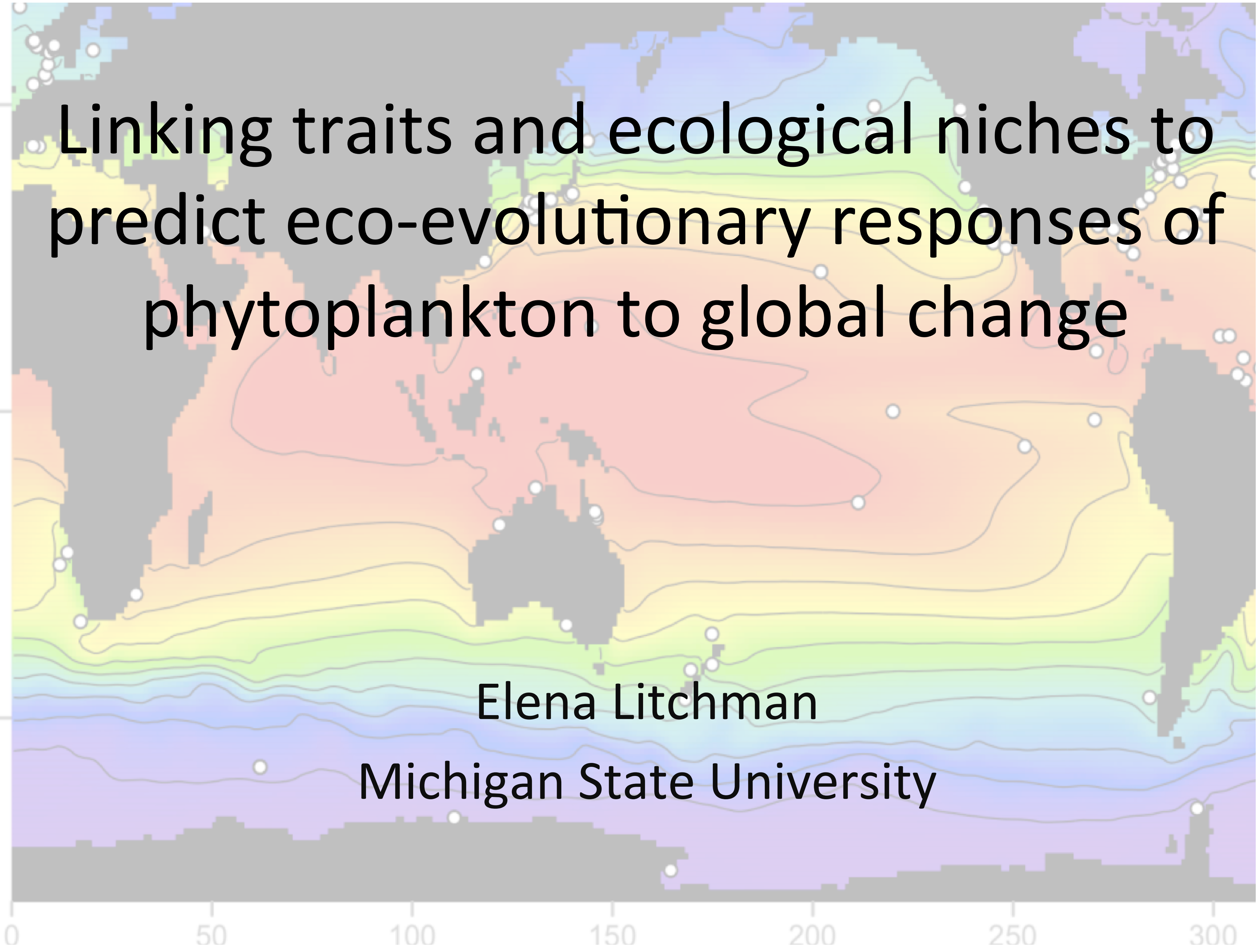
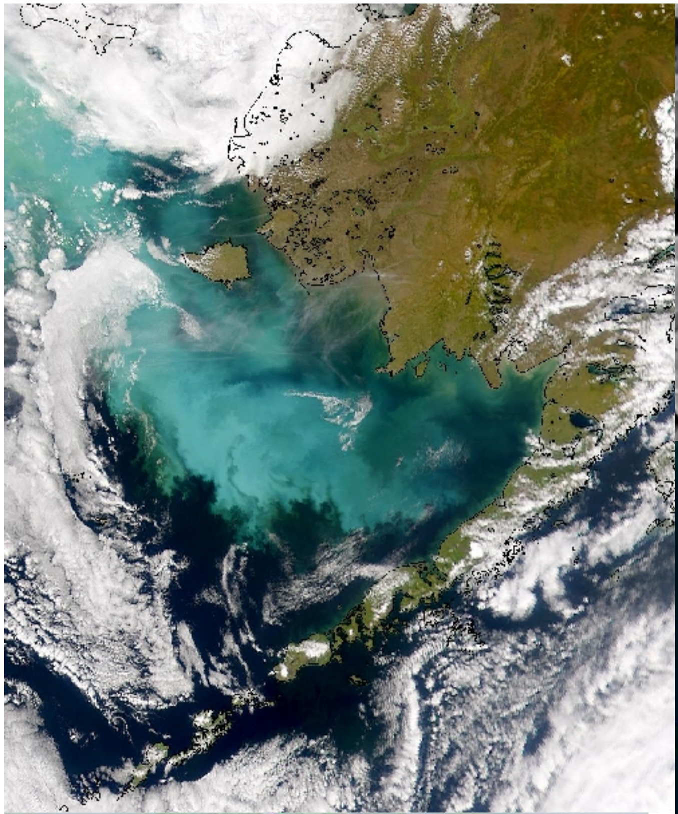
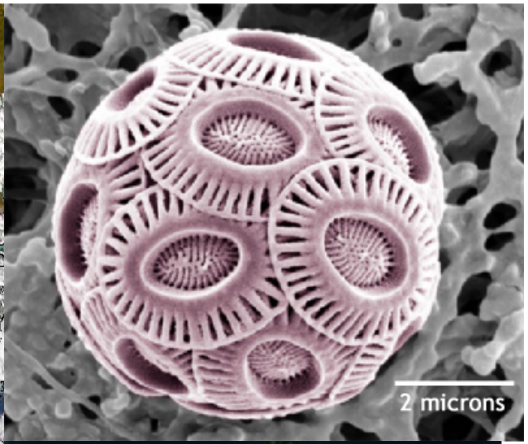
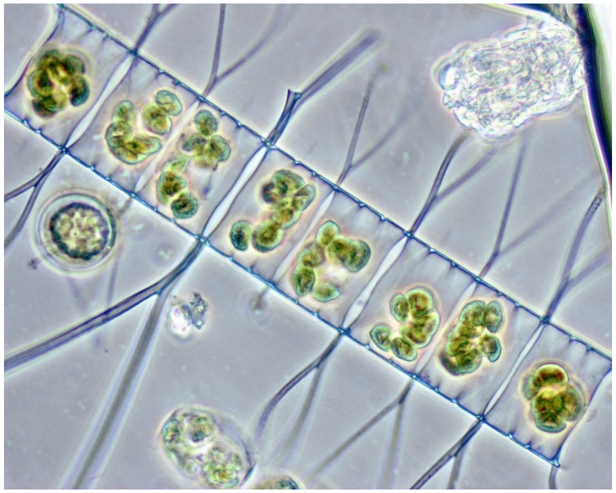
Linking traits and ecological niches to predict eco-evolutionary responses of phytoplankton to global change

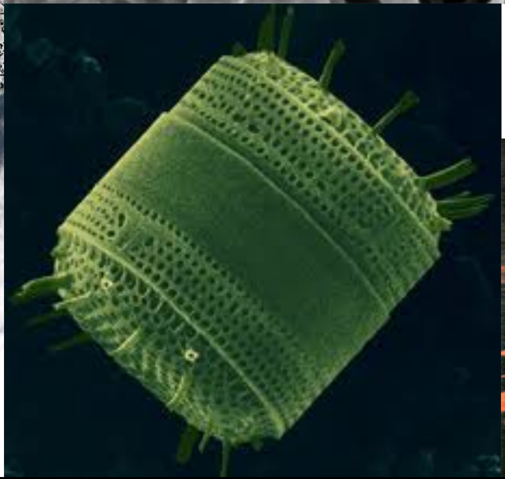
Elena Litchman
Michigan State University



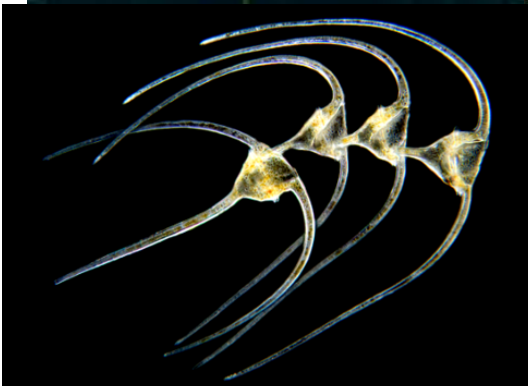



2 microns






@ PJS Franks



Climate Change Impacts on Phytoplankton

- Increase in CO_2 (acidification)
- Increase in temperature
- Change in stratification, nutrient and light availability
- Changes in other trophic levels (predators and parasites)

Key Questions

- How do abiotic constraints and biotic interactions shape community structure and diversity?
- How will communities re-organize under changing conditions (global environmental change?)
- How does community structure affect ecosystem functioning?

Responses of Phytoplankton Communities to Climate Change

- Dispersal
- Phenotypic plasticity
- Selection on new mutations
- Selection on standing genetic (functional) variation
- Species sorting (through competition)

Responses of Phytoplankton Communities to Climate Change

- Dispersal
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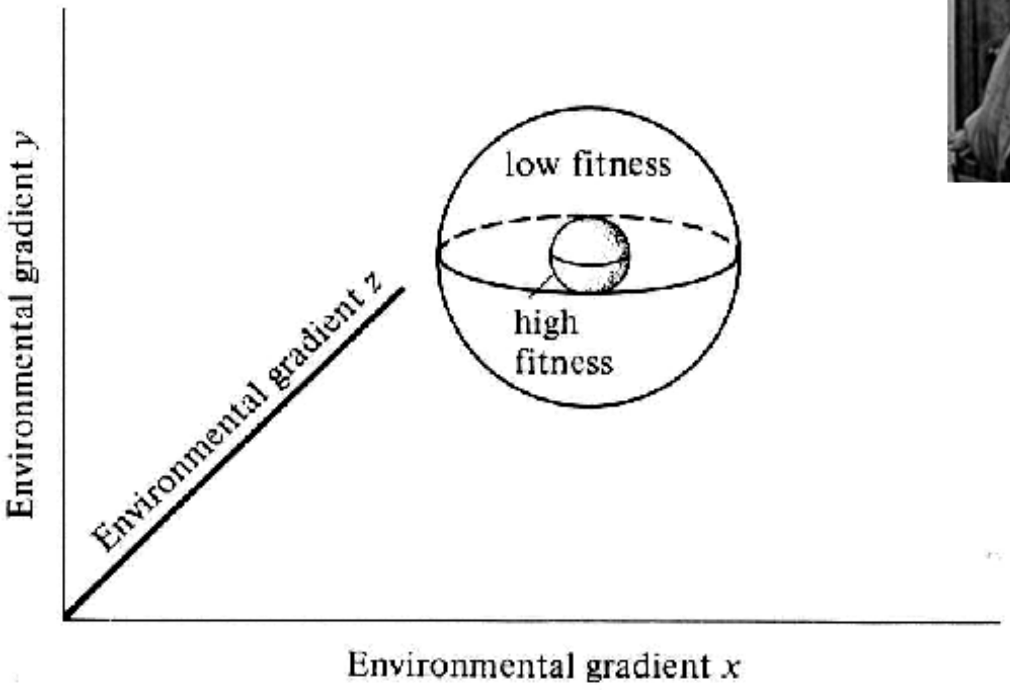
- Selection on standing genetic (functional) variation

Evolution

- Species sorting (through competition)

Ecological Niches of Phytoplankton

Hutchinsonian hypervolume



G. Evelyn Hutchinson

Ecological Niches of Phytoplankton

Niche axes

- Nutrients
- Light
- pH
- Temperature
- Predators, parasites, etc.

Fundamental Niche—set of abiotic conditions where a species can persist

Realized Niche—the portion of the fundamental niche in which a species has positive population growth rates, in the presence of biotic interactions (competition)

Statistical Niche Characterization

Problems: not mechanistic, niche changes (contraction, expansion or shift)

- Realized niche—due to ecological interactions
- Fundamental niche—due to evolutionary changes

How to determine if a niche is static or shifts?

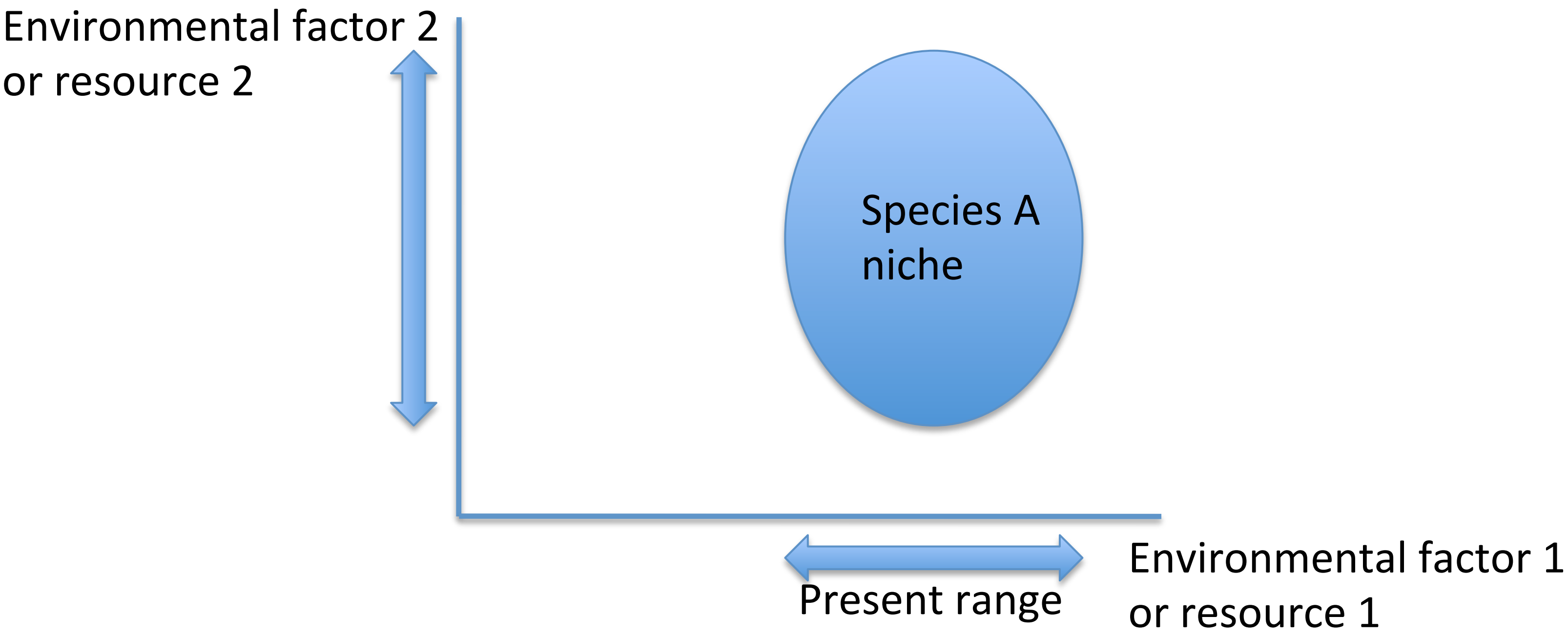
What niche dimensions are more likely to shift?

Can test for niche shifts:

- Predict past species distributions from models fitted under current climate conditions or vice versa
- Use SDMs to predict distributions in different regions

Pearman et al. 2008

Ecological Niche of Phytoplankton



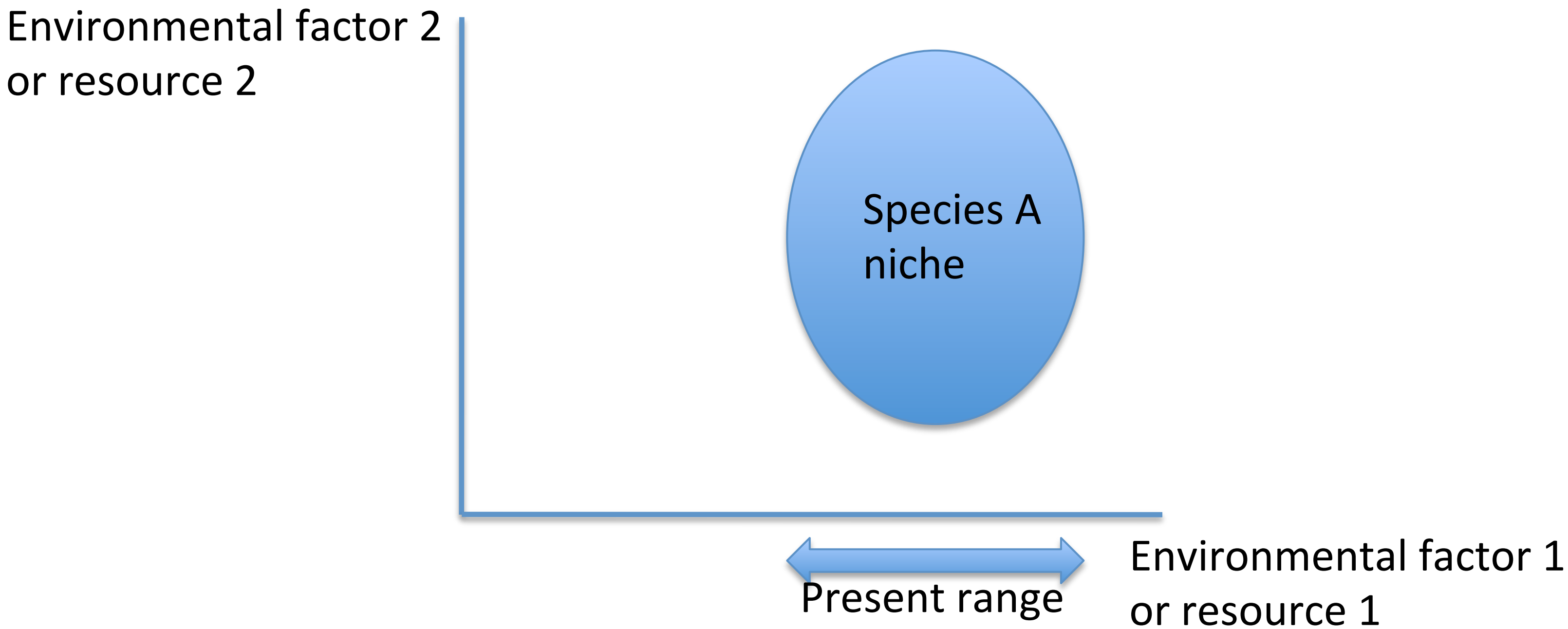
Environmental factor 2
or resource 2

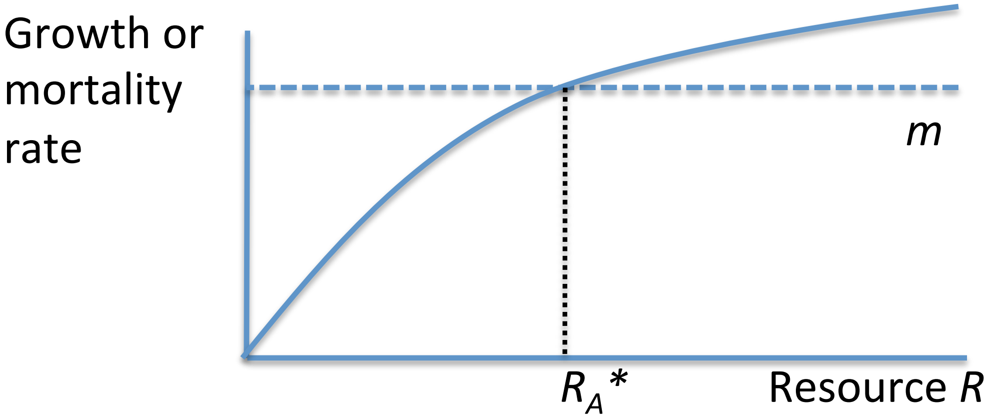
Species A
niche

Present range

Environmental factor 1
or resource 1

Linking Niche and Traits

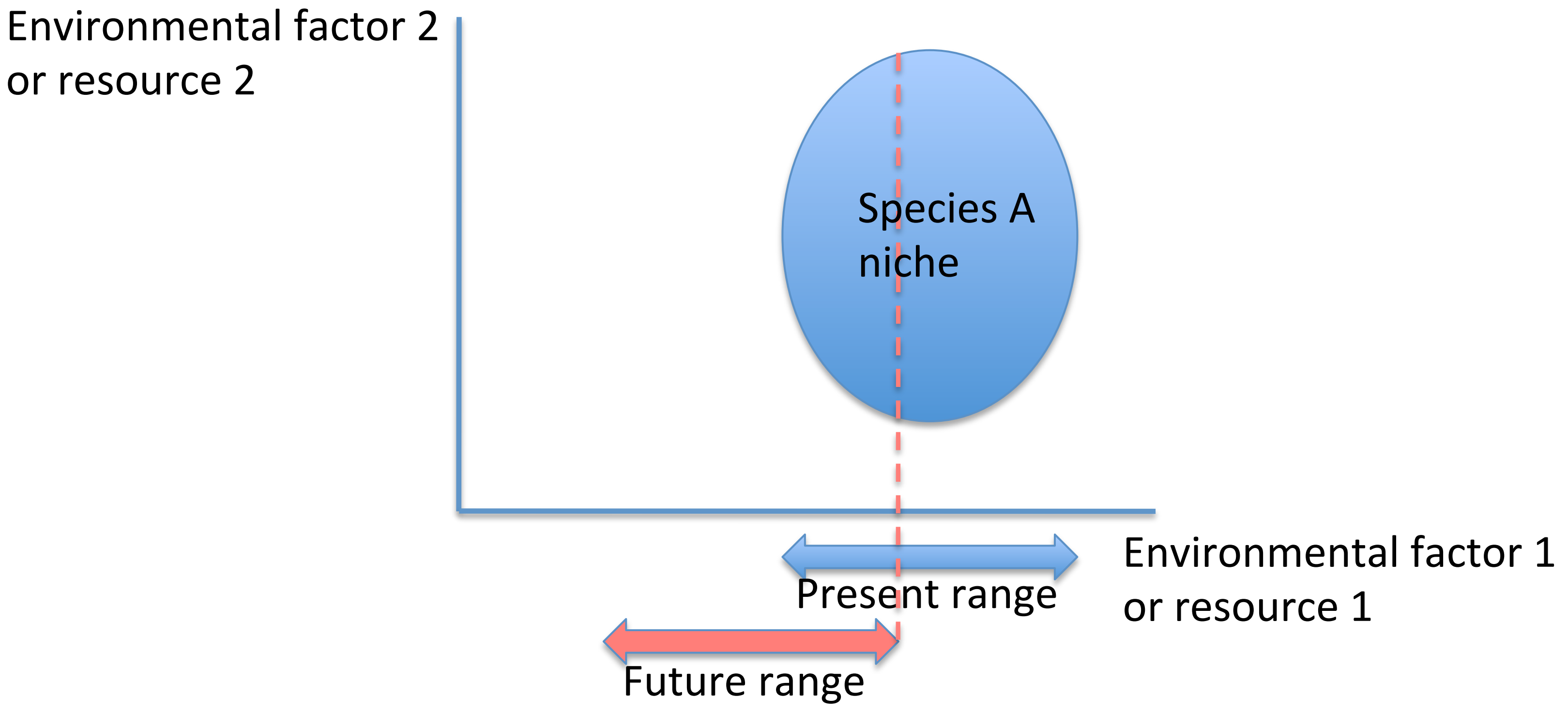




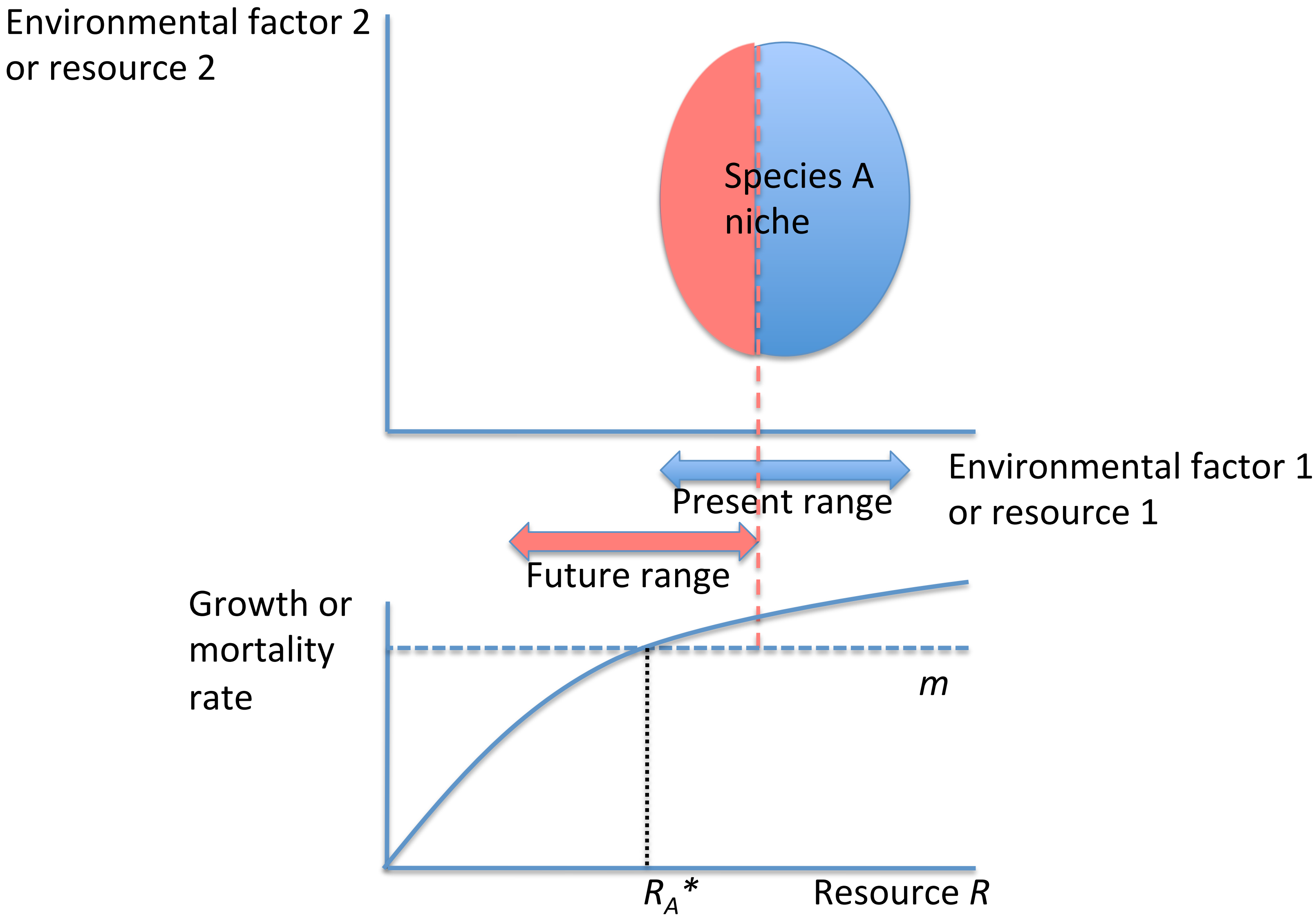
$$\mu = \mu_{\max} \frac{R}{R + k} - m$$

$$R_A{}^* = \frac{mk}{\mu_{\max} - m}$$

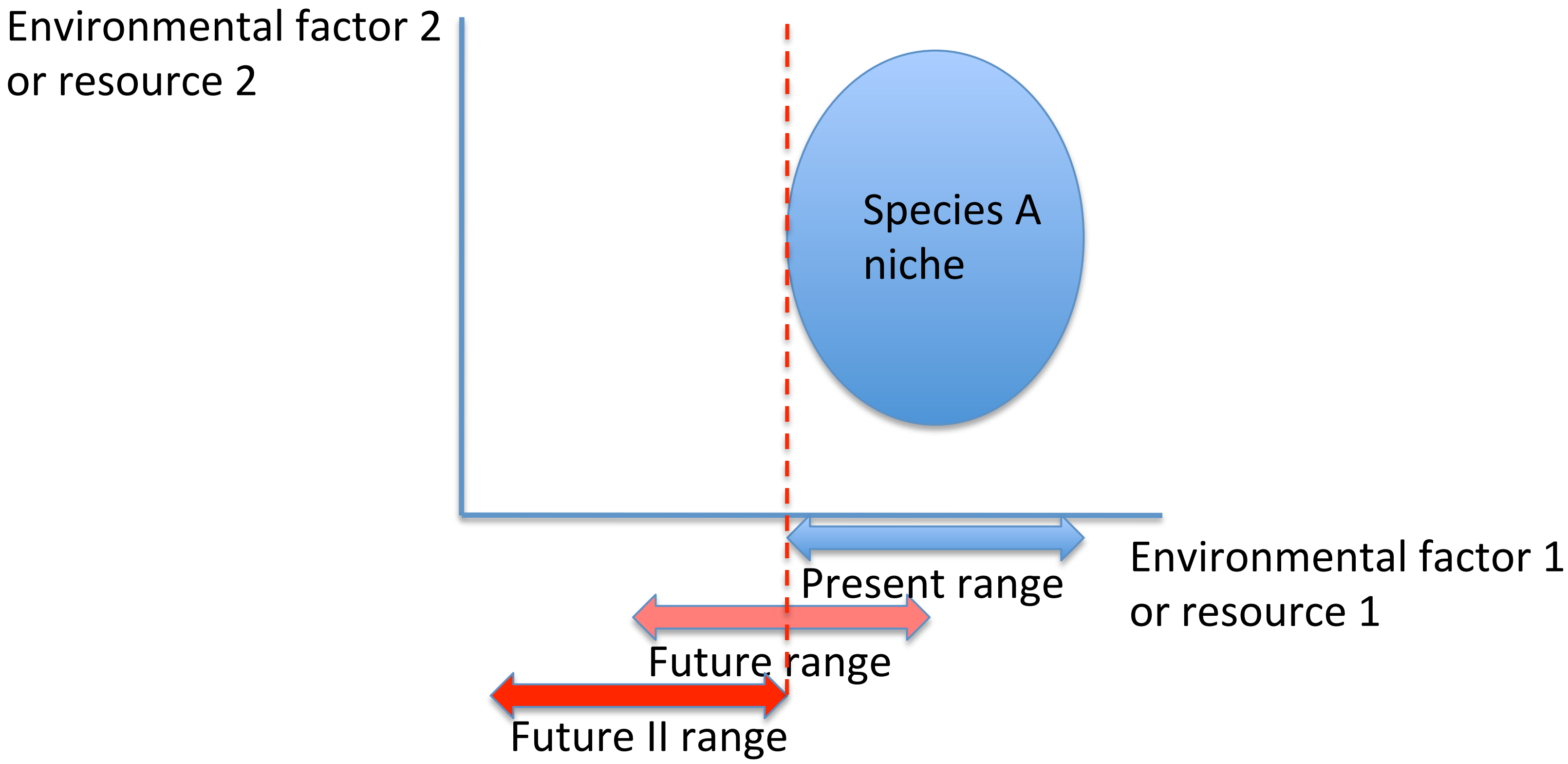
Global Change Effects on Niche



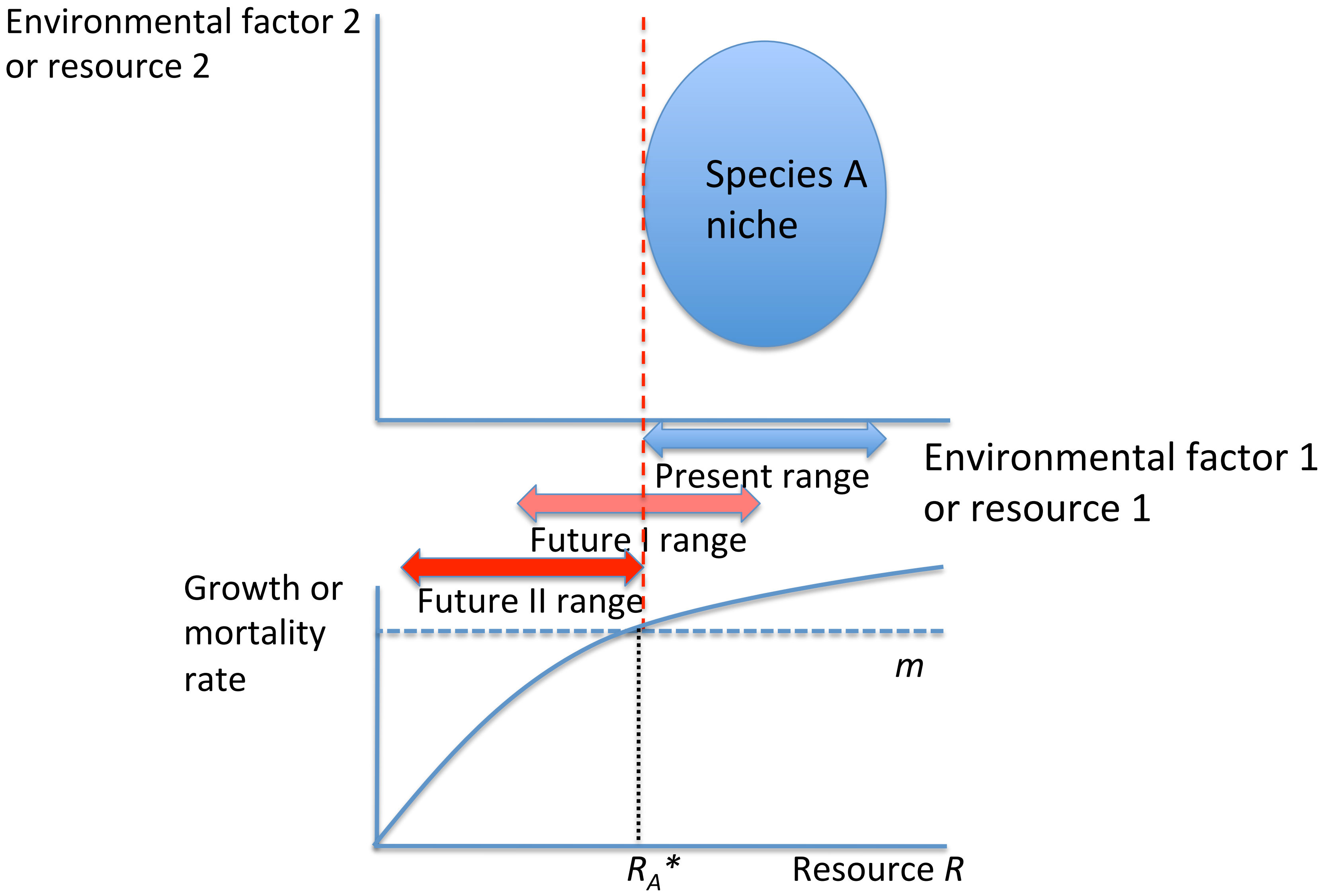
Global Change Effects on Niche



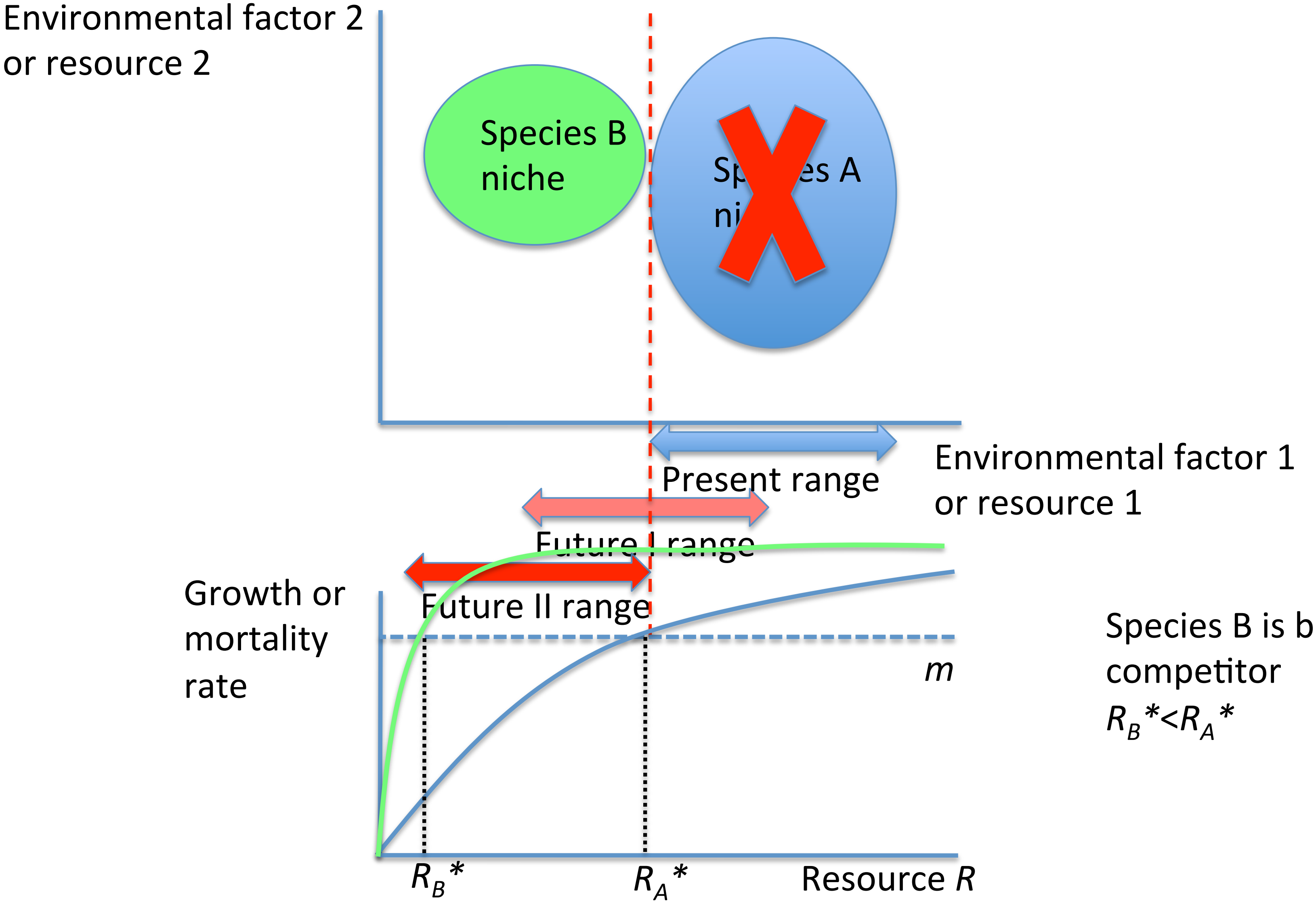
Global Change Effects on Niche



Global Change Effects on Niche



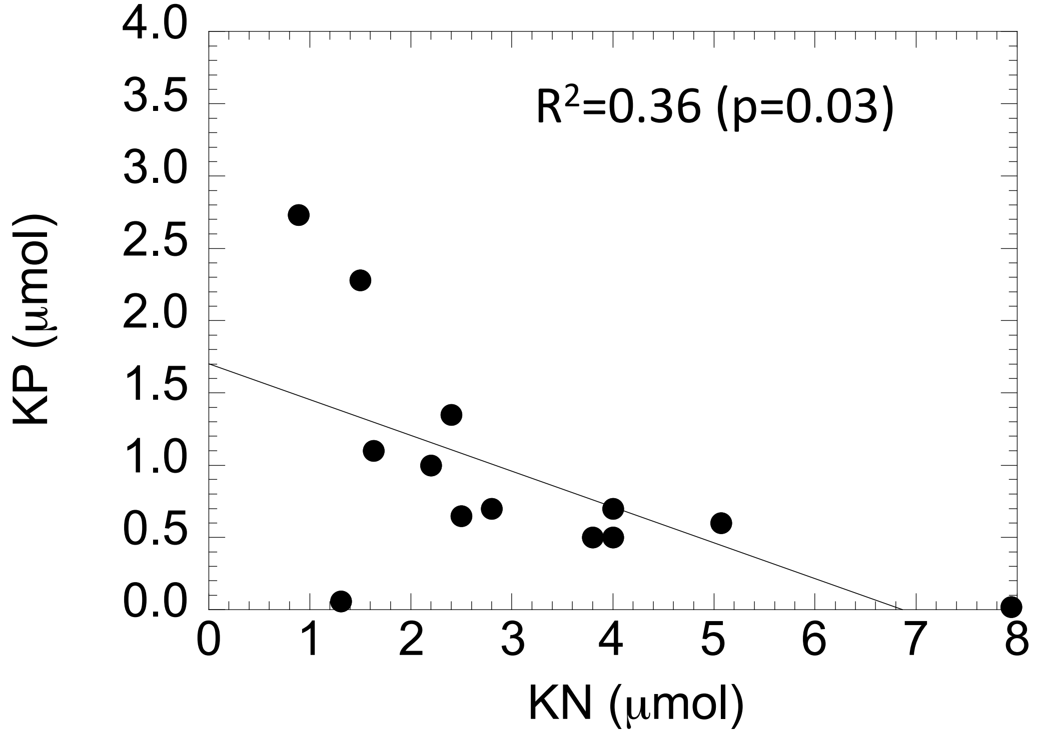
Species Replacement Under Global Change



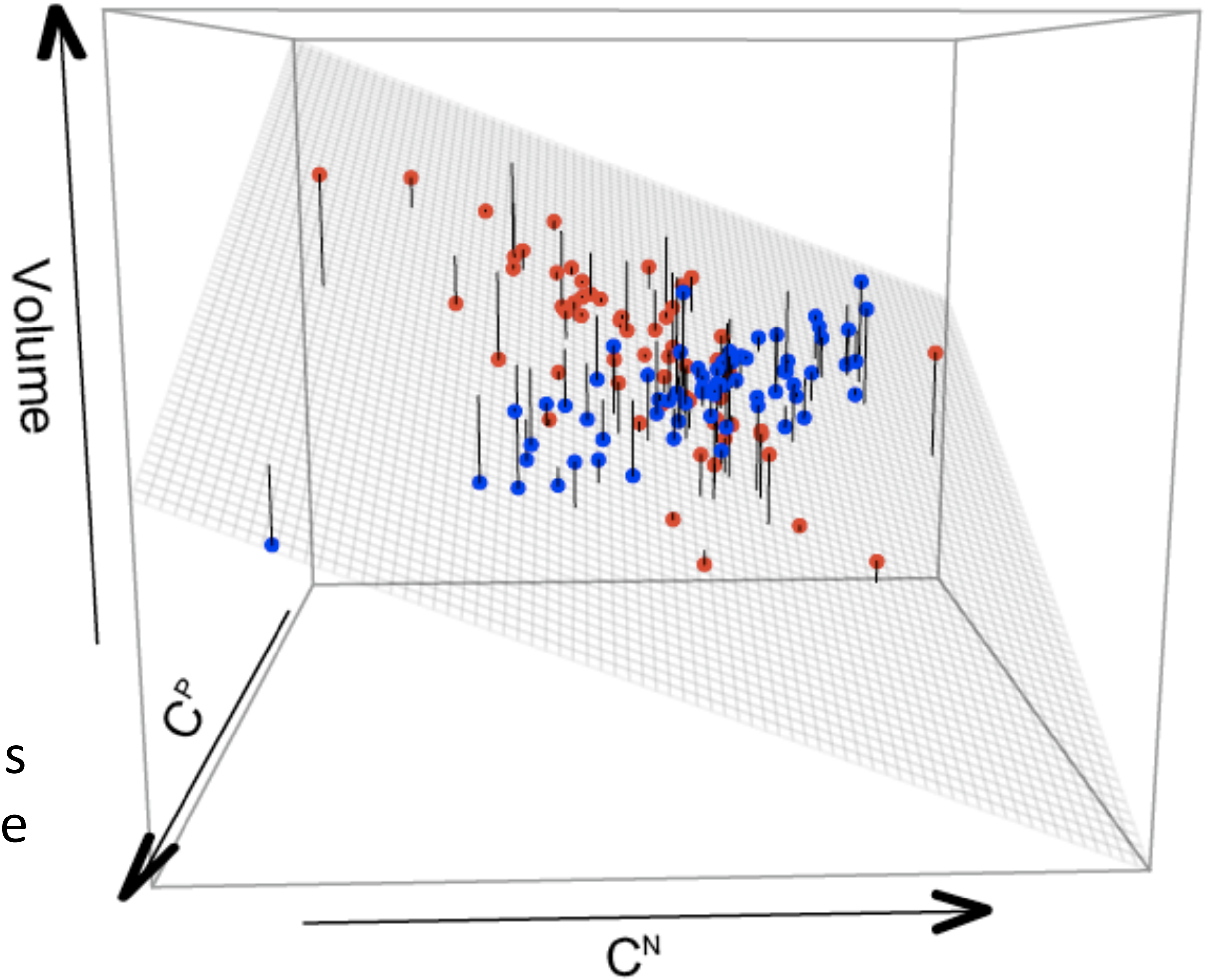
Species B is better competitor
$R_B* < R_A*$

Trade-offs Between Traits

Half-saturation constants for N and P



Three-way trade-off



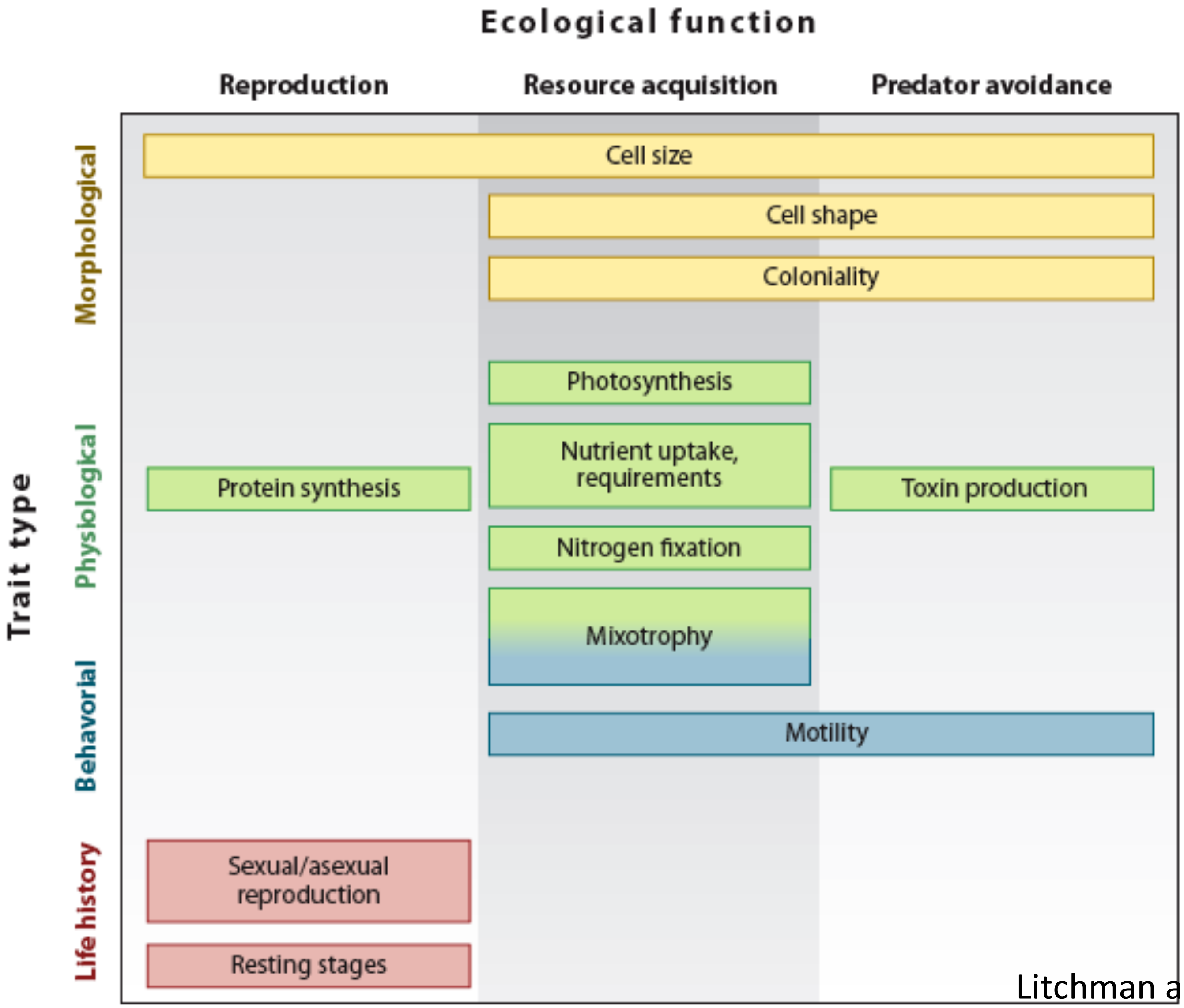
Grazer resistance

Phosphorus competitive ability

Nitrogen competitive ability

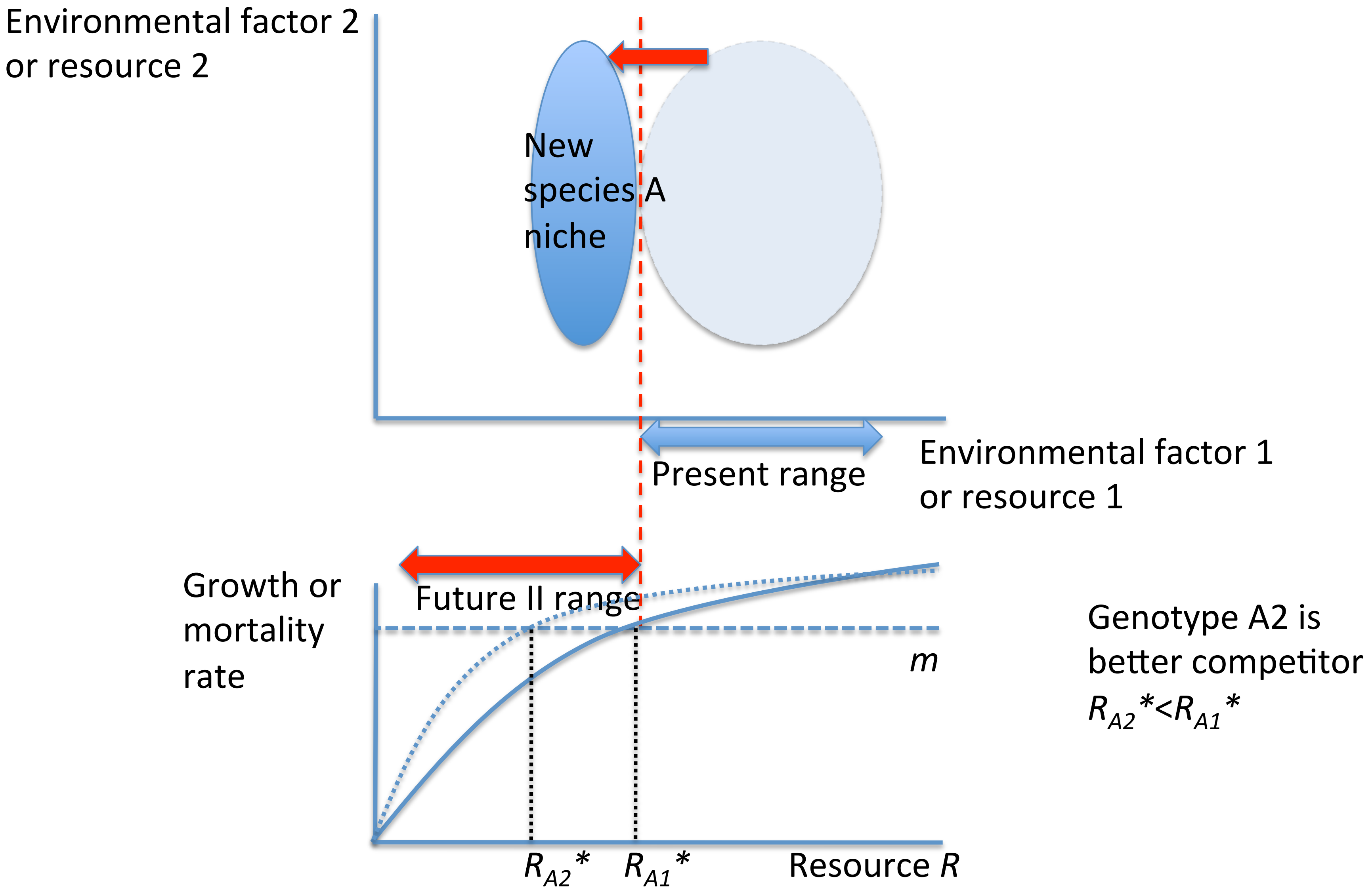
Edwards et al. Ecology 2011

Key Phytoplankton Traits, Multitude of Potential Trade-offs



Litchman and Klausmeier 2008
Ann. Rev. Ecol. Evol. Syst.

Trait Evolution and Niche Shift Under Global Change



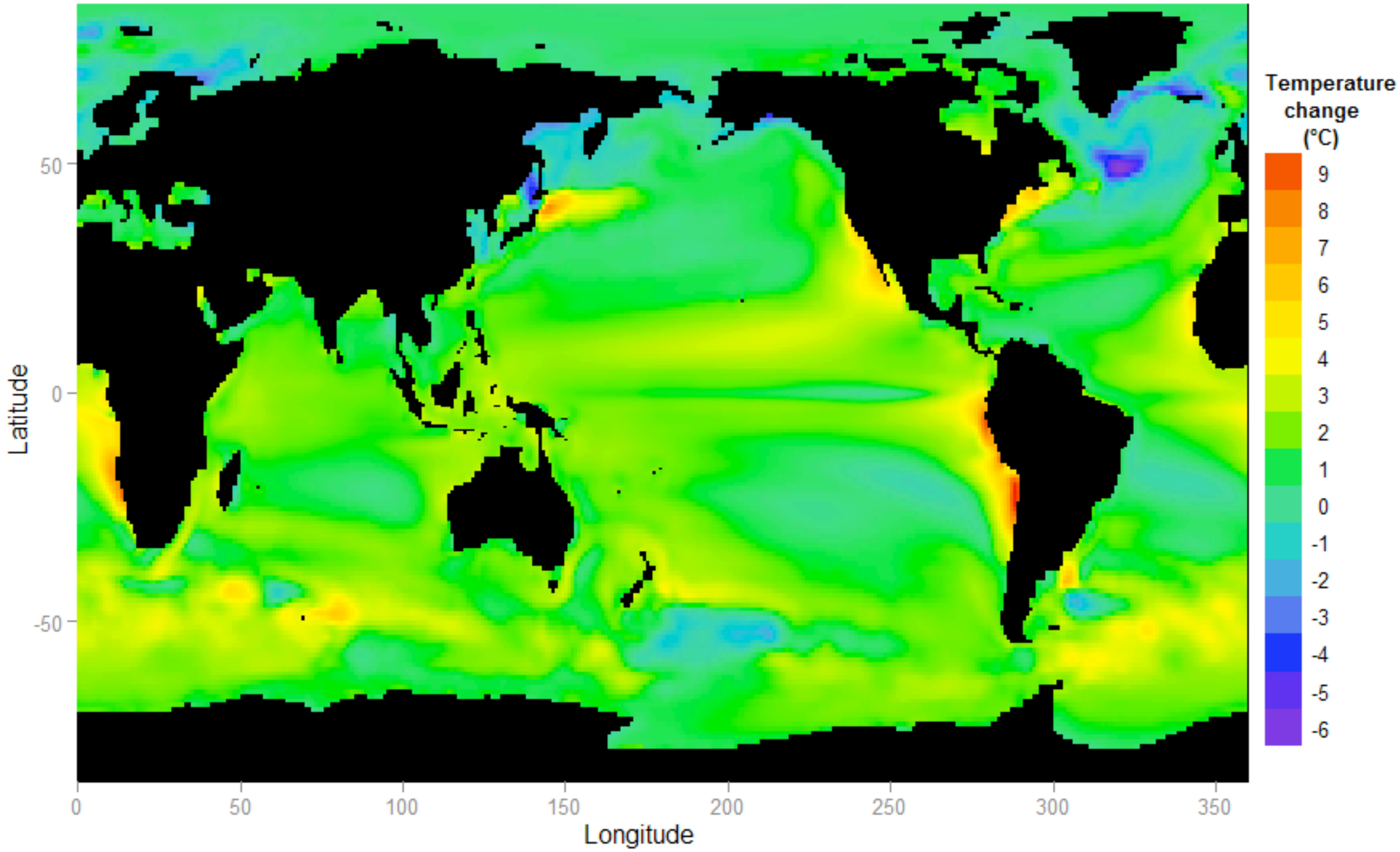
Genotype A2 is better competitor $R_{A2}^* < R_{A1}^*$

Ways to Explore Trait and Niche Evolution

- Adaptive dynamics models, include biotic interactions (competition)
- Evolution experiments with individual species and in community context

Temperature change
Present-2100

Warming at least 2 - 4°C in most of the ocean



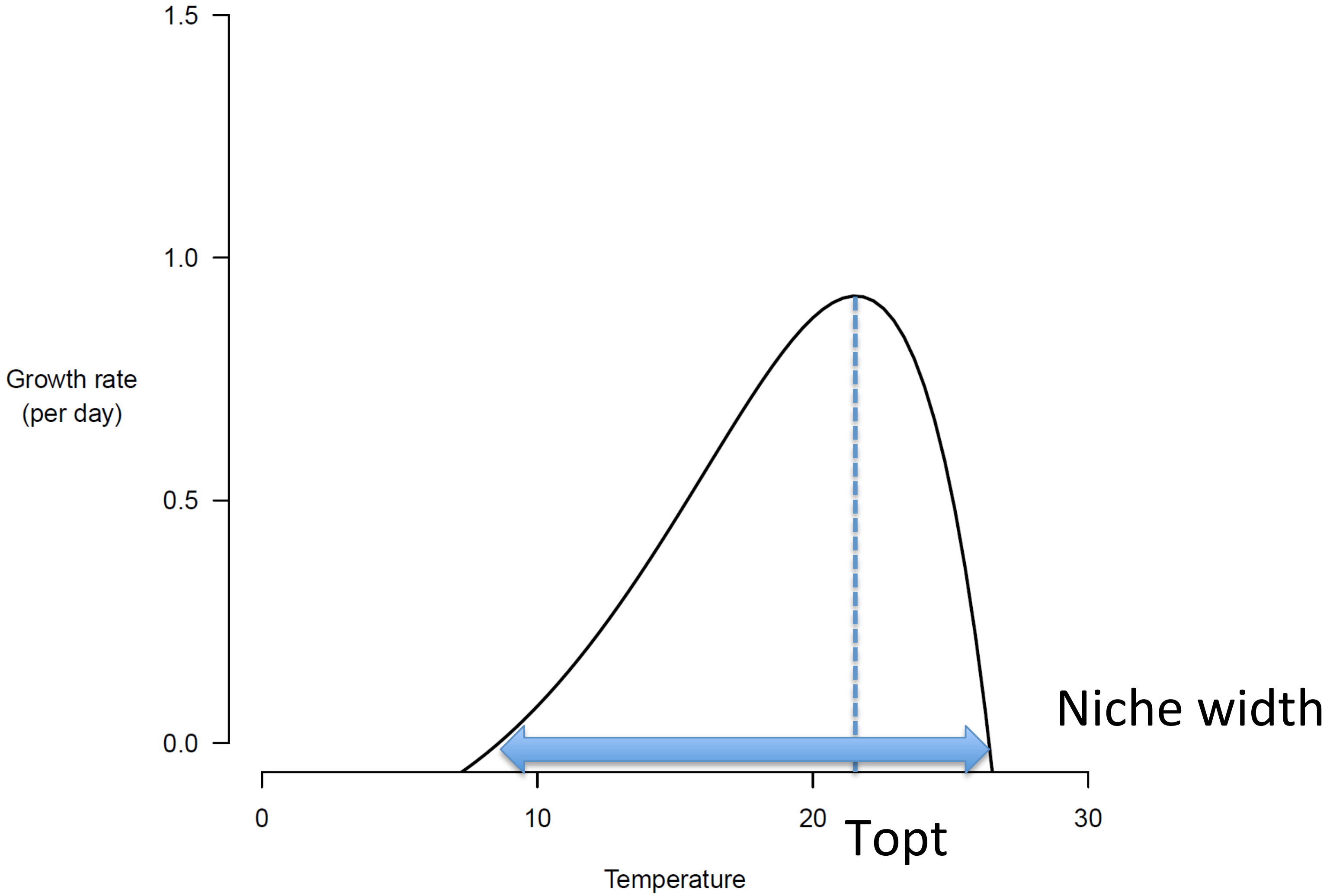
Thermal responses of phytoplankton

[redacted]

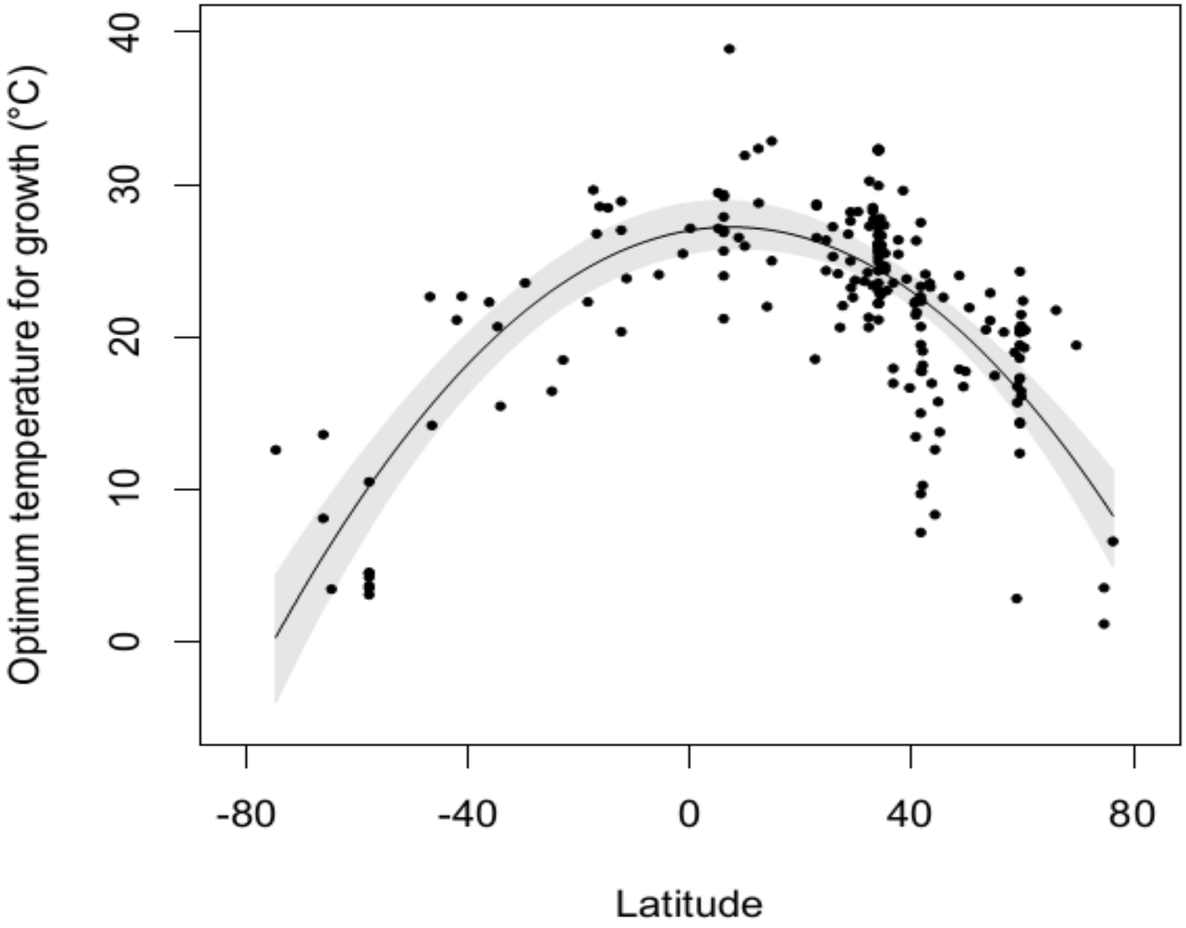
Data analysis

- Collected published data/curves for 194 phytoplankton isolates across >100 different locations from 76°N to 75°S
- Fit growth function to the curves
- Determined optima and niche widths

Thermal tolerance curve

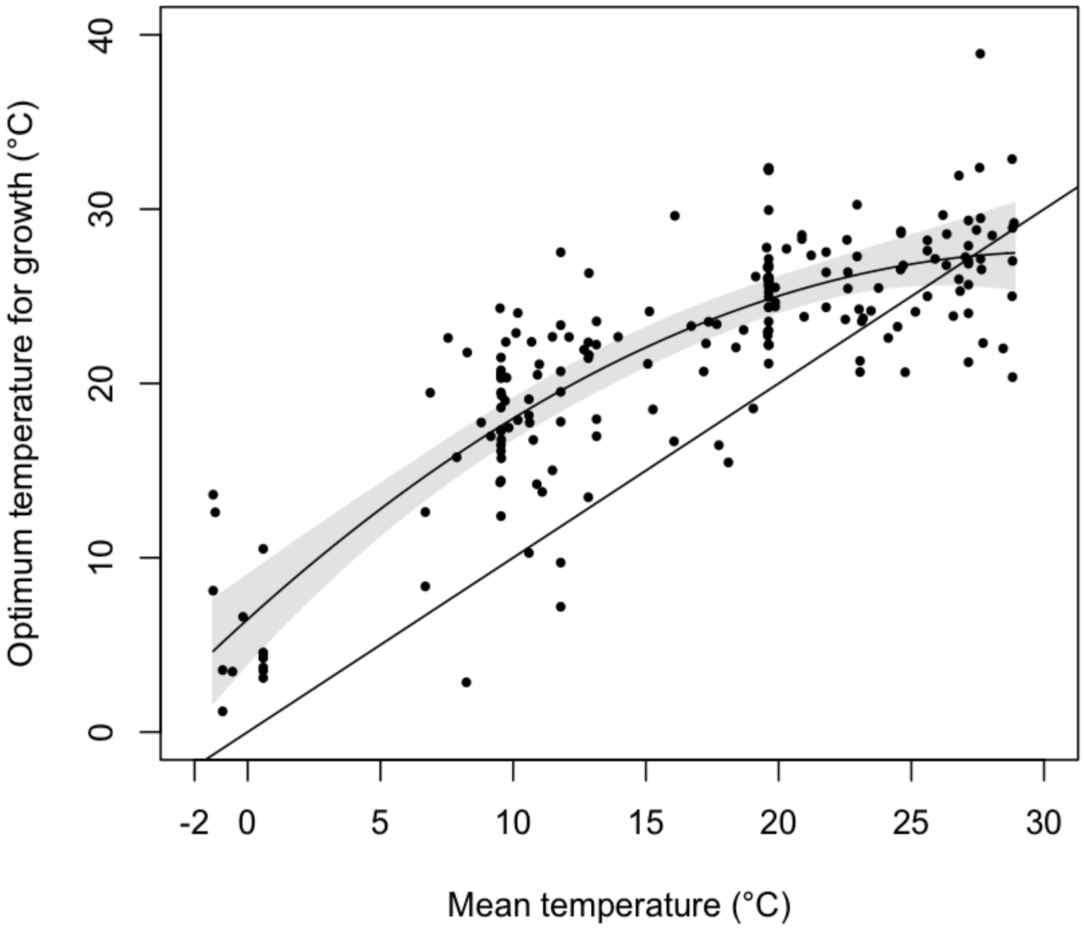


Strong latitudinal gradient in optimal temperature



Thomas et al. Science 2012

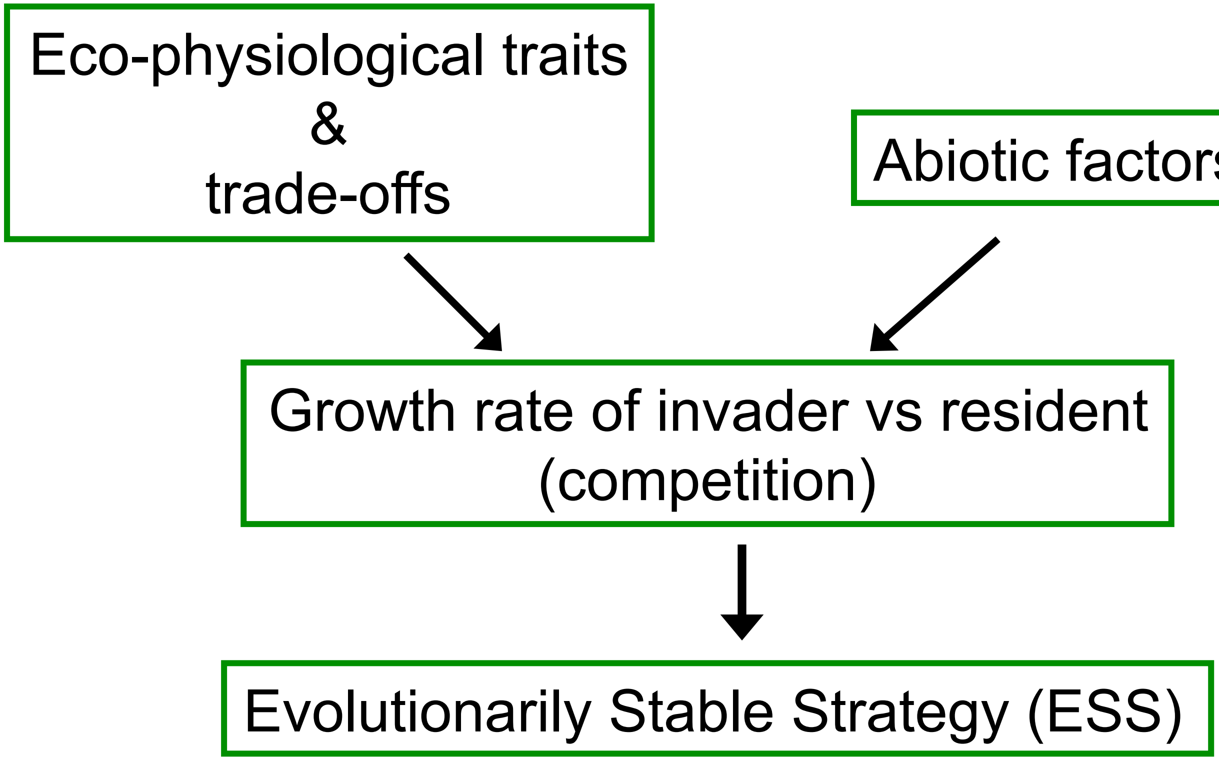
Adaptation to mean ambient temperature



Thomas et al. Science 2012

Adaptive Dynamics Approach

(a trait-based approach to evolutionary ecology)



Eco-physiological traits
&
trade-offs

Abiotic factors

Growth rate of invader vs resident
(competition)

Evolutionarily Stable Strategy (ESS)

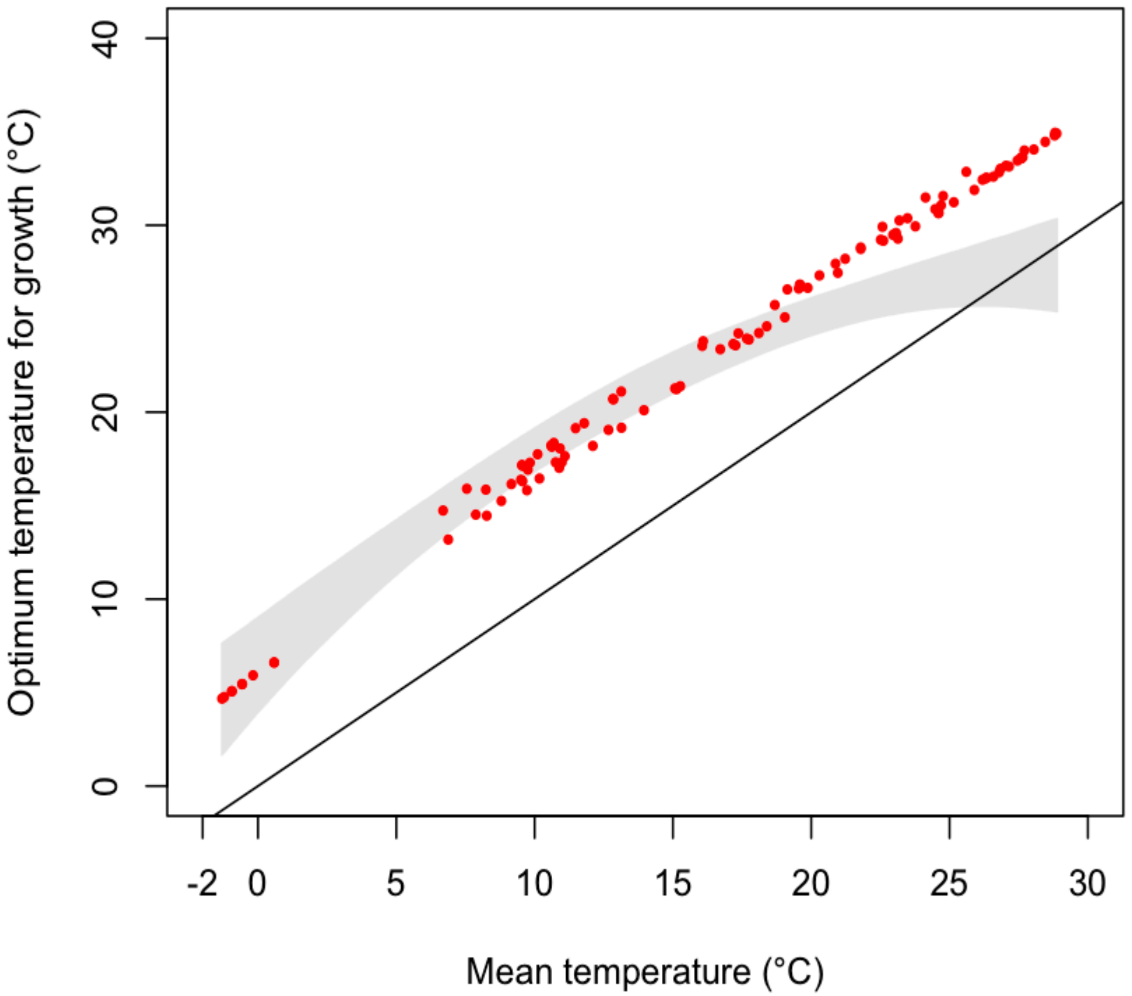
Eco-evolutionary dynamics

$$\frac{dN}{dt} = N \cdot \left(f(Z,T) \cdot \frac{R}{R+k} - m \right)$$

$$R = R_{in} - a \sum_{j=1}^{n} N_i(t)$$

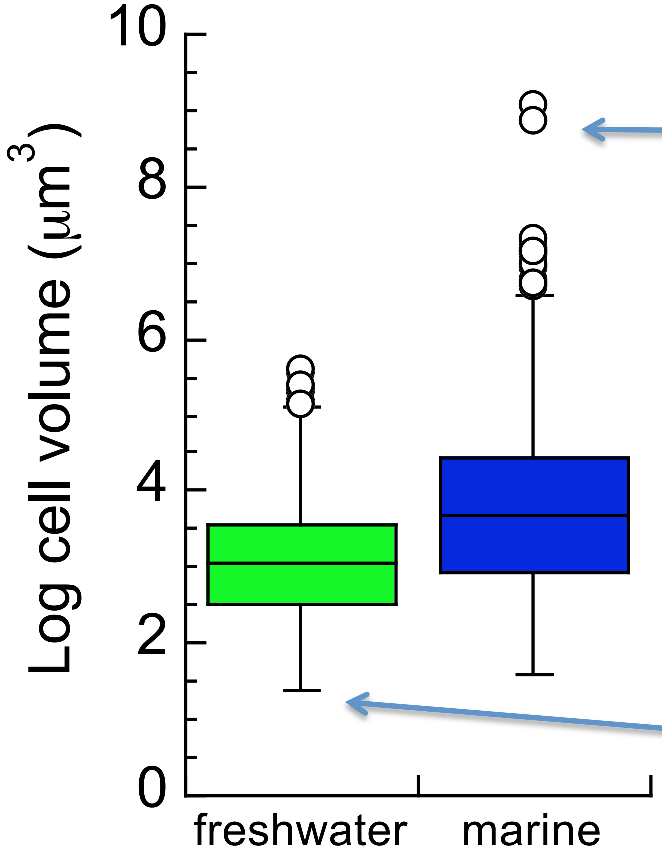
$$\frac{dZ_i}{dt} = \varepsilon \cdot \frac{dg_i}{dZ_i}$$

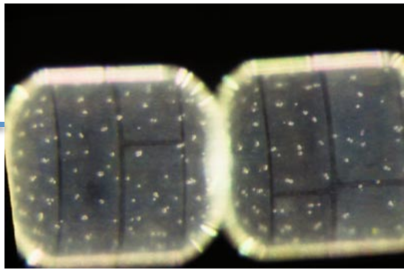
Observed and predicted temperature optima



Thomas et al. Science 2012

Size Distribution in Freshwater and Marine Diatoms

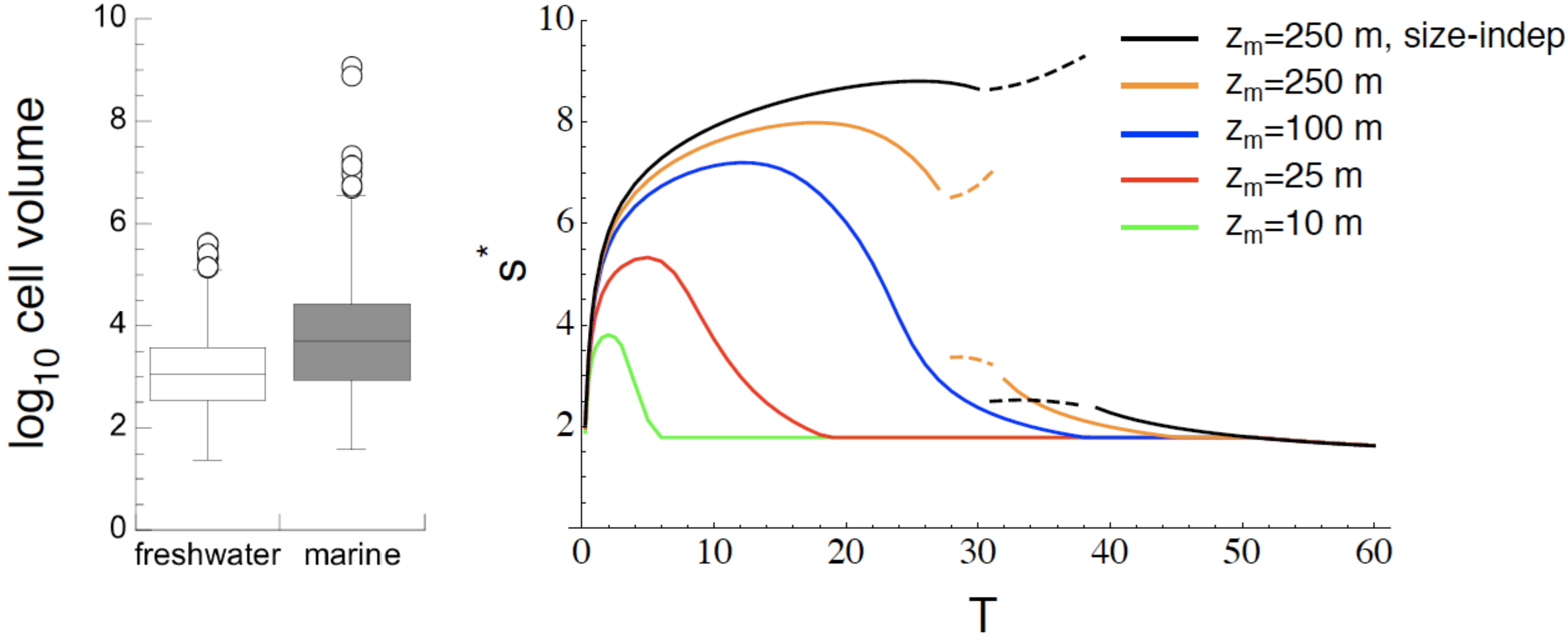




Ethmodiscus rex, 1-3 mm diameter!

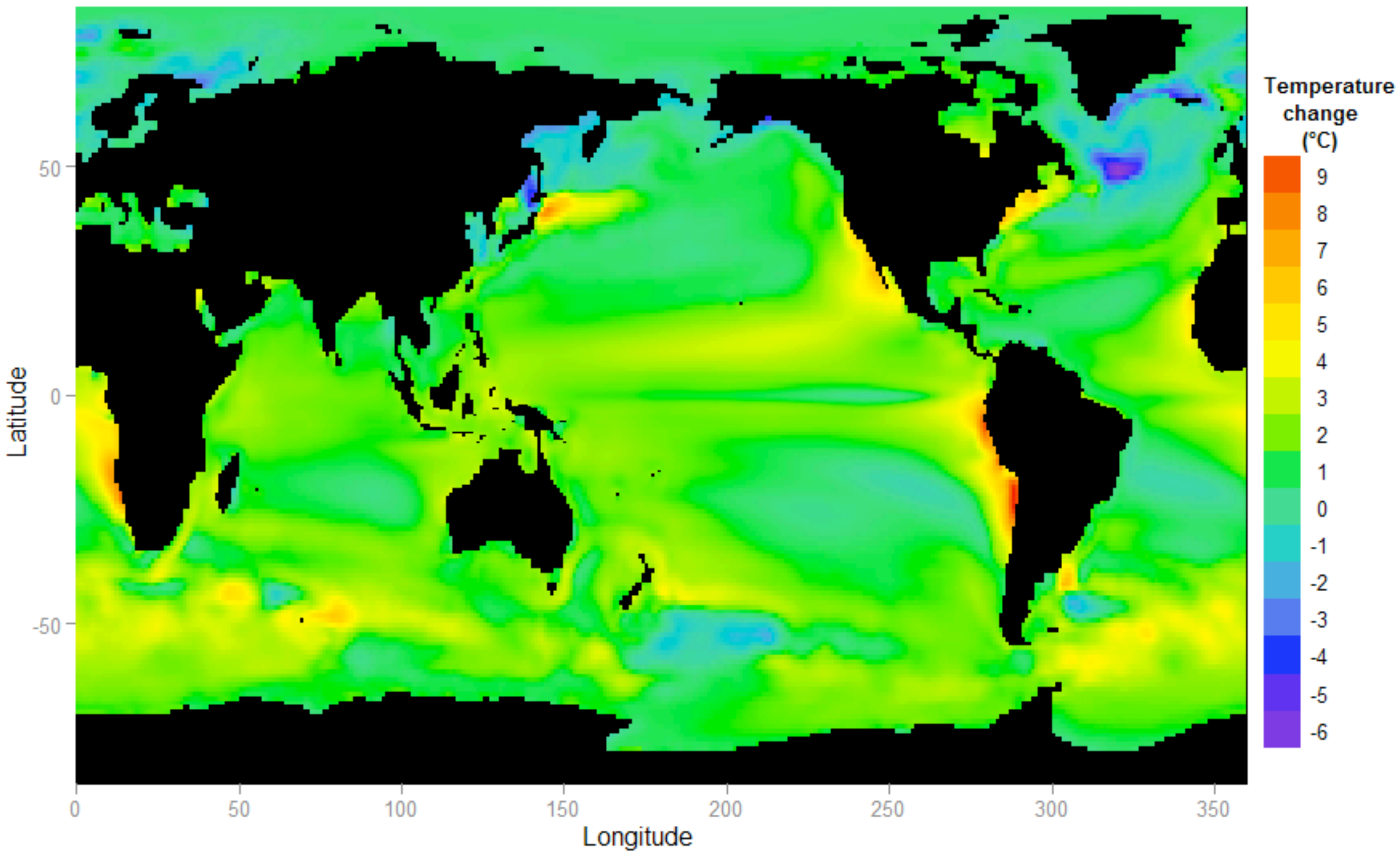
Cyclotella

ESS (N limitation) at different fluctuation periods, mixed layer depth and sinking

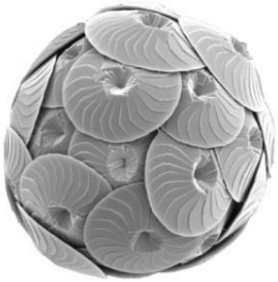


Litchman et al. 2009 PNAS

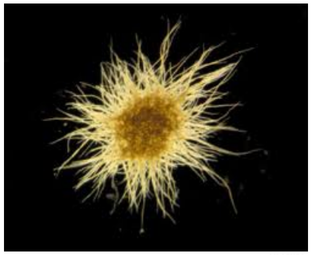
Temperature change
Present-2100



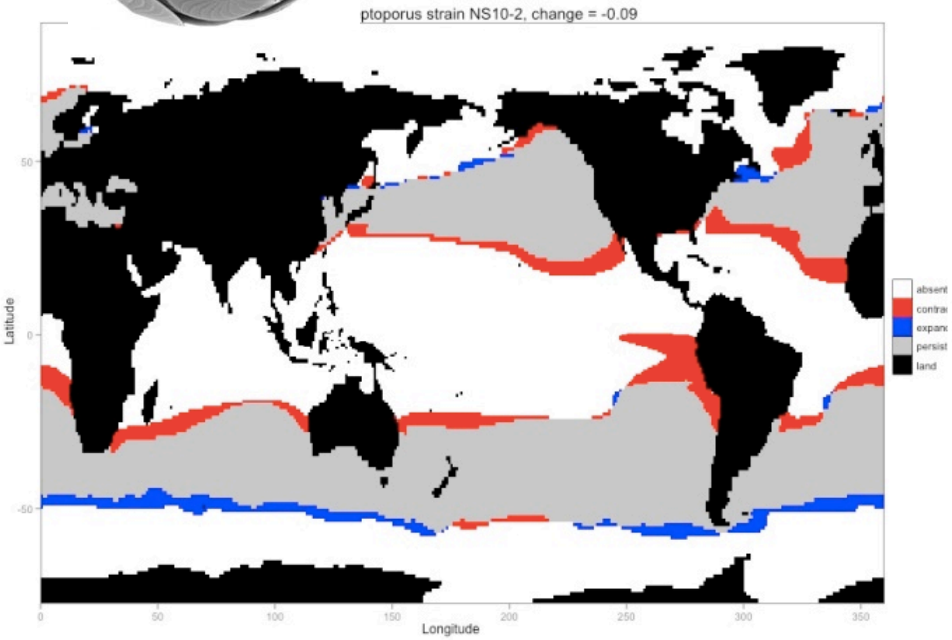
Shifts in Fundamental Thermal Niche

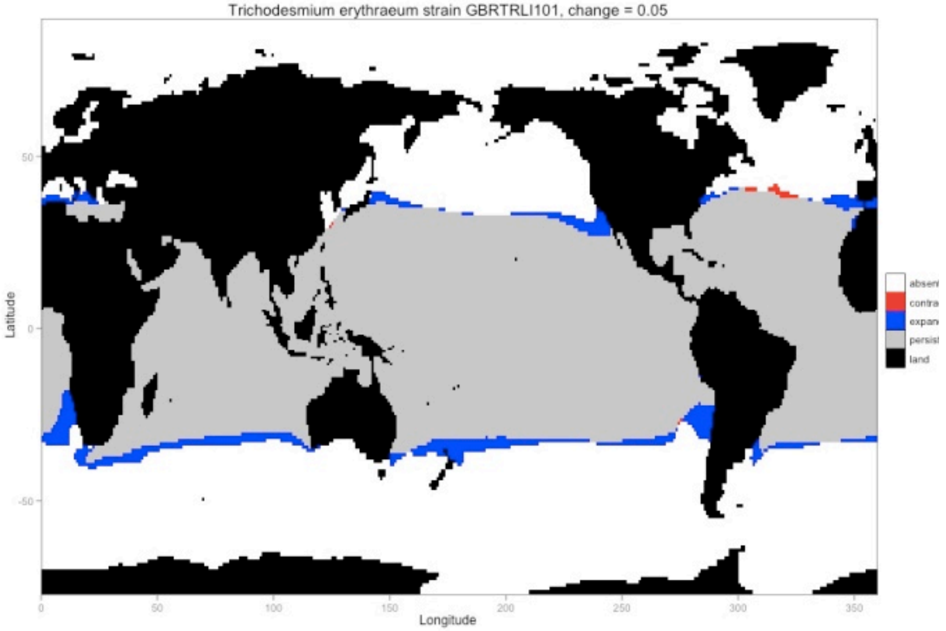


Calcidiscus leptoporus

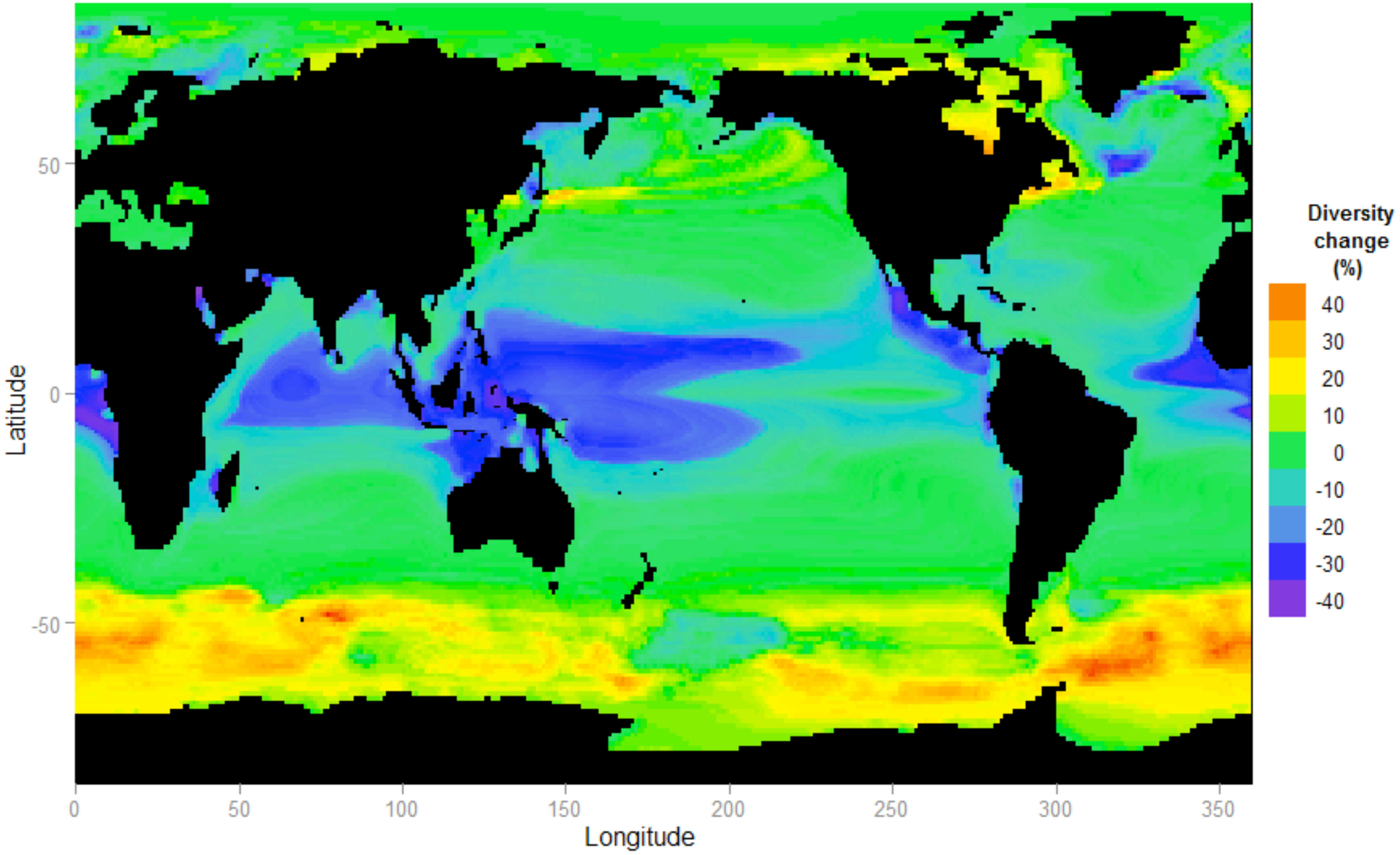


Trichodesmium erythraeum

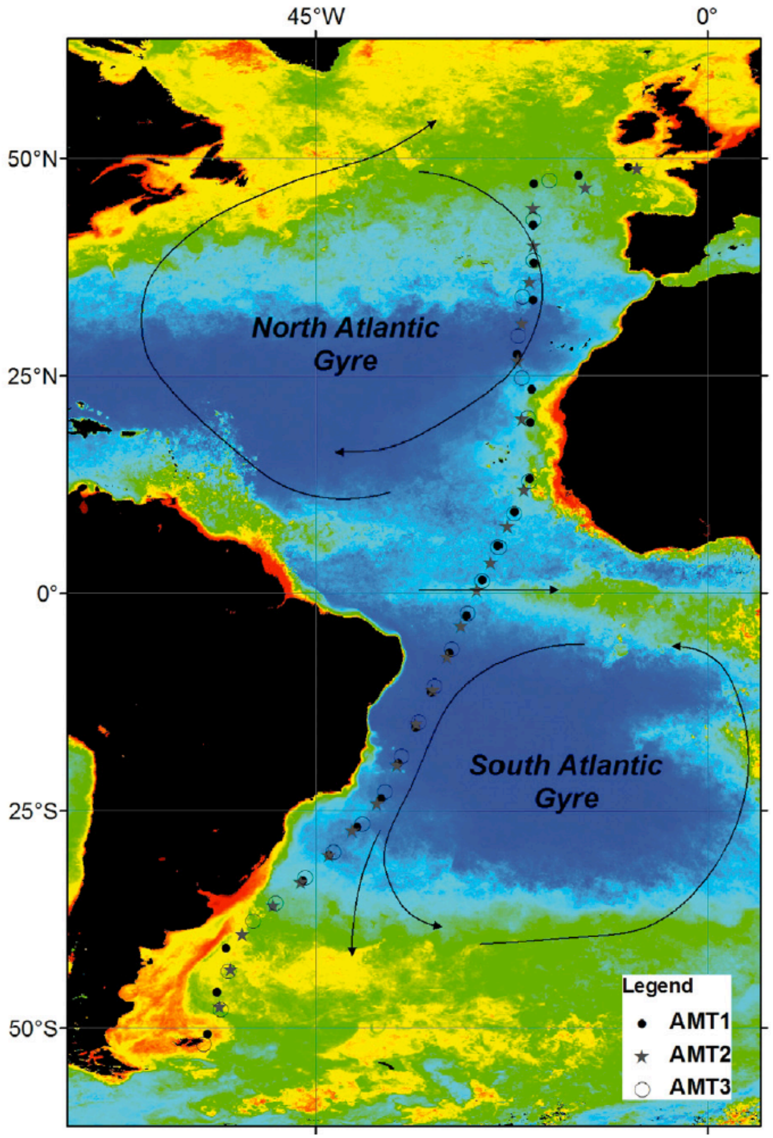




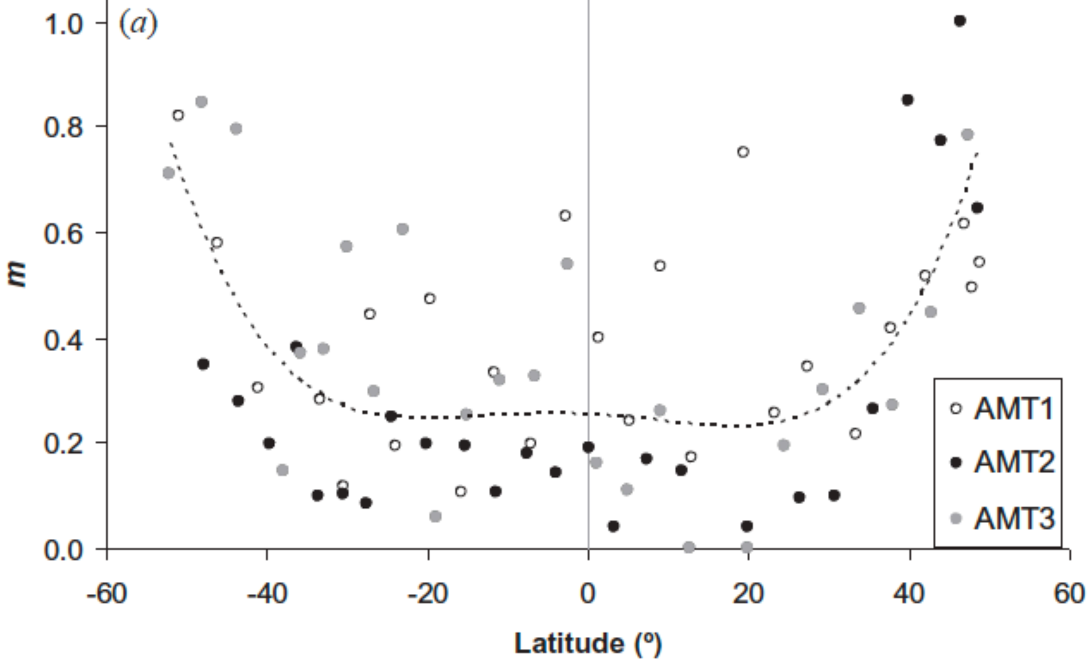
Potential diversity changes due to shifts in thermal niches



Dispersal



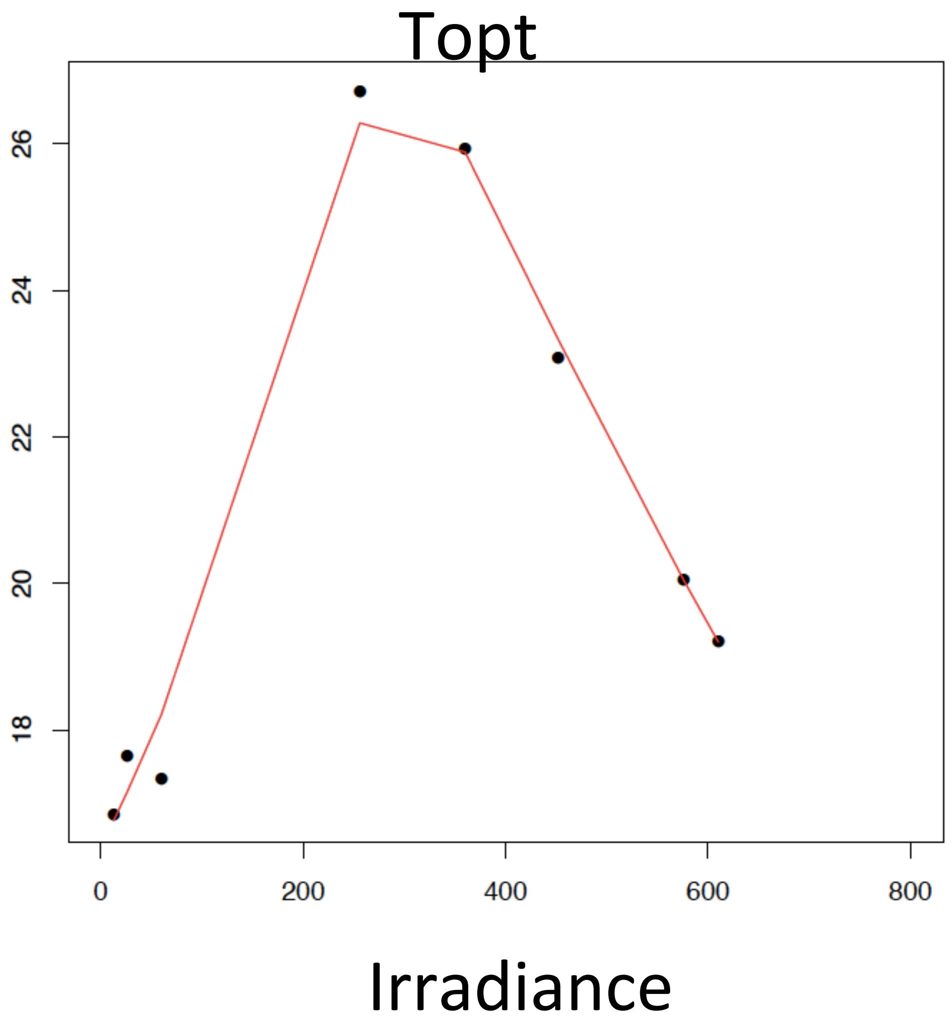
Immigration rate
AMT data



Chust et al. Glob Ecol Biogeogr 2012

Phenotypic Plasticity

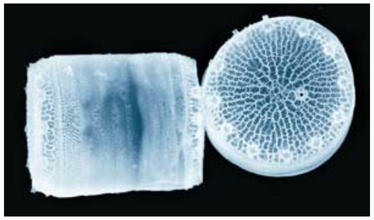
- Important in all organisms
- Not much is known how thermal traits change due to acclimation

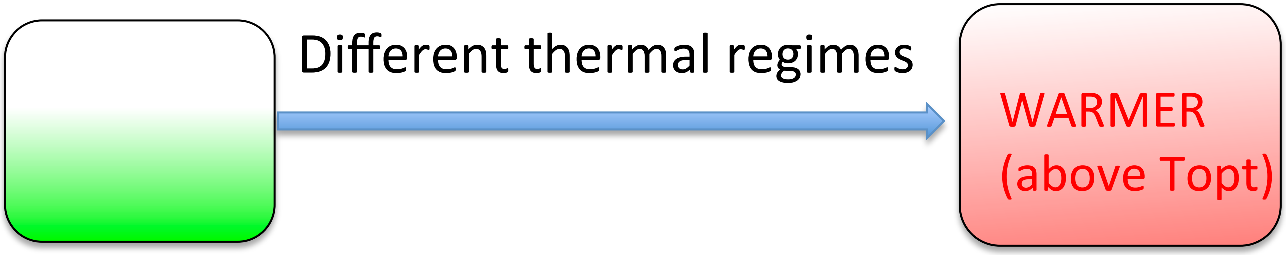


Thomas et al. in prep.

Selection on New Mutations: Evolution Experiments

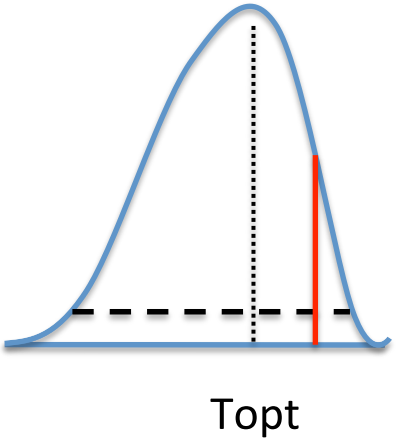
Thalassiosira pseudonana





Different thermal regimes

WARMER (above Topt)



Selection on New Mutations: Evolution Experiments

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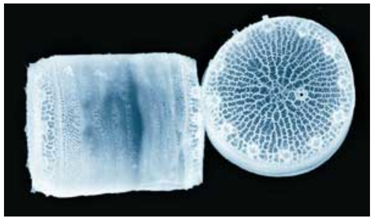
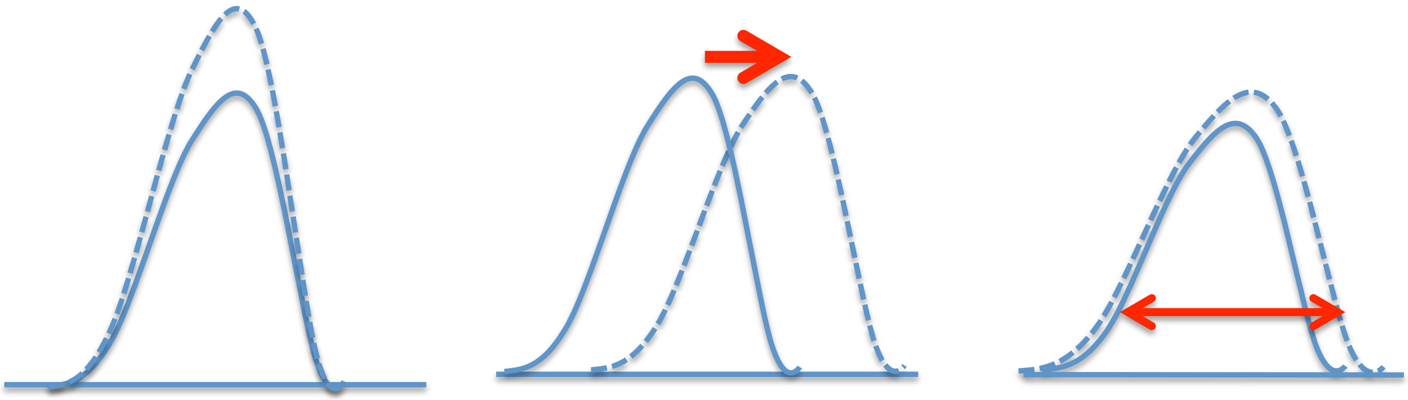


Possible adaptation scenarios



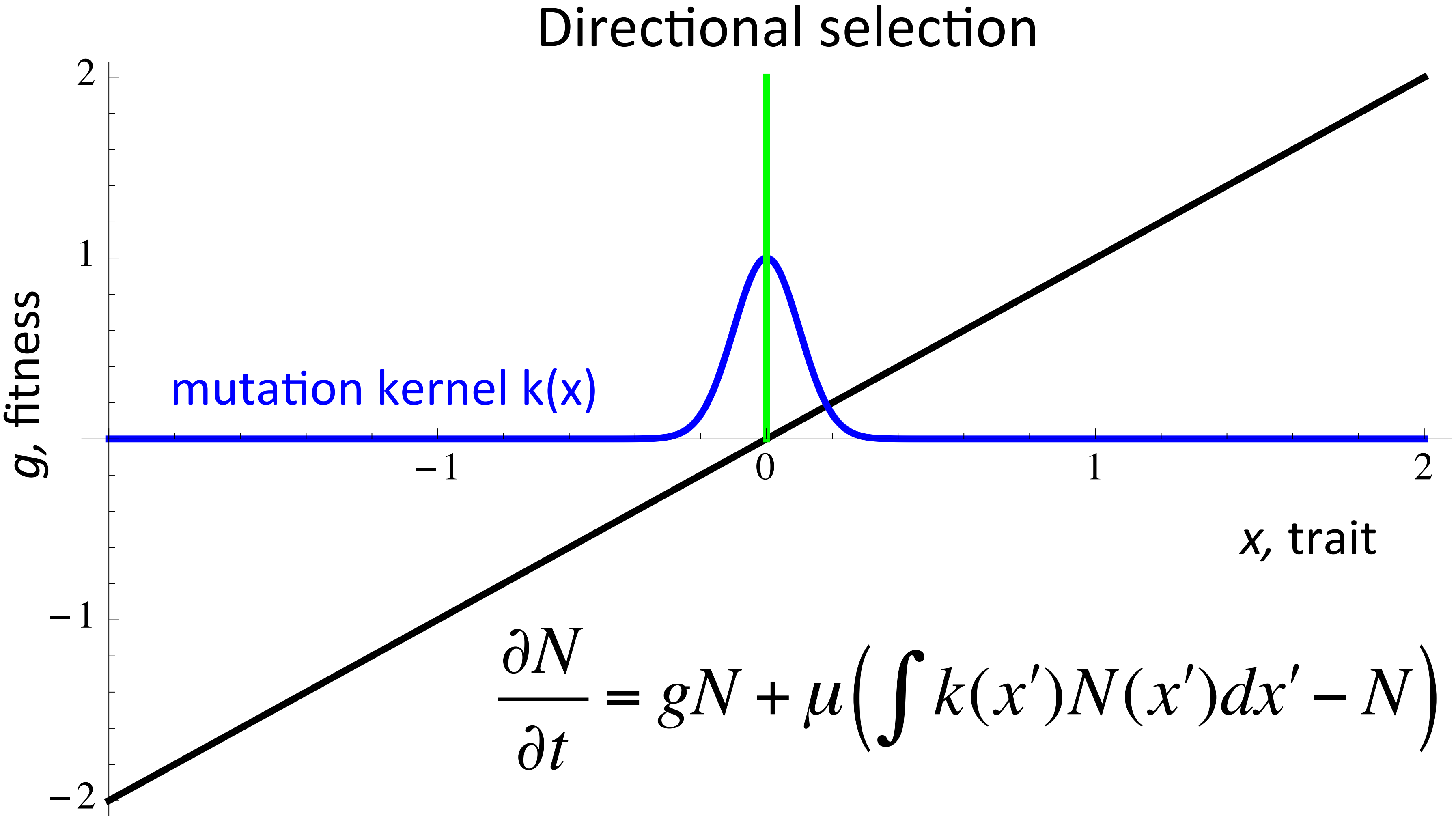
Increase in growth rate

Topt change

Niche width change

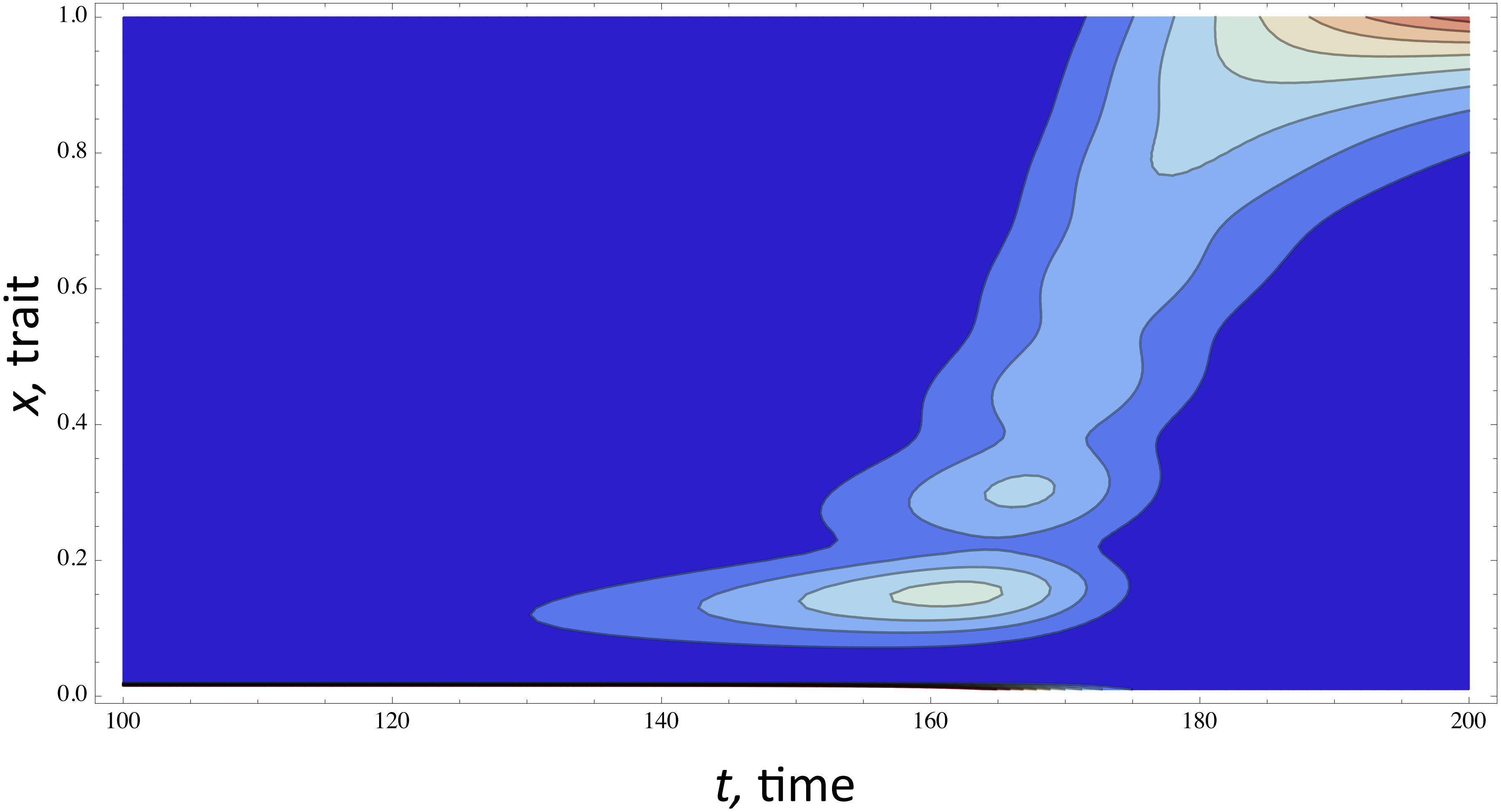
What is the genetic basis of thermal adaptation?

Selection on new mutations: model


Directional selection

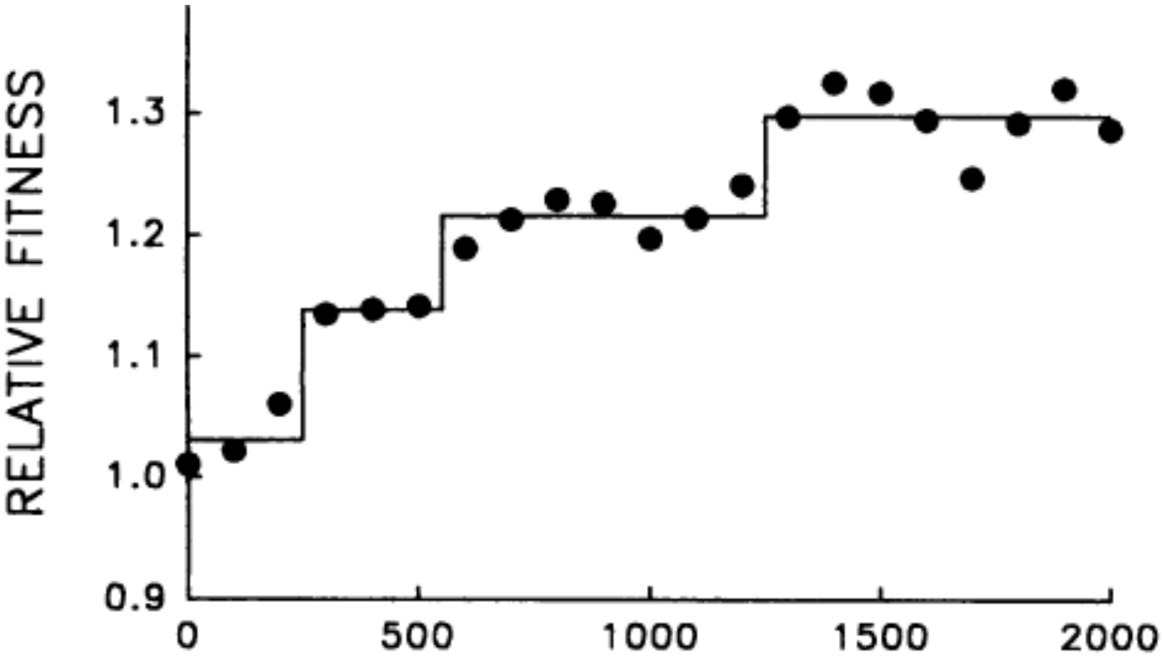
$$\frac{\partial N}{\partial t} = gN + \mu\left(\int k(x')N(x')dx' - N\right)$$

Dynamics of adaptation: jumps



Adaptive jumps: data

Evolution of glucose-limited *E. coli*



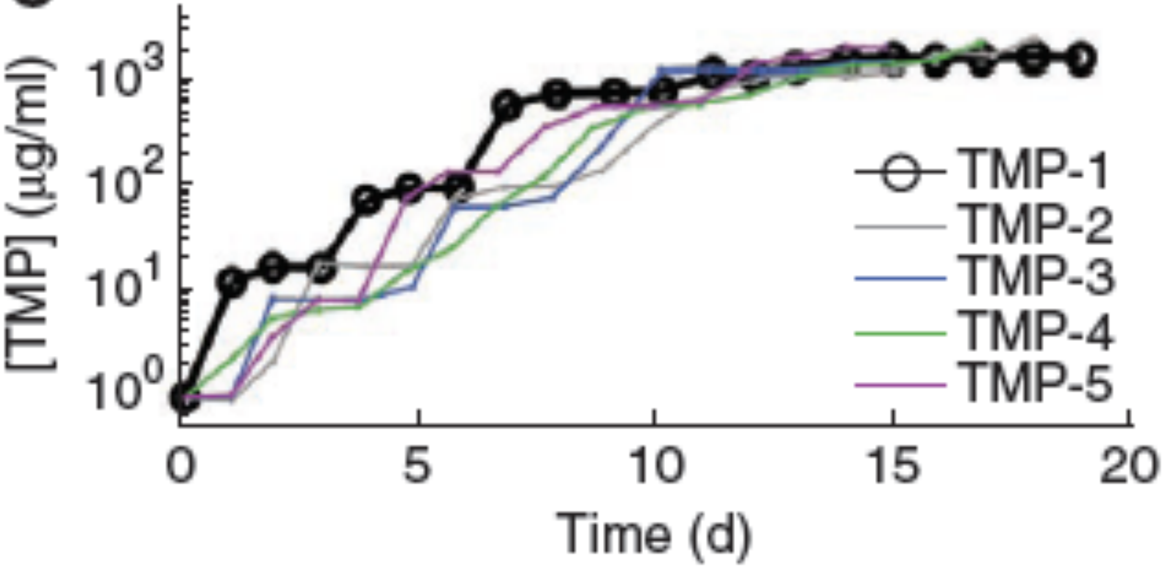
Lenski and Travisano PNAS 1994

Adaptive jumps: data

Evolution of antibiotic resistance (*E. coli*)

resistance

C



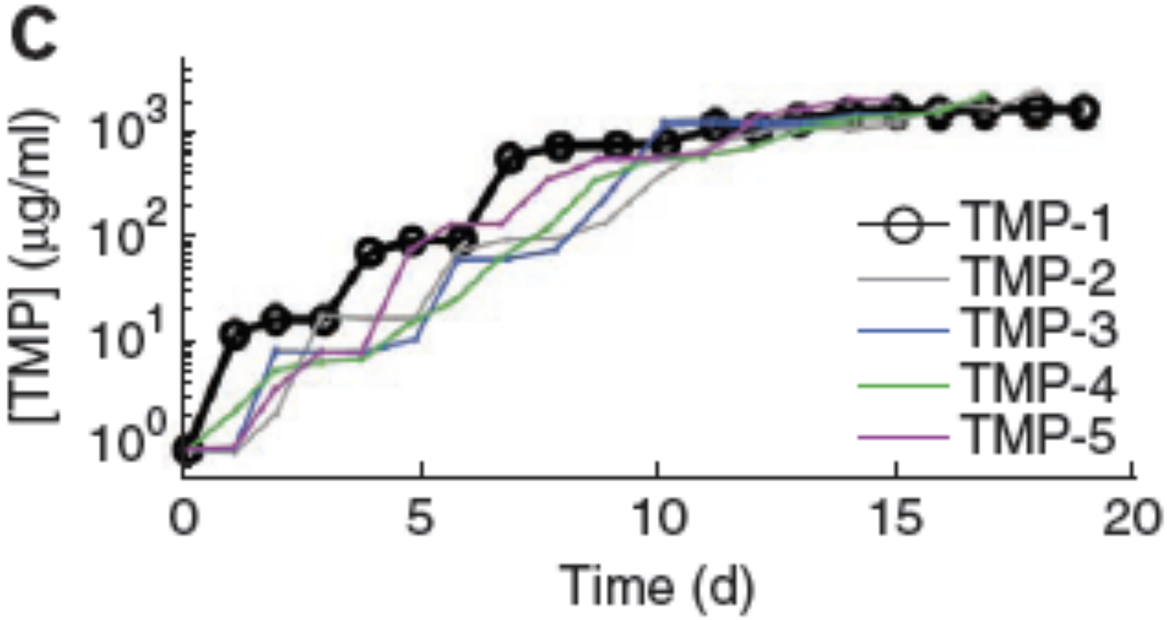
Increasing antibiotic concentration

Toprak et al. Nature Gen. 2012

Adaptive jumps: data

Evolution of antibiotic resistance (*E. coli*)

resistance

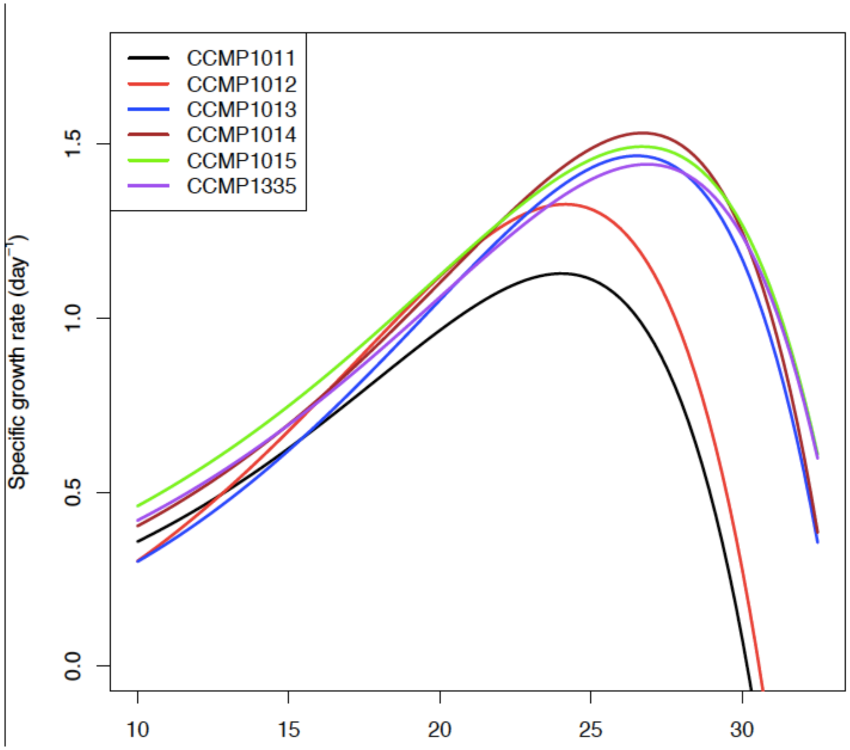


Insights into evolution under climate change

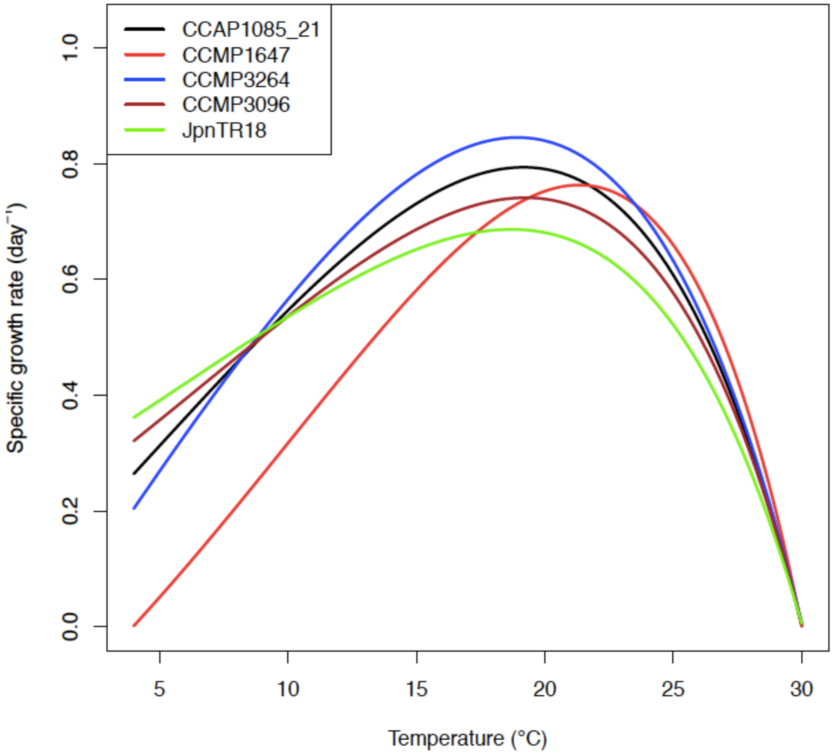
Toprak et al. Nature Gen. 2012

Selection on standing variation

Thalassiosira pseudonana

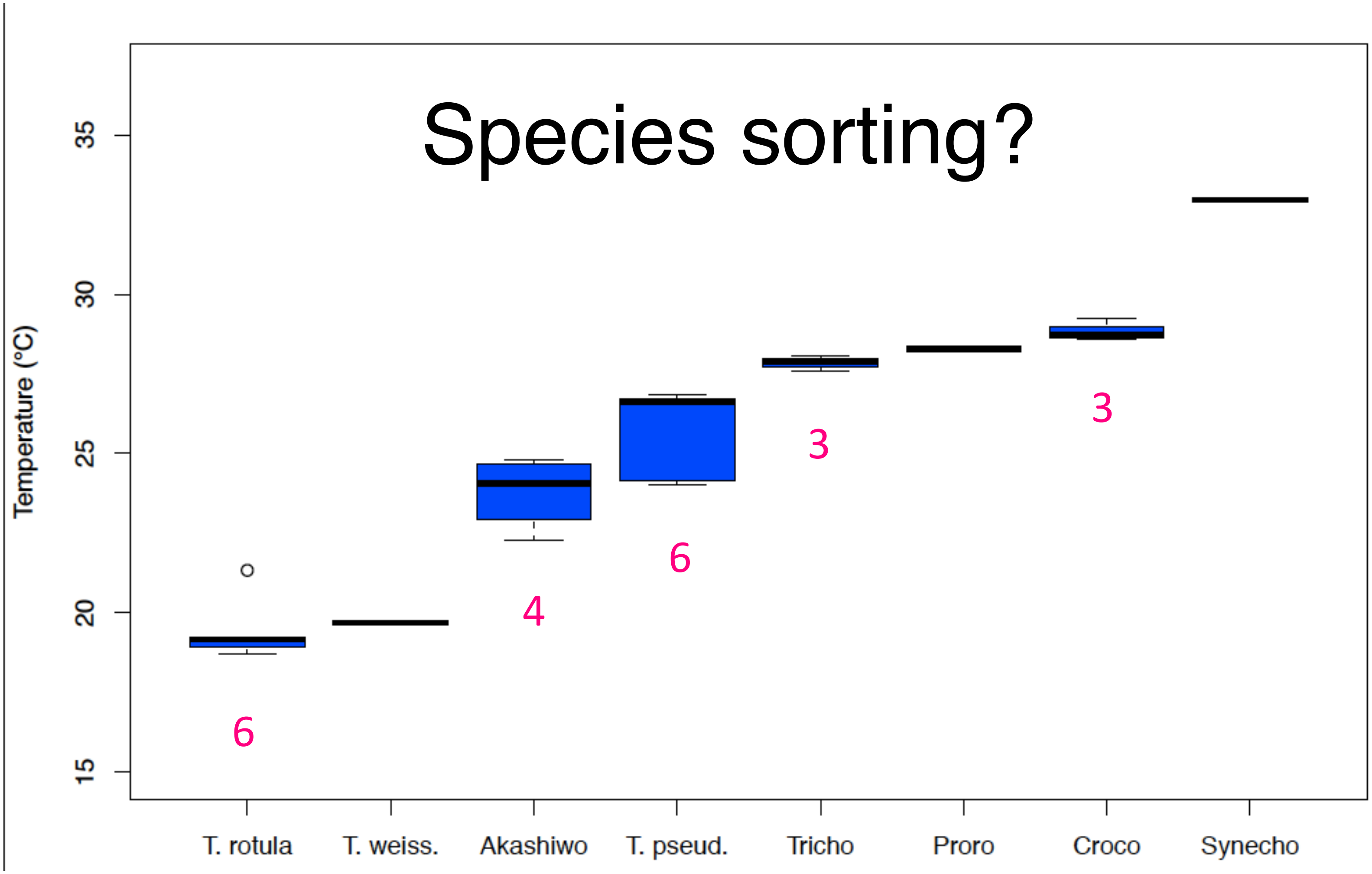


Thalassiosira rotula



Boyd et al. PLoS ONE 2013

Intraspecific vs interspecific variation in temperature optima



Boyd et al. PLoS ONE 2013

Community Responses to Climate Change: Eco-Evolutionary Models

- Need to include multiple mechanisms (phenotypic plasticity, dispersal, evolution, species sorting)
- Example: Norberg et al. 2012

nature climate change

LETTERS

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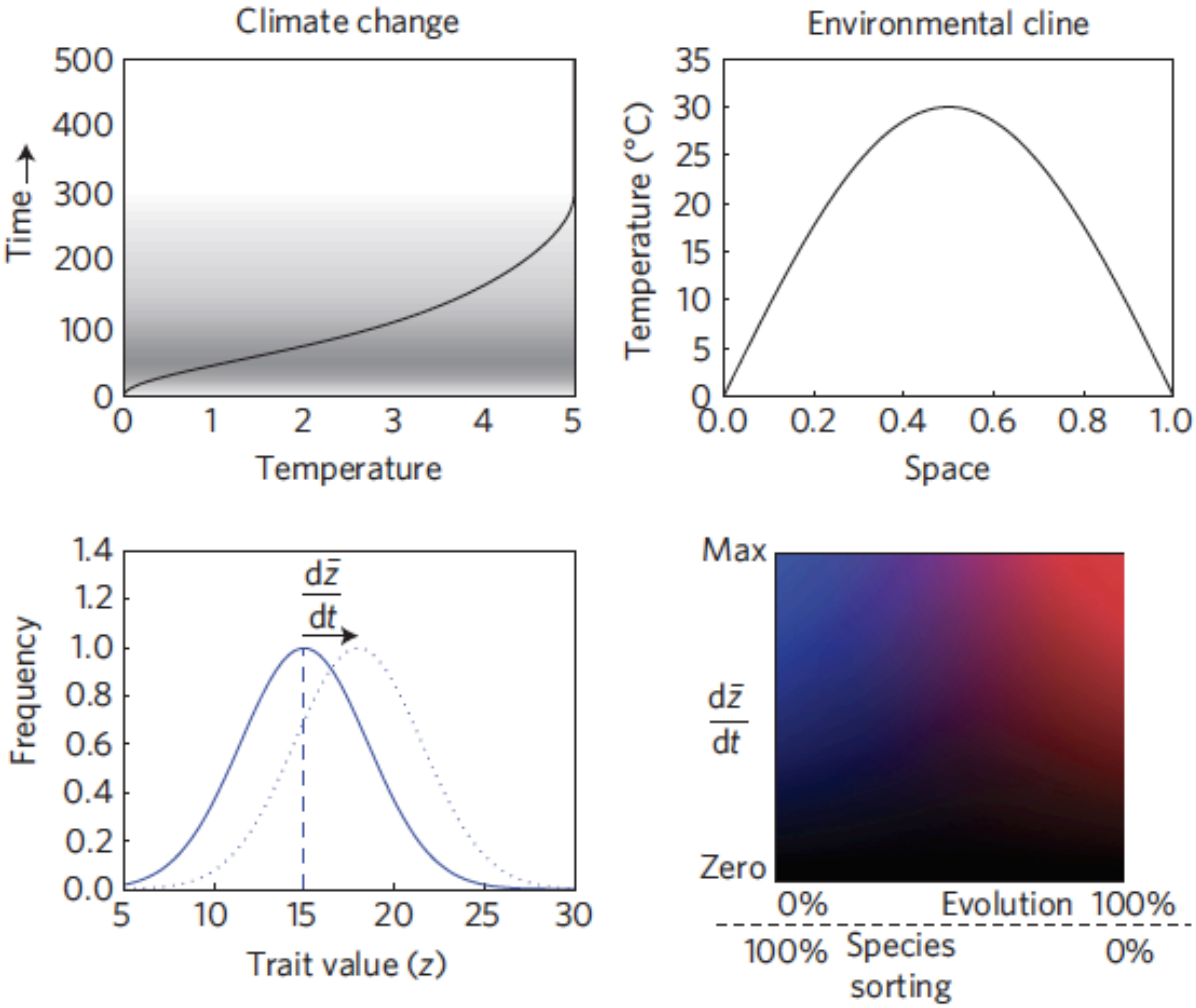
Eco-evolutionary responses of biodiversity to climate change

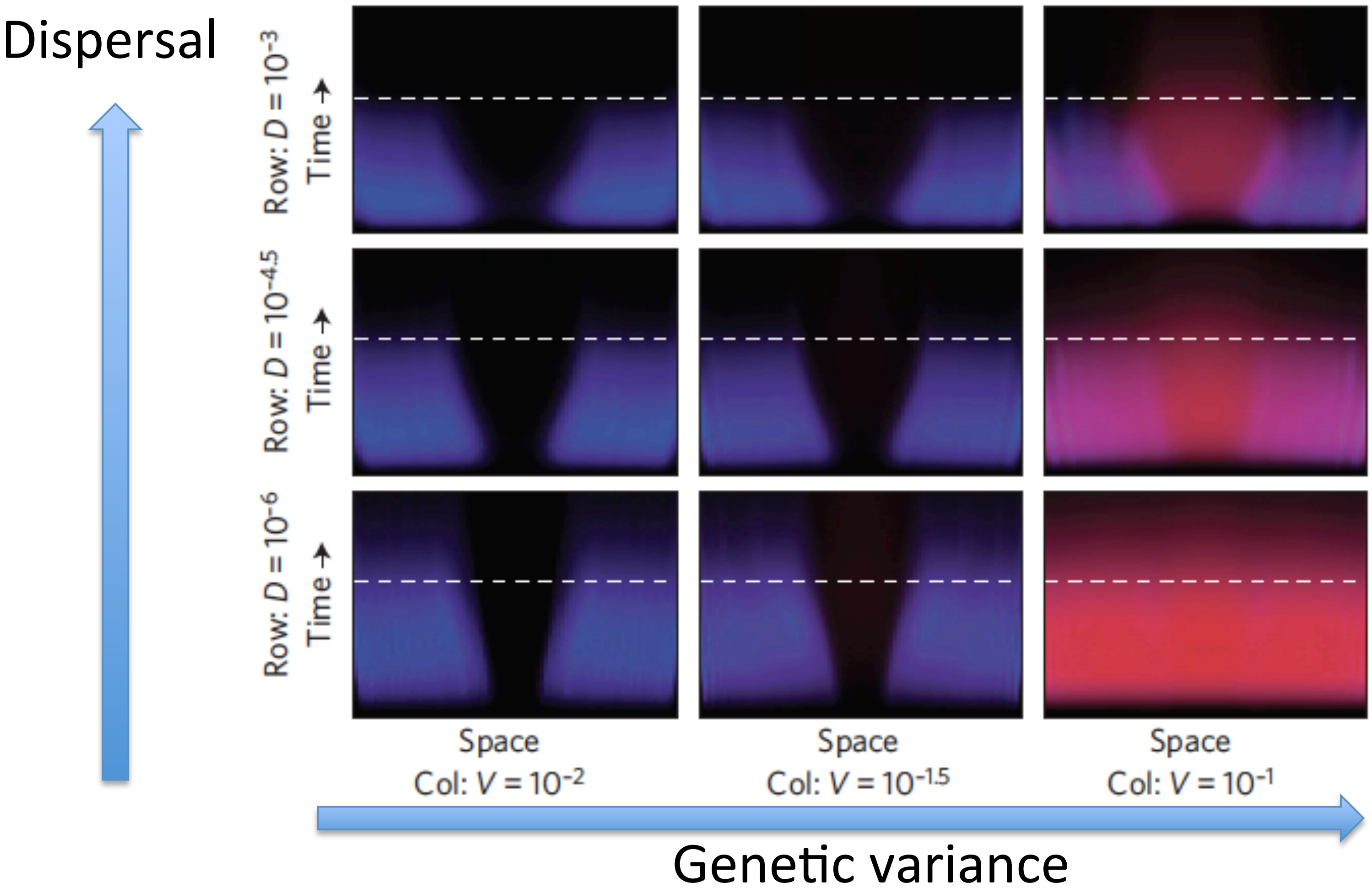
Jon Norberg[1,2]*, Mark C. Urban[3], Mark Vellend[4], Christopher A. Klausmeier[5] and Nicolas Loeuille[6]

Different contribution of Ecological and Evolutionary Processes



Norberg et al. Nature Climate Change 2012

Different contribution of Ecological and Evolutionary Processes

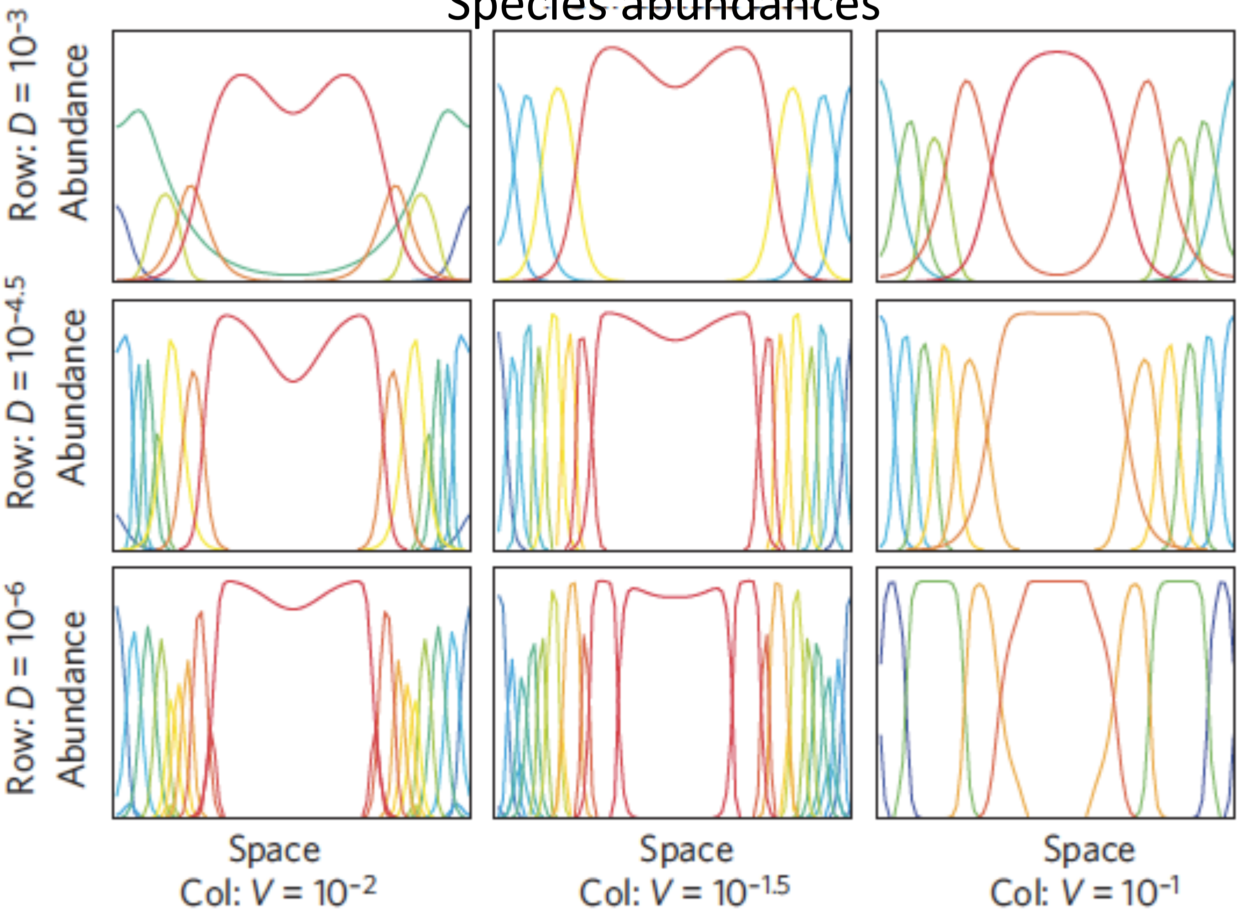


Norberg et al. Nature Climate Change 2012

Different contribution of Ecological and Evolutionary Processes

Species abundances

Dispersal

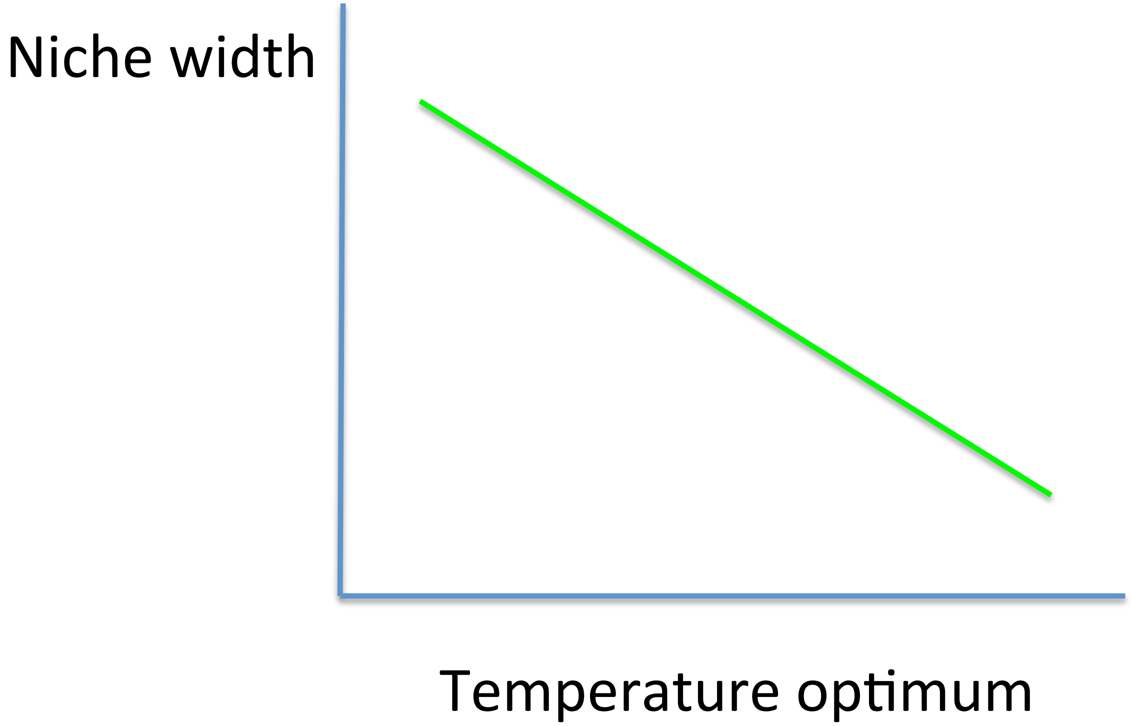


Genetic variance

Norberg et al. Nature Climate Change 2012

Even More Complexity

- Trade-offs among traits (pairwise, multidimensional)



Summary

- Ecological niches can be characterized using traits—more mechanistic description
- Describing trait dynamics and evolution can help predict niche dynamics and evolution

Summary (cont'd)

- Temperature optima in phytoplankton exhibit strong latitudinal pattern and species appear adapted to local temperature regimes
- In the absence of evolution, species diversity may dramatically decline in the tropics due to warming
- Dispersal, evolutionary adaptation and species sorting may counteract negative effects of rising temperature and other stressors
- Need to get estimates of various components of eco-evolutionary responses to parameterize models

What we can do:

- Collect species distribution data and trait information and map ecological niches
- Combine statistical and mechanistic niche descriptions
- Develop new models of (phyto)plankton community organization and evolution
- Conduct eco-evolutionary experiments to assess (phyto)plankton responses to changing conditions
  - --In monocultures
  - --In communities and food webs