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

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Climate Change Impacts on Phytoplankton

• Increase in CO₂ (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)
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Evolution
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

Environmental factor 1
or resource 1

Species A
niche

Environmental factor 2
or resource 2

Present range

Growth or mortality rate

Resource \( R \)

\[ \mu = \mu_{\text{max}} \frac{R}{R + k} - m \]

\[ R_A^* = \frac{mk}{\mu_{\text{max}} - m} \]
Global Change Effects on Niche

- Environmental factor 2 or resource 2
- Present range
- Future range
- Environmental factor 1 or resource 1
- Species A niche

- Global Change Effects on Niche
- Environmental factor 1 or resource 1
- Present range
- Future range

Species A niche
Global Change Effects on Niche

- Environmental factor 2 or resource 2
- Species A niche
- Present range
- Future range
- Growth or mortality rate
- Resource $R$
Global Change Effects on Niche

Environmental factor 2
or resource 2

Species A
niche

Present range

Future range

Future II range

Environmental factor 1
or resource 1
Global Change Effects on Niche

Environmental factor 2 or resource 2

Present range

Future range

Future II range

Species A niche

Environmental factor 1 or resource 1

Growth or mortality rate

Resource $R$

$m$

$R_A^*$
Species Replacement Under Global Change

Environmental factor 2 or resource 2

Species B niche

Species A niche

Present range

Future range

Future II range

Growth or mortality rate

Environmental factor 1 or resource 1

Species B is better competitor

\( R_B^* < R_A^* \)
Trade-offs Between Traits

Half-saturation constants for N and P

\[ R^2 = 0.36 \ (p = 0.03) \]
Three-way trade-off

Grazer resistance

Phosphorus competitive ability

Nitrogen competitive ability

Key Phytoplankton Traits, Multitude of Potential Trade-offs

Litchman and Klausmeier 2008
Trait Evolution and Niche Shift Under Global Change

Environmental factor 2 or resource 2

New species A

Present range

Future II range

Growth or mortality rate

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
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

Temperature

Growth rate (per day)

Topt

Niche width
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

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

\[
R = R_{in} - a \sum_{j=1}^{n} N_j(t)
\]

\[
\frac{dZ_i}{dt} = \varepsilon \cdot \frac{dg_i}{dZ_i}
\]
Observed and predicted temperature optima
Size Distribution in Freshwater and Marine Diatoms

Log cell volume (µm³)

freshwater  marine

Ethmodiscus rex, 1-3 mm diameter!

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

Topt
Selection on New Mutations: Evolution Experiments

*Thalassiosira pseudonana*

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*)

Increasing antibiotic concentration

Adaptive jumps: data

Evolution of antibiotic resistance
(*E. coli*)

Insights into evolution under climate change

Selection on standing variation

Thalassiosira pseudonana  
Thalassiosira rotula

Boyd et al. PLoS ONE 2013
Intraspecific vs interspecific variation in temperature optima

Species sorting?

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

Eco-evolutionary responses of biodiversity to climate change

Jon Norberg¹,²*, Mark C. Urban³, Mark Vellend⁴, Christopher A. Klausmeier⁵ and Nicolas Loeuille⁶
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

Norberg et al. Nature Climate Change 2012
Even More Complexity

• Trade-offs among traits (pairwise, multidimensional)

![Graph showing the relationship between Niche width and Temperature optimum. The graph depicts a negative correlation, with Niche width decreasing as Temperature optimum increases.]
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