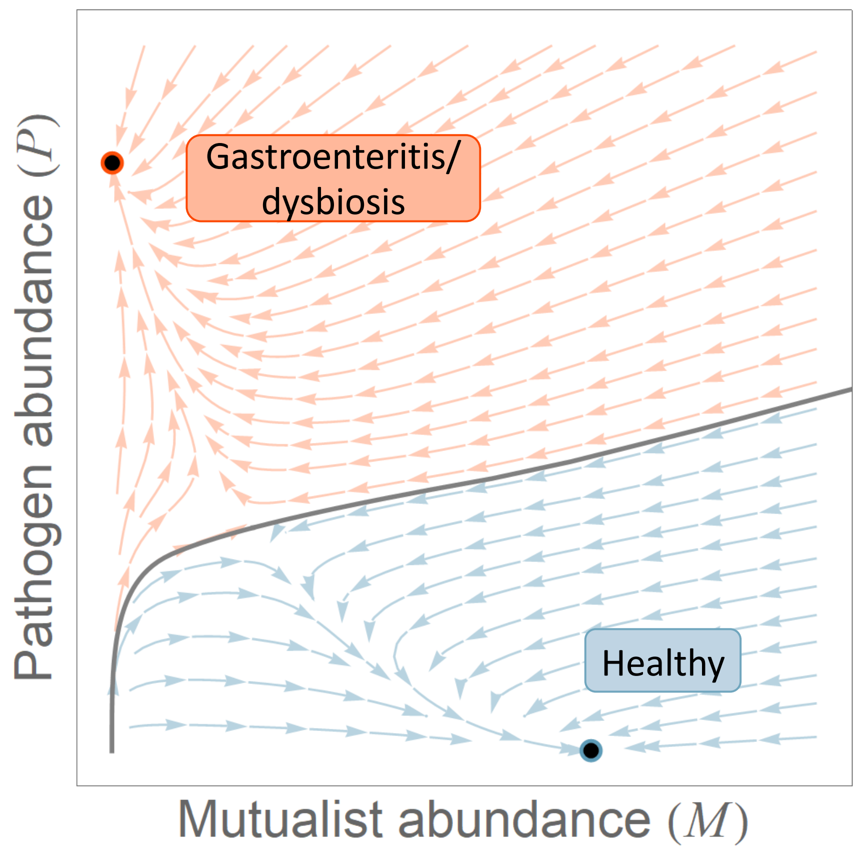
O_2 stress

Δ Mutualist	$$\frac{dM}{dt} = [\min(\mu_M, \alpha_{CM}C) - \overline{\beta_M O} - m_M]M \quad (1)$$
Δ Pathogen	$$\frac{dP}{dt} = [\min(\alpha_{CP}C, \alpha_{OP}O) - m_P]P \quad (2)$$
Δ Carbohydrate	$$\frac{dC}{dt} = a_C(C_{\text{in}} - C) - q_{CM} \cdot \min(\mu_M, \alpha_{CM}C)M - q_{CP} \cdot \min(\alpha_{CP}C, \alpha_{OP}O)P \quad (3)$$
Δ Oxygen	$$\frac{dO}{dt} = a_O(O_{\text{in}} - O) - q_{OP} \cdot \min(\alpha_{CP}C, \alpha_{OP}O)P + \underline{\frac{\gamma_{OP}}{\kappa_{OP} + O}P} - \underline{\frac{q_{OE}\alpha_E E_{\text{cell}}O}{a_B + q_{BE}\alpha_E E_{\text{cell}}O}\gamma_{BM}M} \quad (4)$$

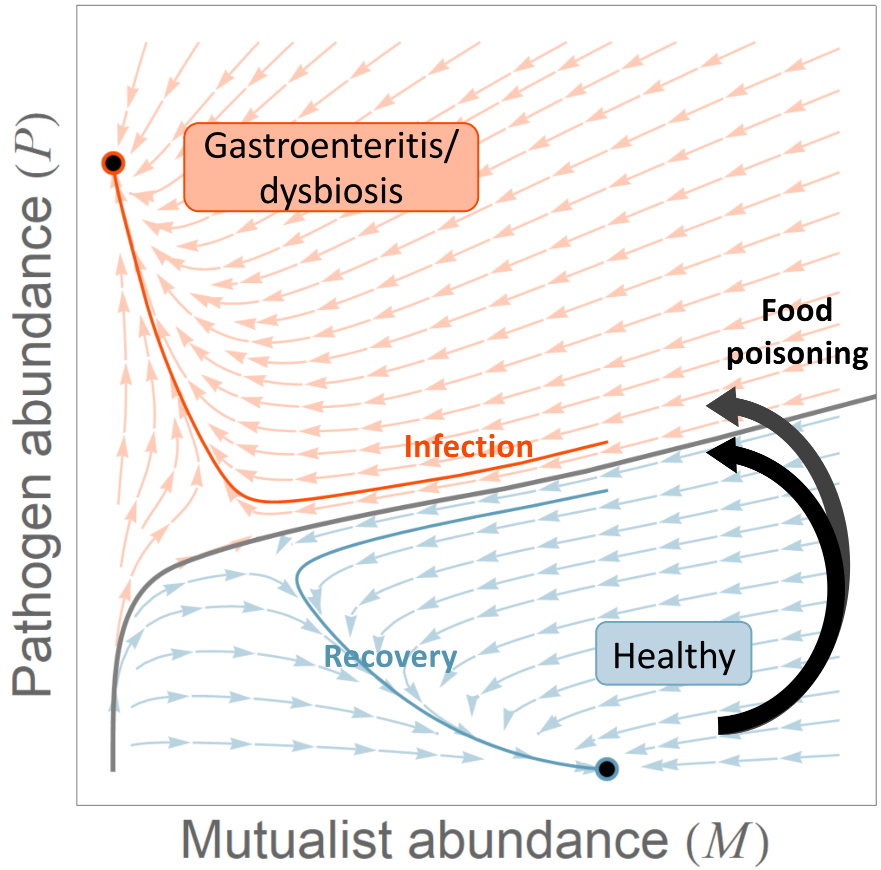
Pathogen-triggered release of O_2

Host butyrate and O_2 consumption

Alternative stable states

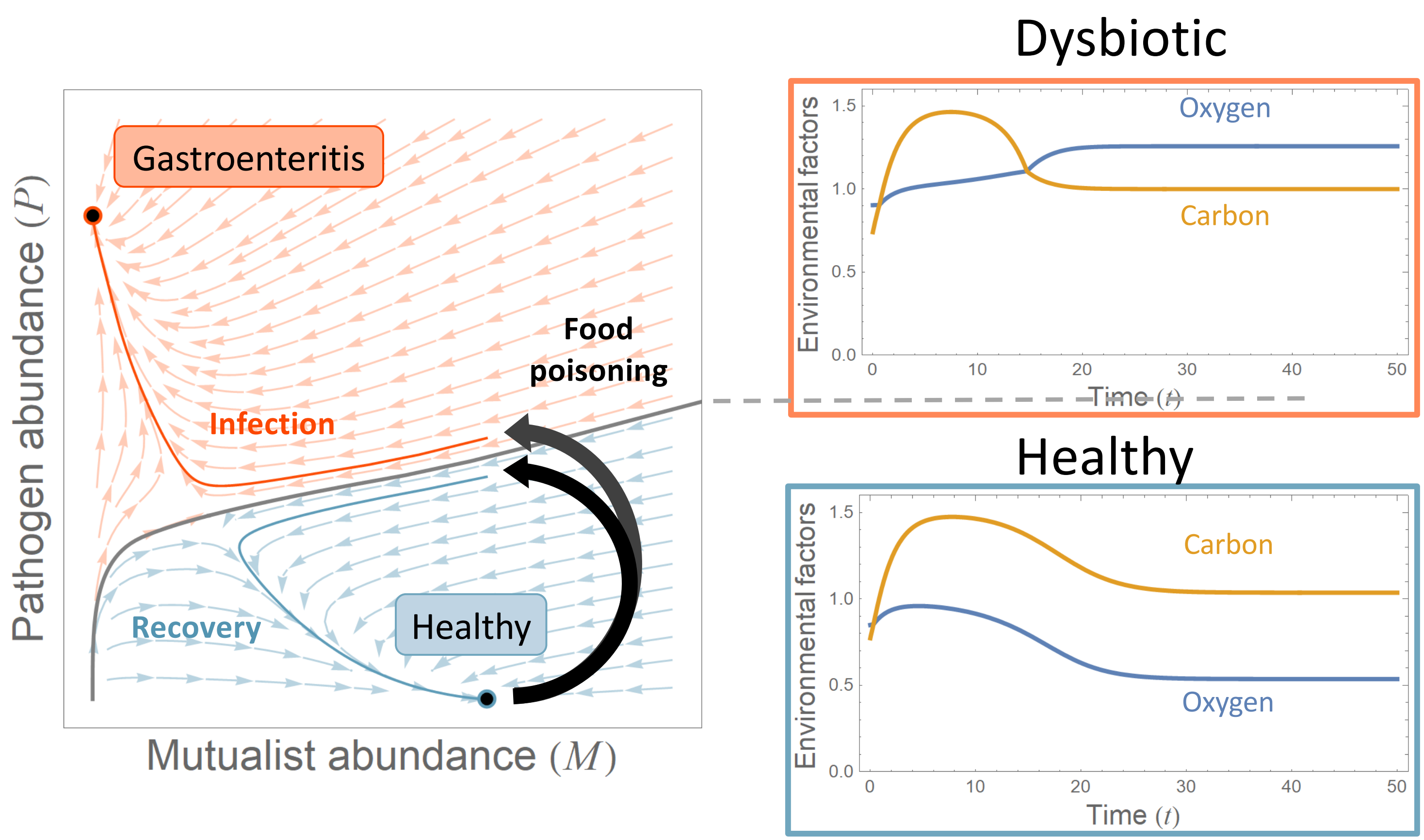


Alternative stable states

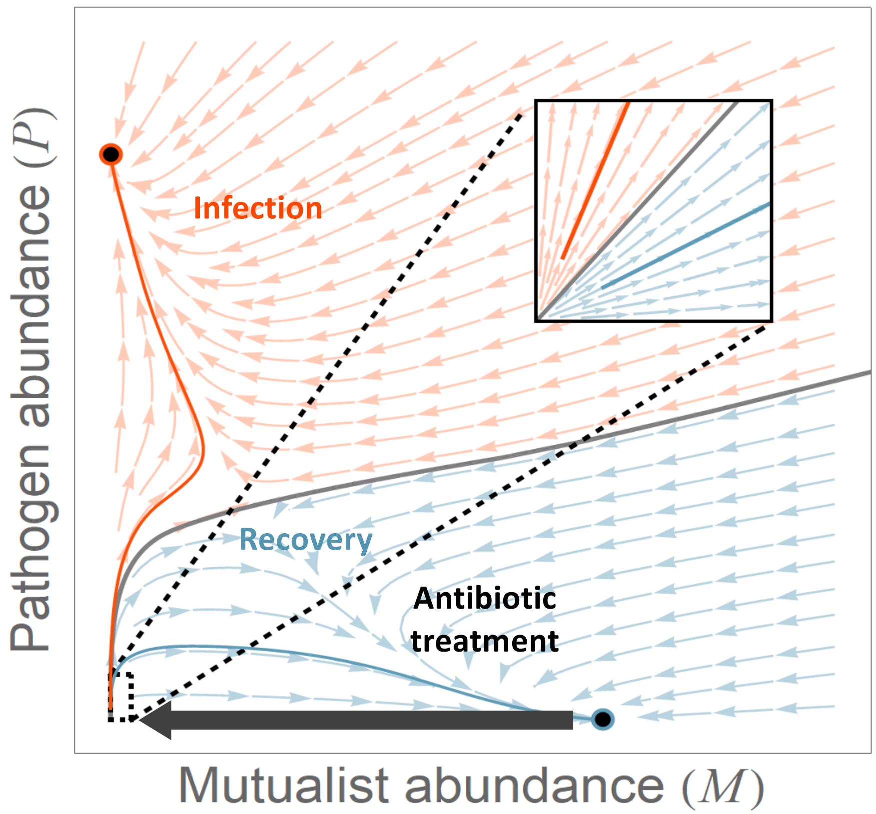


The outcome depends on the amount of pathogen ingested

Alternative stable states

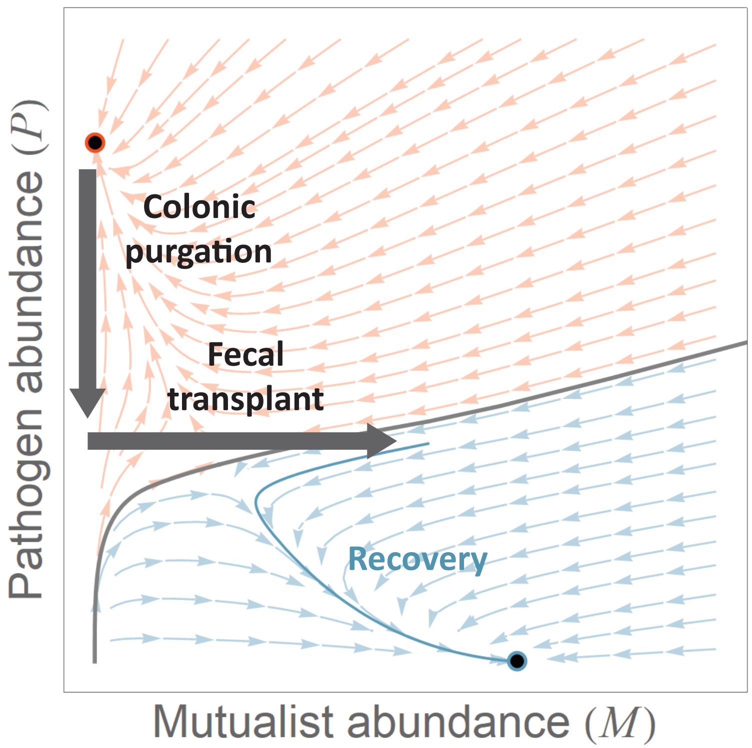


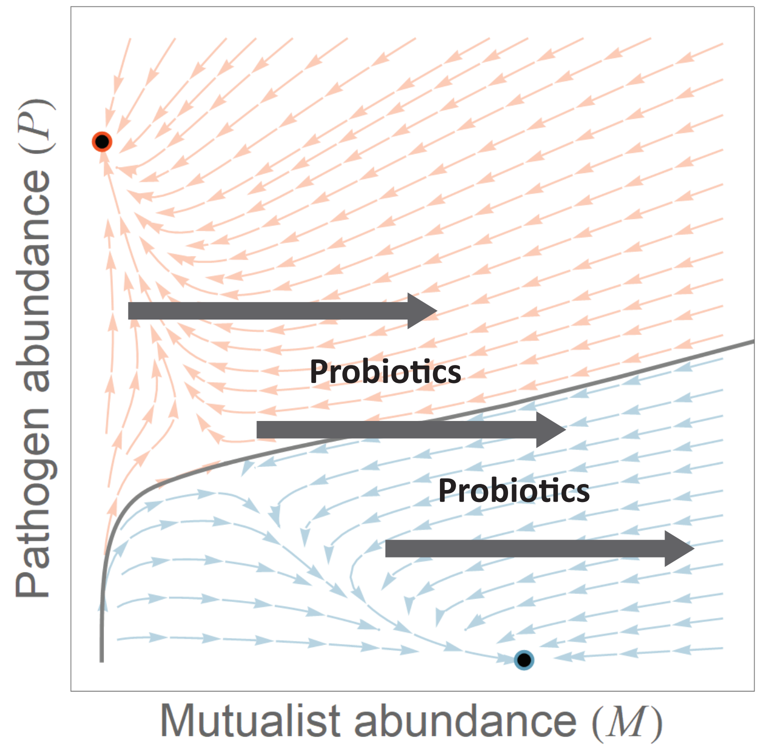
Effect of antibiotics



Antibiotics increase sensitivity to catastrophic shifts

Perturbations lead to shifts between alternative states

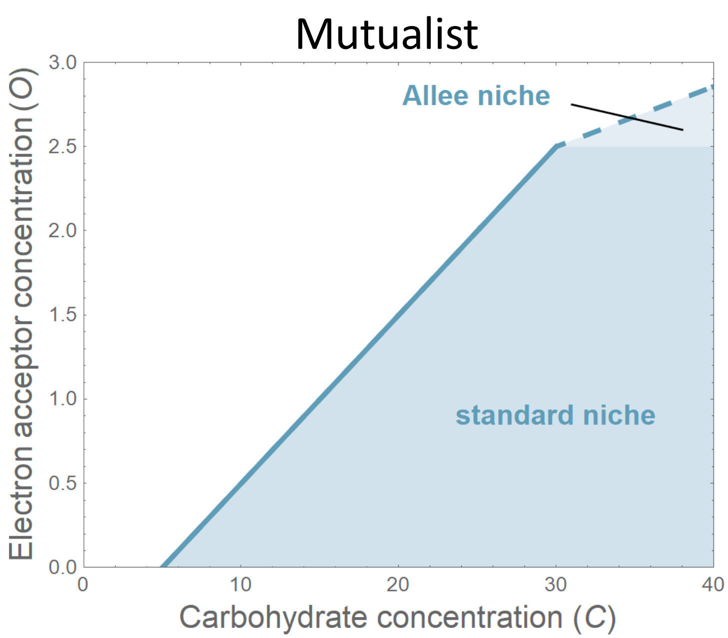


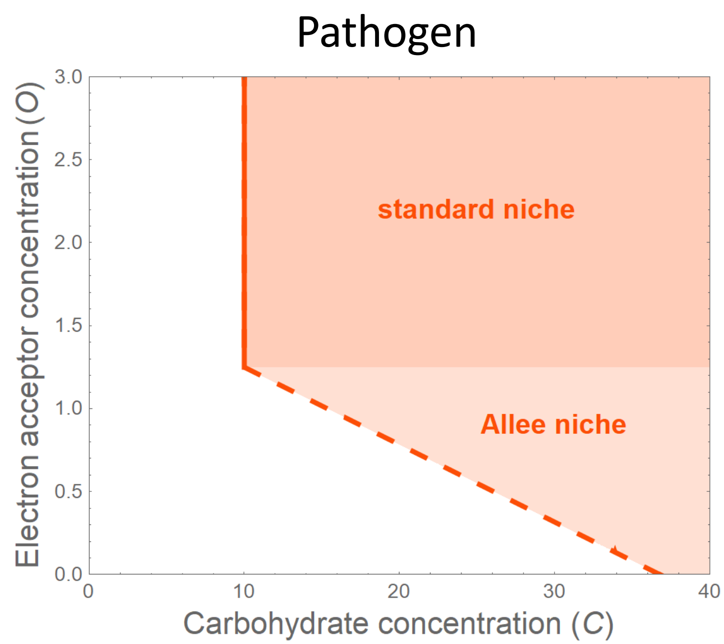


How does diet and other environmental changes affect gut health (alternative stable states)?

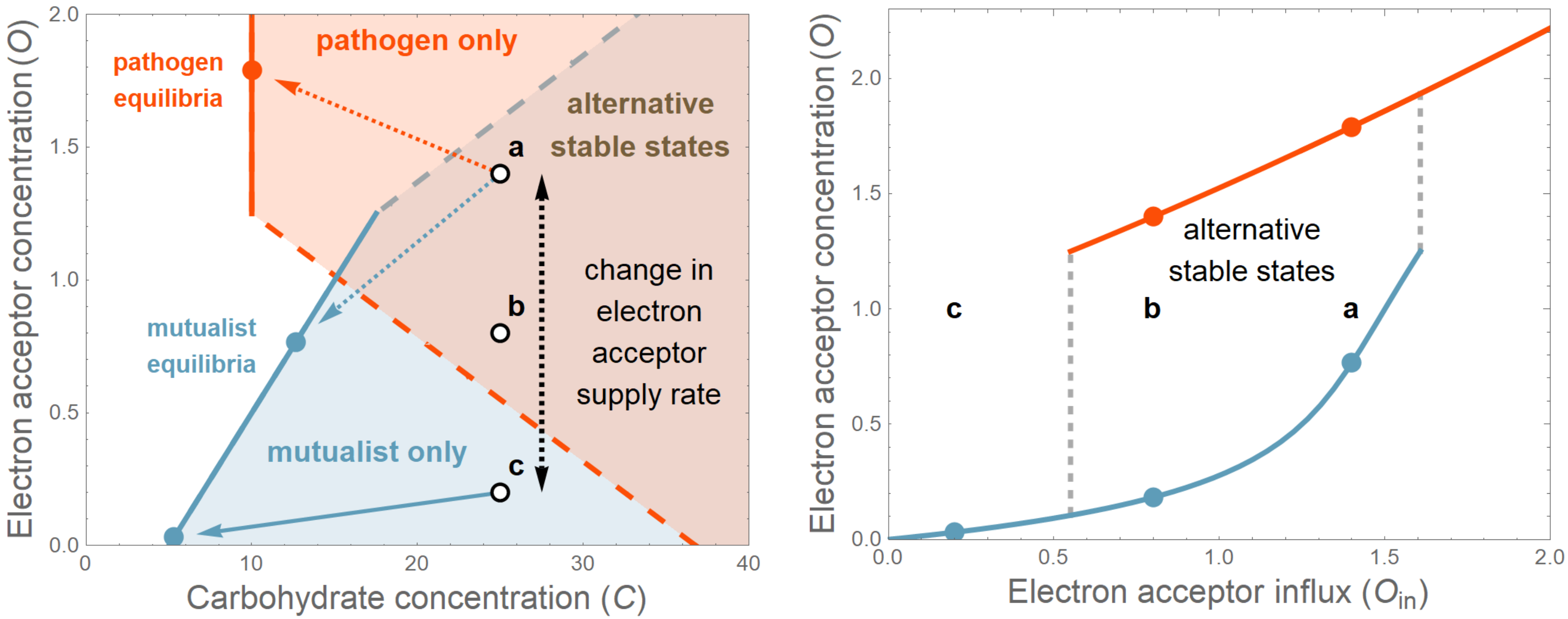
Microbial niches

Mutualist and pathogen have different ecological niches





Competition along environmental gradients
Increase in O_2 supply leads to dysbiosis



Competition along environmental gradients
Fiber effect depends on the initial state