Modelling Bacteria-enhanced Thermal Tolerance in Marine Phytoplankton

Aarshi Jain\textsuperscript{1}, Colin T. Kremer\textsuperscript{1}
\textsuperscript{1}University of California, Los Angeles

Questions? jainaarshi2000@ucla.edu

Introduction

Phytoplankton (or algae) fuel marine food webs, regulate major nutrient cycles, and produce about 50% of Earth’s oxygen. Warming oceans will affect algal growth, productivity, and geographic ranges. However, few predictive models consider effects of species interactions, especially mutualisms. Recent lab studies show algae-bacteria interactions enhance algal thermal tolerance.\textsuperscript{1,2} We modeled this mutualism to study:

1. How stable is this ecological interaction across temperatures?
2. What mechanisms protect this mutualism from collapse via the evolution of cheaters?

Algae-Bacteria Model

Changes in algae (A) and bacteria (B) biomass depend on their temperature (T) dependent growth and death rates. The mutualists (A & B) synthesize photosynthetic (C) and cobalamin (B12) for their partner’s benefit, yet compete for nitrogen (N).

\[ A' = (\mu_A [B_{12}, N, T] + \mu_B [N, T]) - m_A(T) \]
\[ B' = (\mu_B [C, N, T] - m_B(T)) \]
\[ N' = \rho (N_{\text{max}} - N) - (\mu_A A + \mu_B B) \]
\[ B_{12}' = \rho (B_{12\text{in}} - B_{12}) - (\mu_A A + s_{B12} B) \]
\[ C' = \rho (C_{\text{in}} - C) - \mu_B B + s_{C} A \]

Equilibrium Abundance (logged)

At high temperatures, both species were limited by the nutrients provided by their partner, highlighting mutualism’s importance in warming oceans.

Evolutionary Instability

Prior models\textsuperscript{3} ignore the costs of mutualism. We explored two trade-offs linking growth $\mu$ to substrate synthesis $s$, governed by $\phi$ which ranged between 0 (only growth) and 1 (only synthesis).

\[ s \text{ linked to } \mu \]
\[ s = (1 - \phi) s \]
\[ s \text{ linked to } \mu - m \]
\[ s = (1 - \phi) s \]

Then we studied the effects of selection on optimal $\phi$ using a quantitative genetics approach:\textsuperscript{4}

Private substrate exchange

Addressing limitations of our initial work, we built a second model of this interaction, where:

- Costs of substrate production and sharing are explicit (and tied to internal nutrient stores)
- Substrates can be exchanged privately and/or publicly between algae and bacteria

We predicted this would stabilize the evolutionary dynamics of the mutualism. Key relationships in the new model are shown here:

Temperature Dependence

We analyzed this ODE model using a quasi-equilibrium framework\textsuperscript{5} to investigate how temperature changes equilibrium abundances and which nutrients limit each mutualist.

Protection from Cheaters

Private substrate exchange prevents non-participating members from accessing nutrients shared by mutualists\textsuperscript{6}. We explored how the degree of coupling, governed by $\Delta$, affected the evolution of nutrient sharing ($\phi$).

Irrespective of $\Delta$, only A-B pairs with moderate $s$ survived. Low $s$ led to unmet nutrient requirements whereas high $s$ resulted in overinvestment in mutualism at the cost of growth.

Conclusions

- Algae species that depend on METH should rely on close associations with bacteria, especially at high temperatures.
- Typical models of microbial mutualisms neglect costs and are evolutionarily unstable.
- Tracking costs and allowing partners to exchange substrate privately stabilizes these interactions.