# Exploring marine phytoplankton biogeography through theory and models: applications to climate change studies

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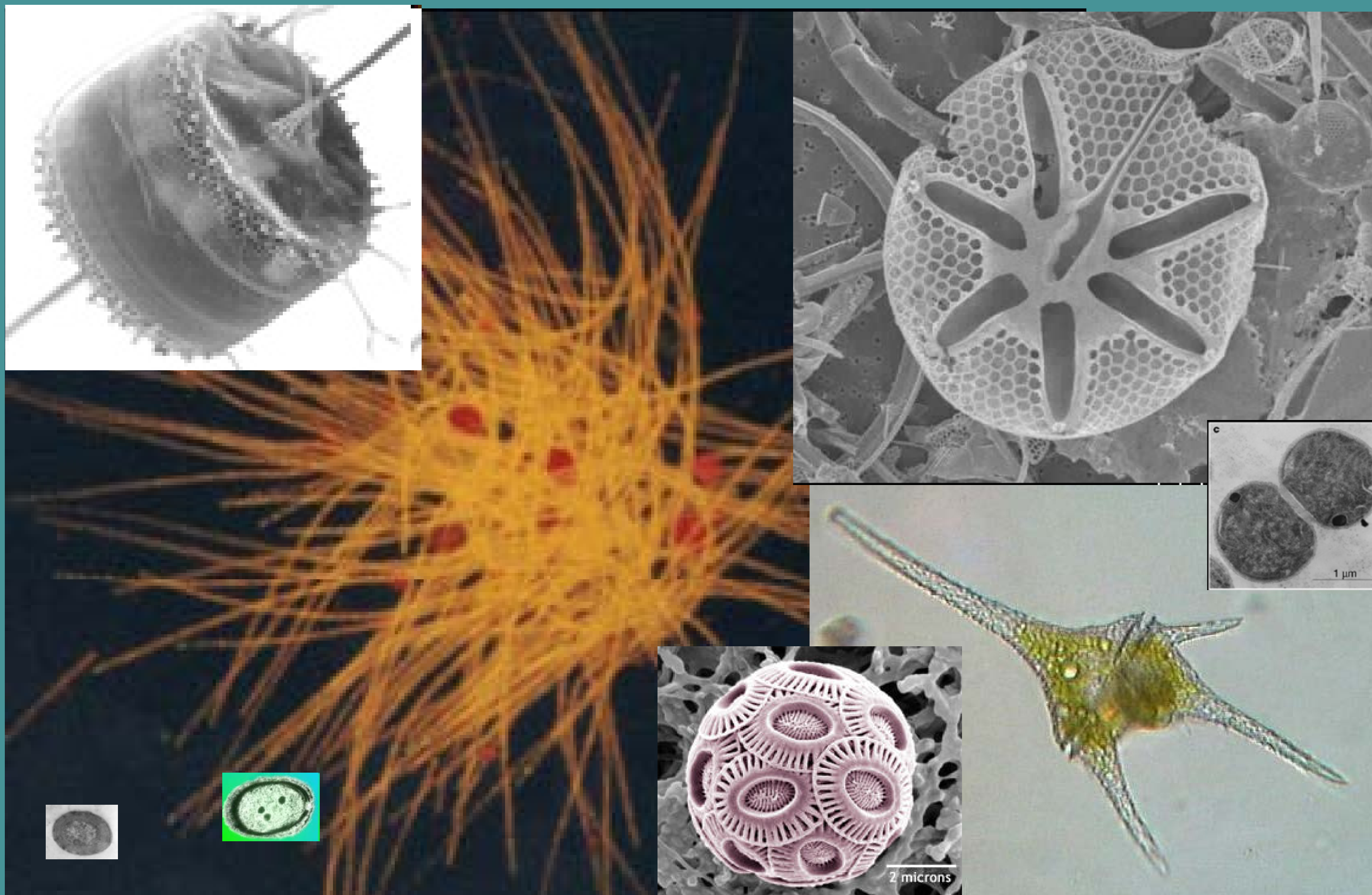
## OUTLINE

- Trait based approach to modeling phytoplankton
- Phytoplankton response to climate change
  - diazotrophs
  - ocean acidification
- Final thoughts (with naïve ideas on application to HABs)

# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON



# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

**Traits:** key physiological characteristics

e.g. size, resource-acquisition abilities, pigments, predator susceptibility

*For reviews see: Litchman et al, Ann Rev Ecol Evol Syst, 2008*
*Follows and Dutkiewicz, Ann Rev Mar Sci, 2011*

# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

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**Trade-offs:** some traits come at a cost

*For reviews see: Litchman et al, Ann Rev Ecol Evol Syst, 2008*
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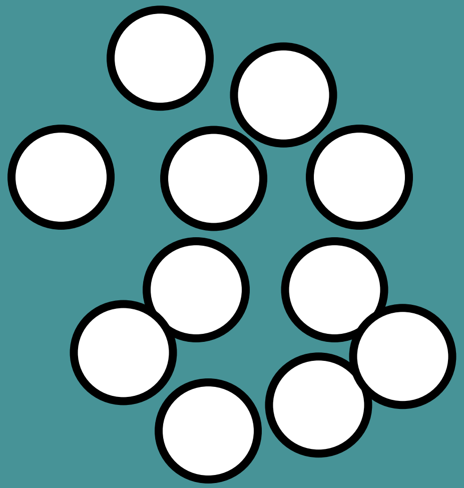
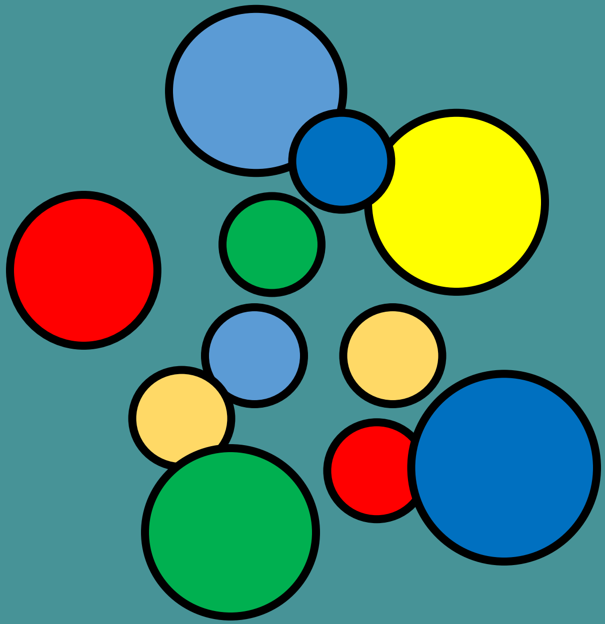
# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

**Start with number of phytoplankton types with**



# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

**Assign them combination of traits**
(e.g size, nutrient-acquisition ability, optimum light, optimum temperature)



Place in 3D physical, biogeochemical, and grazer environmental

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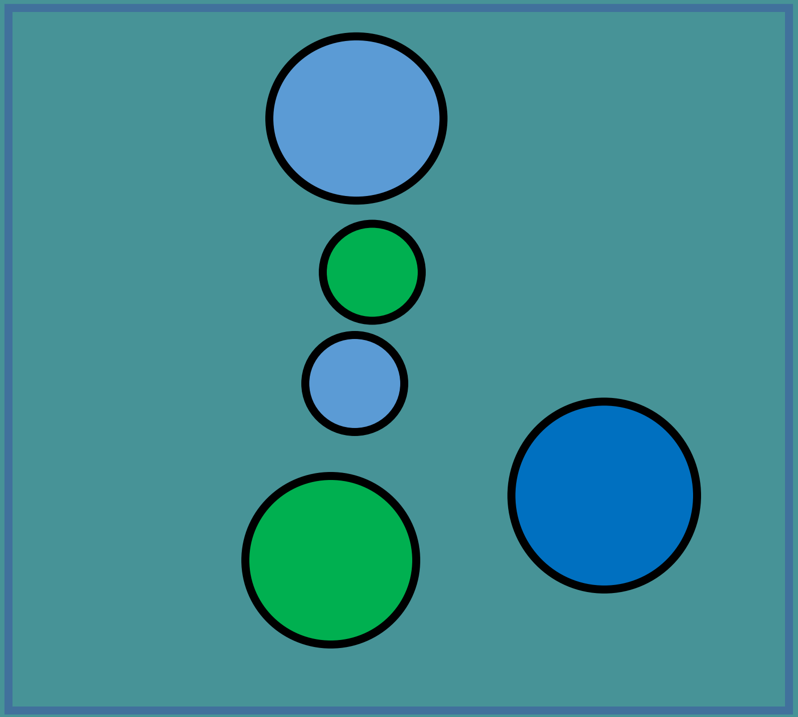

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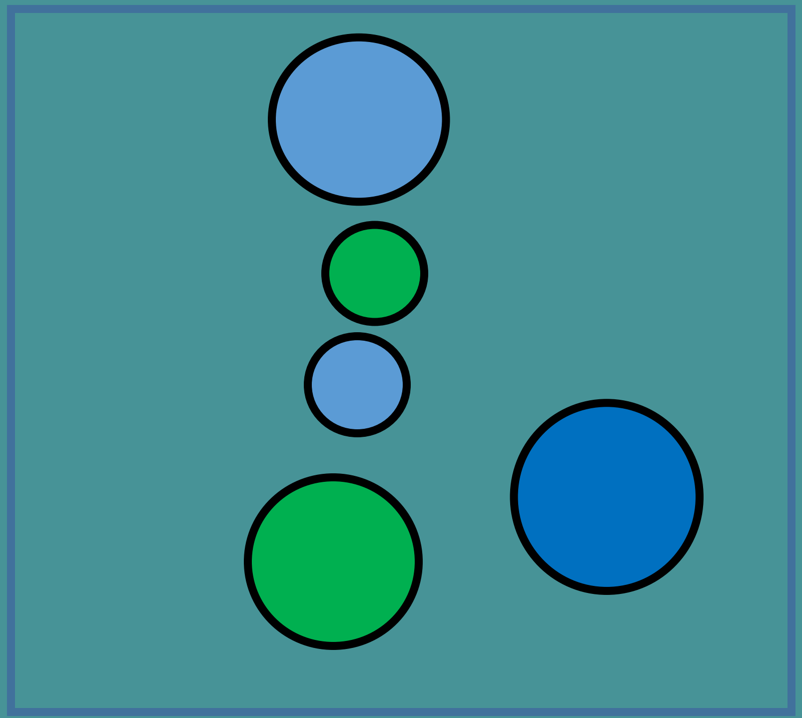

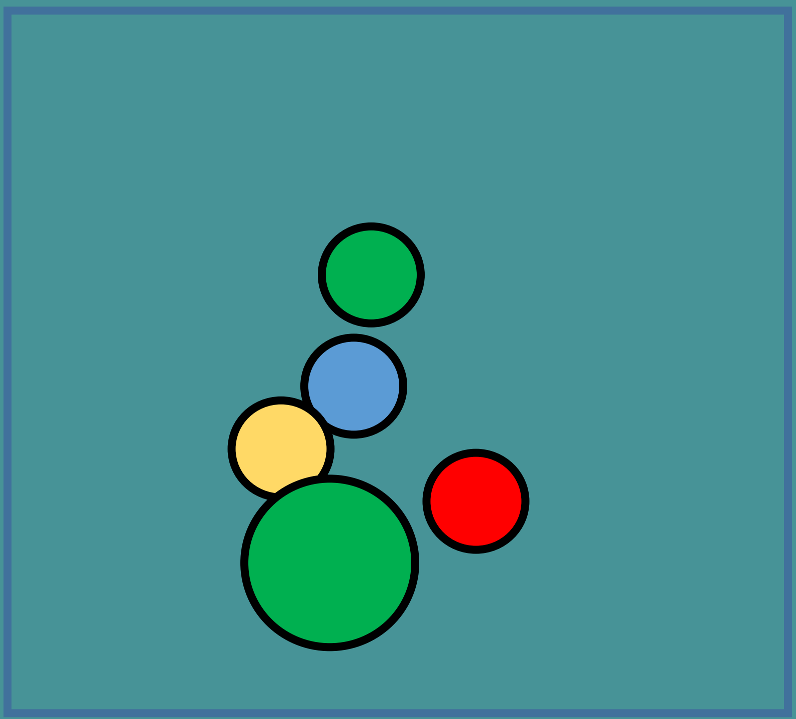

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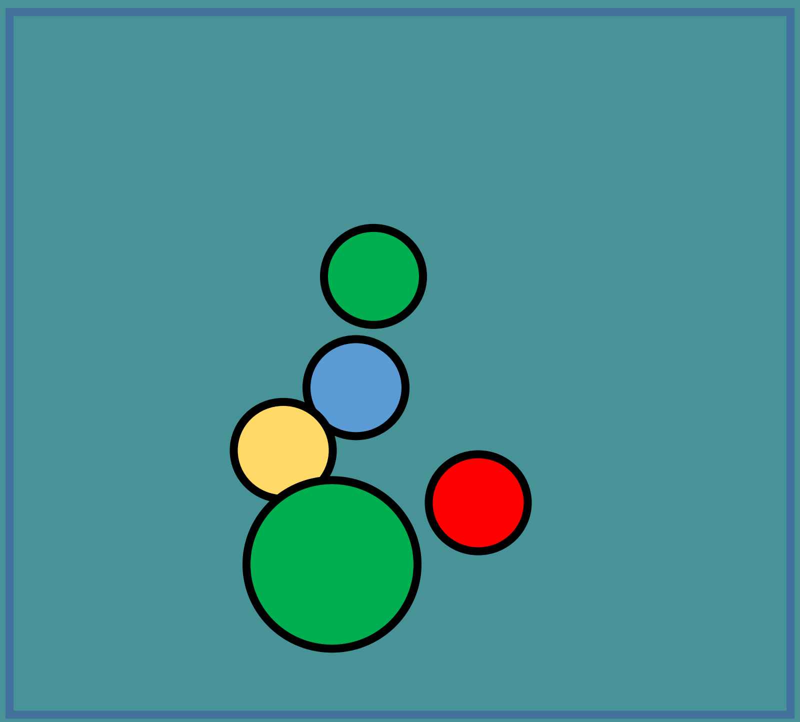
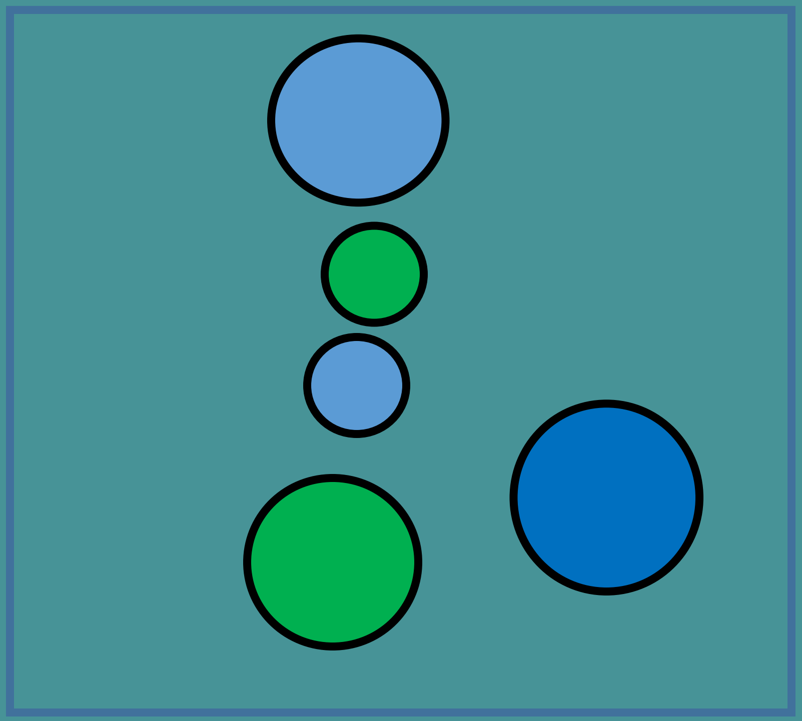




- Environment selects which combinations co-exist
- right types in right place, and exclude all non-viable combinations of traits

# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

**Traits:** key physiological characteristics

e.g. size, resource-acquisition abilities, pigments, predator susceptibility

**Trade-offs:** some traits come at a cost

**Advantages of approach :** - reductionist
- reduced amount of parameters
- environment "selects"
- allows communities to "self-assemble"

*see e.g. Follows et al, Science, 2007; Dutkiewicz et al, GBC, 2009; 2012; Monteiro et al, GBC, 2010; Ward et al., L+O, 2011*

# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

1. Identify key traits and trade-offs

2. Understand the specific environmental control that selects for those traits

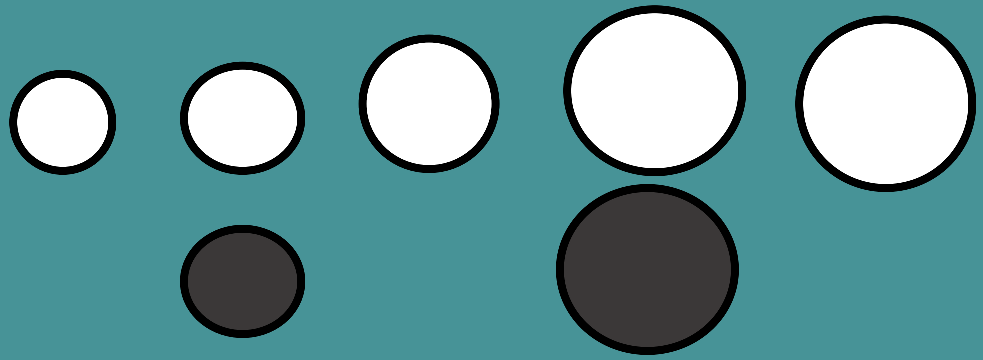
## OUTLINE

- Trait based approach to modeling phytoplankton
- Phytoplankton response to climate change
  - diazotrophs
  - ocean acidification
- Final thoughts (with naïve ideas on application to HABS)

## 1. What are the key traits and trade-offs of diazotrophs?

**Trait:** diazotrophs can fix nitrogen (i.e. never nitrogen limited)

**Trade-off:** grow slower than other phytoplankton



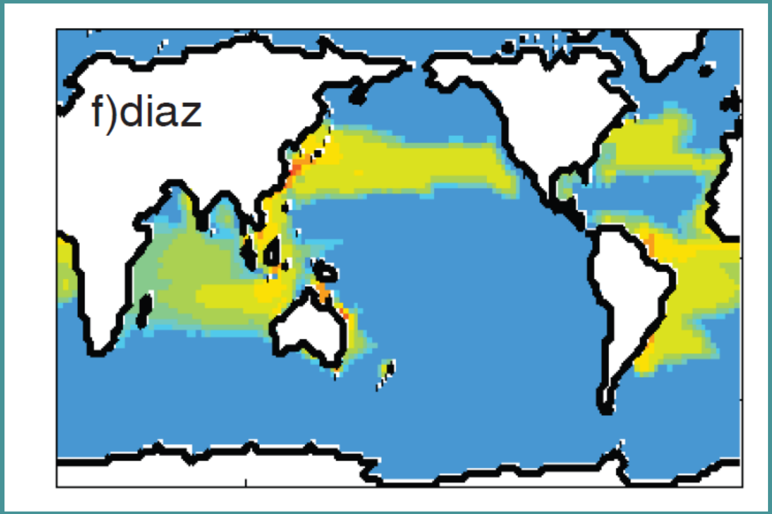
*non-diazotrophs*

*diazotrophs*

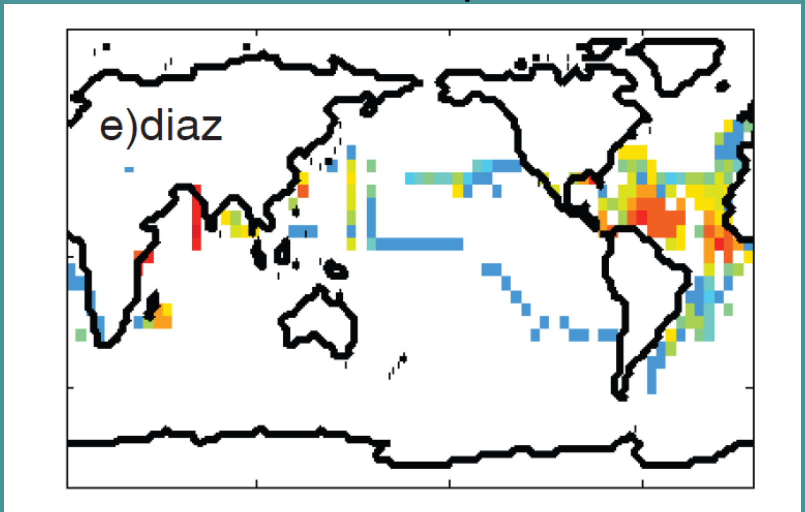
# 1. What are the key traits and trade-offs of diazotrophs?

not nitrogen limit, lower growth rate than non-diazotrophs

*model diazotroph biomass*




*observed diazotroph biomass*




mg C/m3

0.01 1 100

*Luo et al, ESDD 2011*

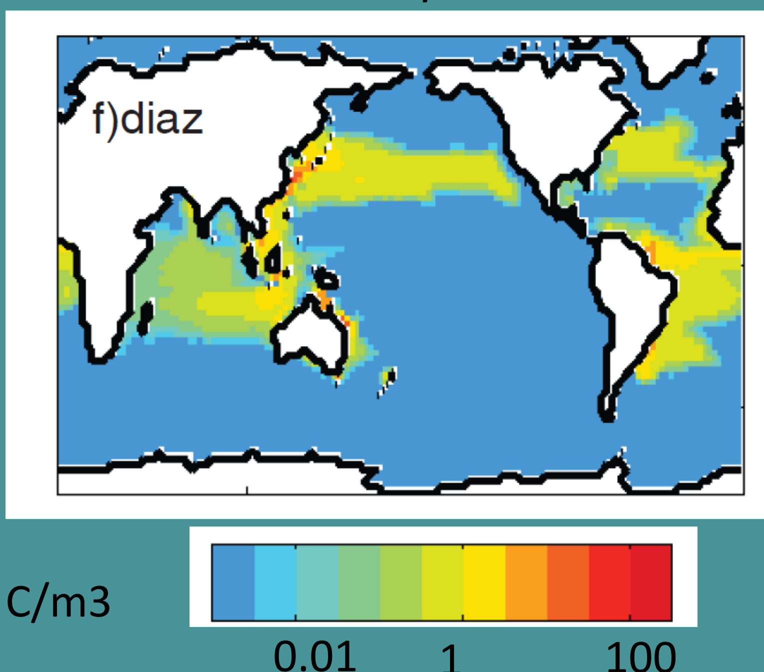
*Dutkiewicz et al, Biogeosciences, 2014*

## 1. What are the key traits and trade-offs of diazotrophs?

not nitrogen limit, but lower growth rate than non-diazotrophs

## 2. What are the environmental control of diazotroph biogeography?

*model diazotroph biomass*




mg C/m3

temperature, light, iron???

*see e.g. Sohm et al, Ann Rev. Micro, 2011*
*Monteiro et al, GBC, 2011*

## 1. What are the key traits and trade-offs of diazotrophs?

not nitrogen limit, but lower growth rate than non-diazotrophs

## 2. What are the environmental control of diazotroph biogeography?

### Resource Supply Ratio Theory

$$\frac{dB}{dt} = \mu_B \gamma_B B - m_B B$$

$$\frac{dD}{dt} = \mu_D \gamma_D D - m_D D$$

$$\frac{dN}{dt} = -\mu_B \gamma_B B + m_D D + I_N - O_N$$

$$\frac{dP}{dt} = -\mu_B \gamma_B R_{B_{P:N}} B - \mu_D \gamma_D R_{D_{P:N}} D + I_P - O_P$$

$$\frac{dFe}{dt} = -\mu_B \gamma_B R_{B_{Fe:N}} B - \mu_D \gamma_D R_{D_{Fe:N}} D + I_{Fe} - O_{Fe}$$

steady state solutions

$$N_B^* = \frac{\kappa_{NB} m_B}{\mu_B - m_B}$$

$$P_B^* = \frac{\kappa_{PB} m_B}{\mu_B - m_B}$$

$$Fe_B^* = \frac{\kappa_{FeB} m_B}{\mu_B - m_B}$$

$$P_D^* = \frac{\kappa_{PD} m_D}{\mu_D - m_D}$$

$$Fe_D^* = \frac{\kappa_{FeD} m_D}{\mu_D - m_D}$$

$$\phi_{PN} = 1 + \frac{m_D D R_{NP_D}}{R_{NP_B} I_N^*} + \frac{O_P - O_N R_{NP_B}}{R_{NP_B} I_N^*}$$

$$\phi_{FeN} = 1 + \frac{m_D D R_{NFe_D}}{R_{NFe_B} I_N^*} + \frac{O_{Fe} - O_N R_{NFe_B}}{R_{NFe_B} I_N^*}$$

*Dutkiewicz et al, Biogeosciences, 2014*

# CLIMATE CHANGE EXAMPLE: DIAZOTROPHS

## 1. What are the key traits and trade-offs of diazotrophs?

not nitrogen limit versus lower growth rate than non-diazotrophs

## 2. What are the environmental control of diazotroph biogeography?

diazotrophs can only exist where supply rate of Fe and P relative to N are higher than the non-diazotrophs N requirements

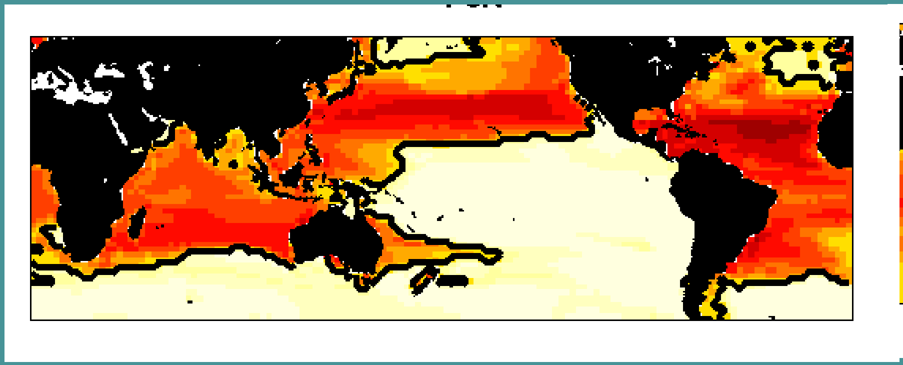
diazotrophs can exist if

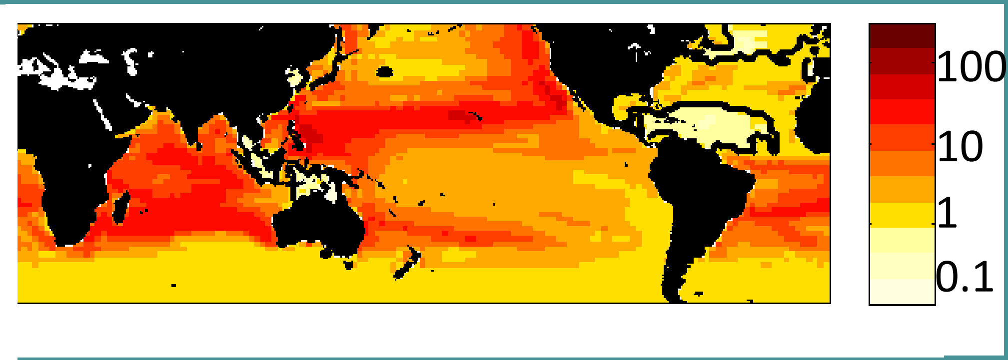
$$\frac{\textit{supply rate of iron}}{\textit{(supply rate of nitrate)(non-diazotroph Fe:N)}} = \phi_{FeN} = \frac{S_{Fe}}{S_N \Omega_{Fe:N_B}} > 1$$

$$\frac{\textit{supply rate of phosphate}}{\textit{(supply rate of nitrate)(non-diazotroph P:N)}} = \phi_{PN} = \frac{S_P}{S_N \Omega_{P:N_B}} > 1$$

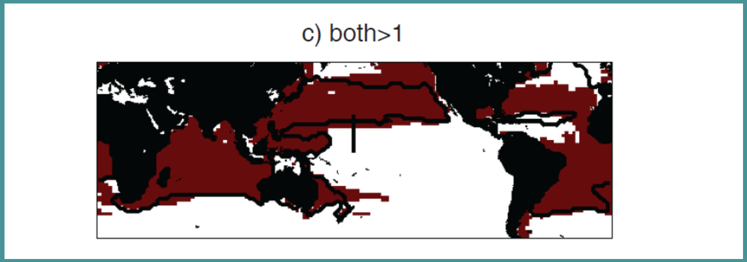
*Dutkiewicz et al, Biogeosciences, 2014*

# CLIMATE CHANGE EXAMPLE: DIAZOTROPHS






$$\phi_{FeN} = \frac{S_{Fe}}{S_N \Omega_{Fe:N_B}}$$

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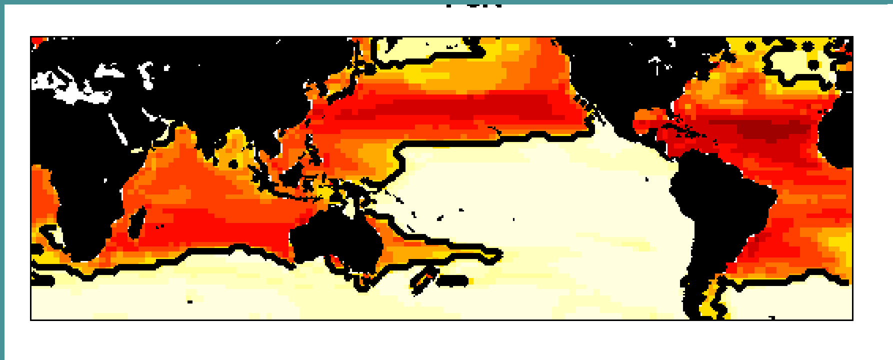

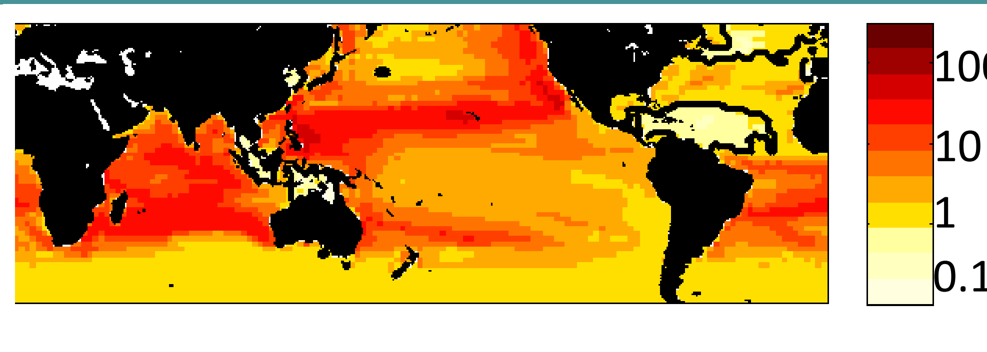


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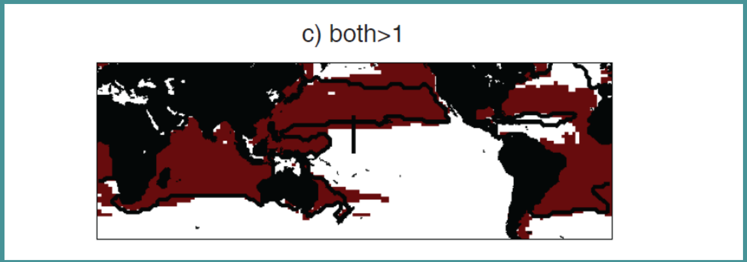
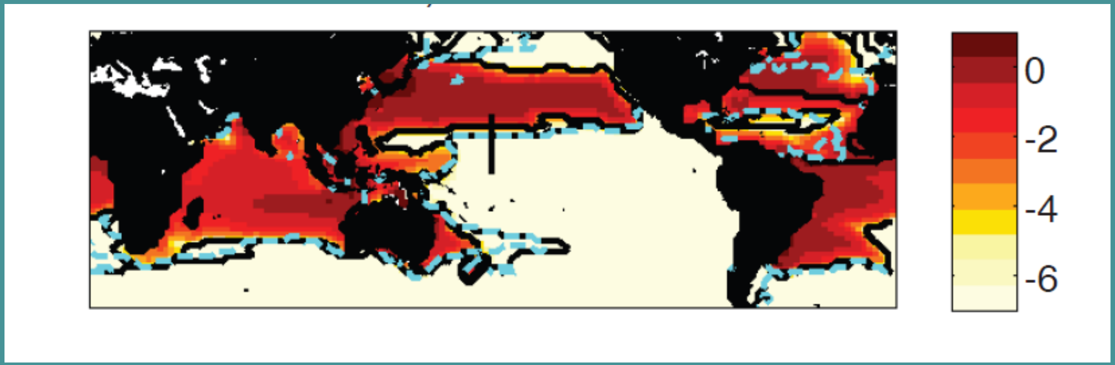



$$\phi_{PN} = \frac{S_P}{S_N \Omega_{P:N_B}}$$

***model diazotroph biogeography***

*(nitrogen fixation)*




*Dutkiewicz et al, Biogeosciences, 2014*

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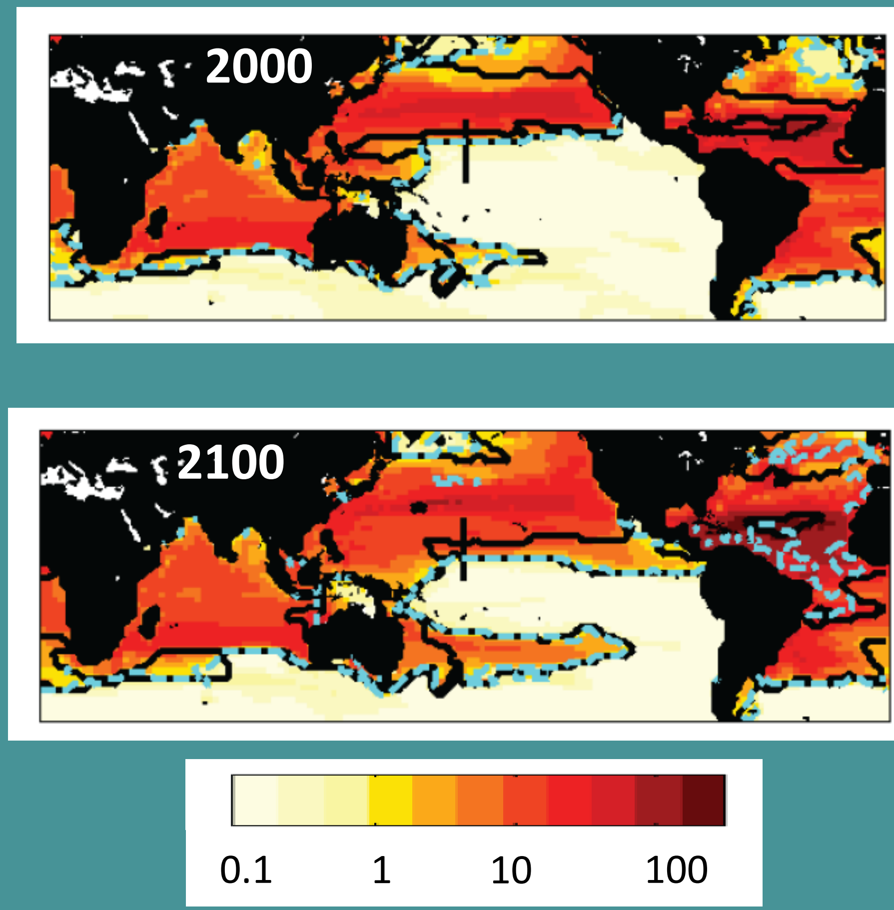
## 3. How will climate change alter than environmental control?

*Dutkiewicz et al, Biogeosciences, 2014*

# CLIMATE CHANGE EXAMPLE: DIAZOTROPHS

*simulated nutrient supply ratios*

$$\phi_{FeN} = \frac{S_{Fe}}{S_N \Omega_{Fe:N_B}}$$




Supply of nitrate reduced

Supply of iron potentially increases

$$\uparrow \phi_{FeN} = \frac{S_{Fe}}{S_N \Omega_{Fe:N_B}} \downarrow$$

*Dutkiewicz et al, Biogeosciences, 2014*

Massachusetts Institute of Technology

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# CLIMATE CHANGE EXAMPLE: DIAZOTROPHS

*simulated nitrogen fixation*

*simulated nutrient supply ratios*

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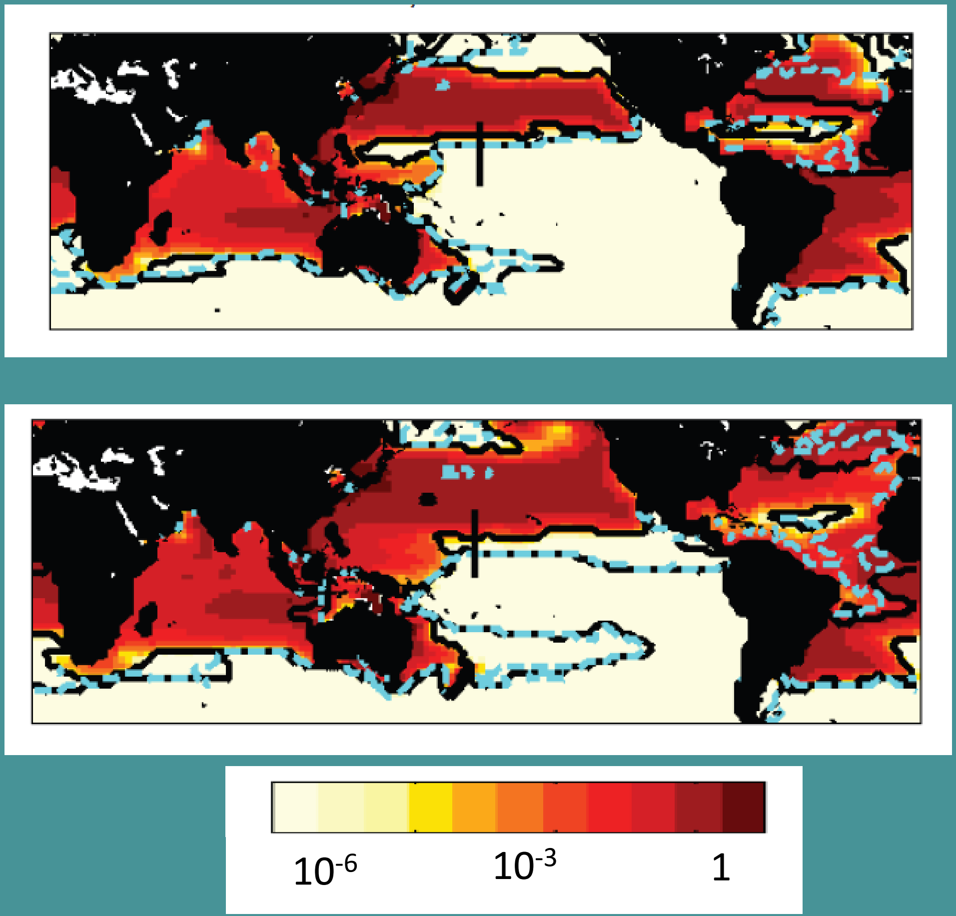


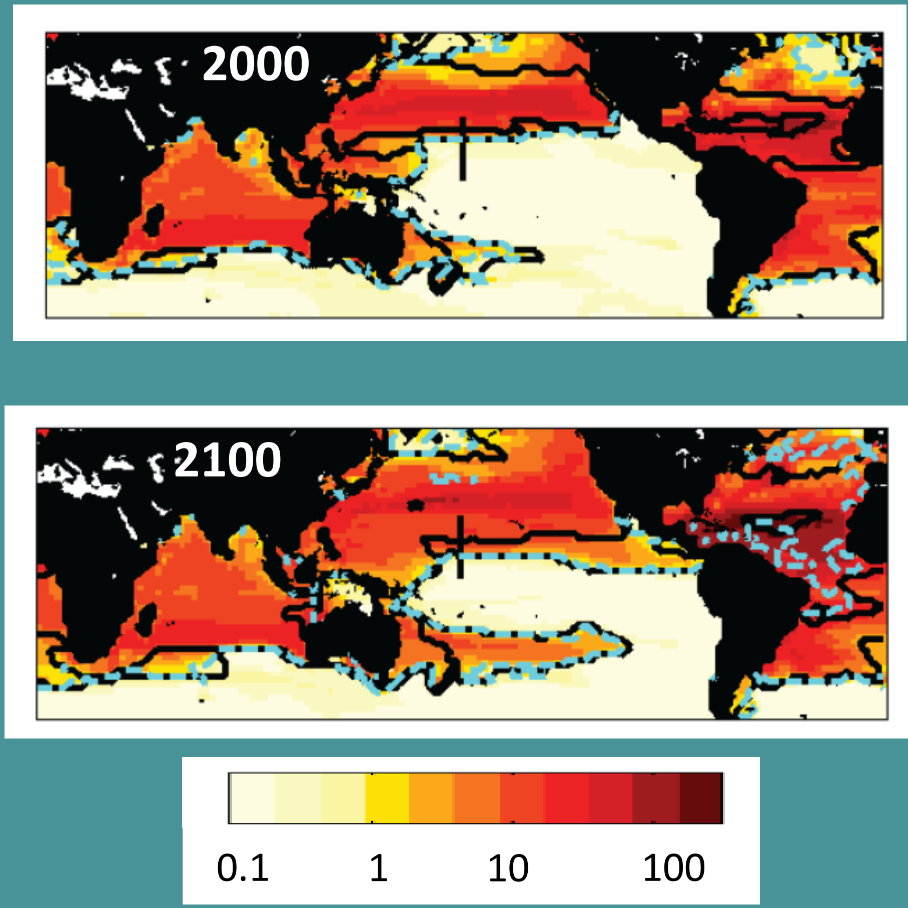


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nutrient supply ratio:
diazotrophs can only exist where supply rate of Fe and P relative to are higher than the non-diazotrophs N requirements

## 3. How will climate change alter than environmental control?

decrease in nitrate supply will lead to increase in regions with excess Fe supply

*Dutkiewicz et al, Biogeosciences, 2014*

# CLIMATE CHANGE EXAMPLE: DIAZOTROPHS

- Theoretical basis has been used to explain diazotroph distribution in Atlantic
  (e.g. Schlosser et al, 2014)

- Covers diverse set of diazotrophs
  (ongoing work to understand finer scale, role of oxygen etc)

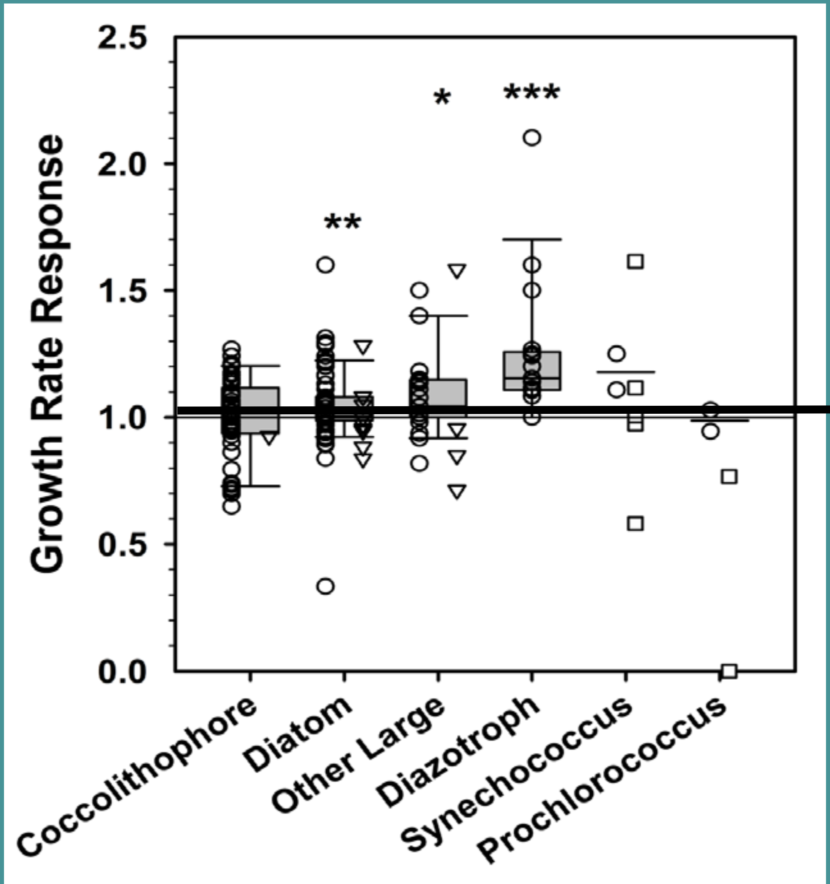
- Probably other controls important too…
  (but could some of those previously suggested just be correlated, not causative)

- Theory relates to ratio of nutrient supply rates NOT ratio of nutrient concentrations

## OUTLINE

- Trait based approach to modeling phytoplankton
- Phytoplankton response to climate change
  - diazotrophs
  - ocean acidification
- Final thoughts (with naïve ideas on application to HABS)

# CLIMATE CHANGE EXAMPLE: OCEAN ACIDIFICATION



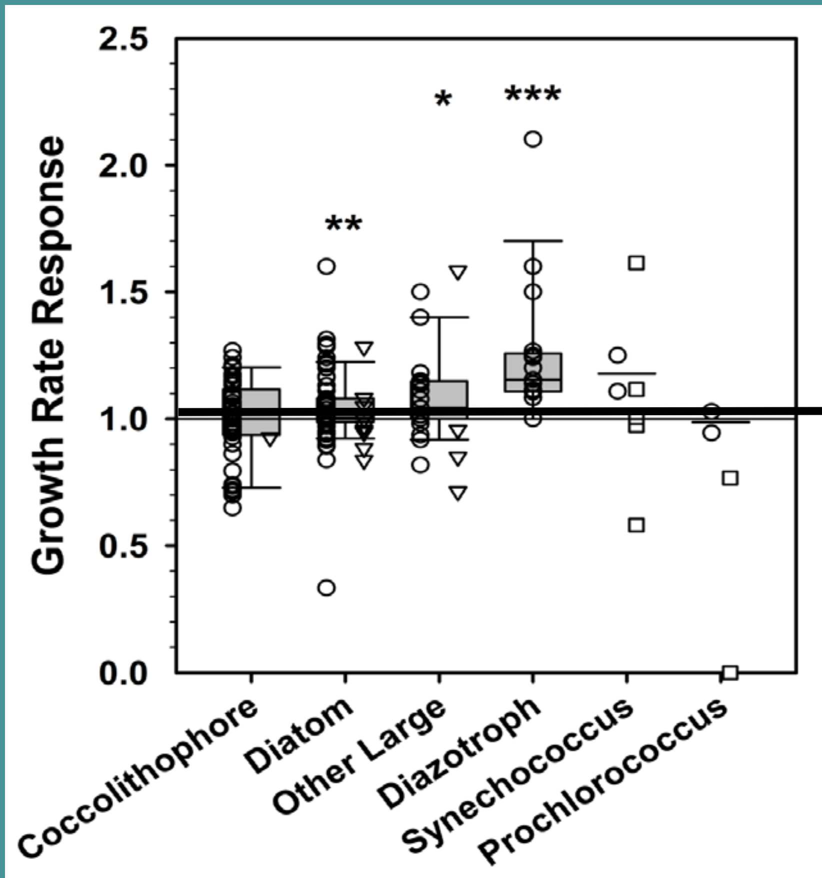

increased growth rate under enhanced $CO_2$

decreased growth rate under enhanced $CO_2$

*meta-analysis of OA experiments (Jeff Morris, U Alabama)*

*Dutkiewicz et al, in review*

# CLIMATE CHANGE EXAMPLE: OCEAN ACIDIFICATION

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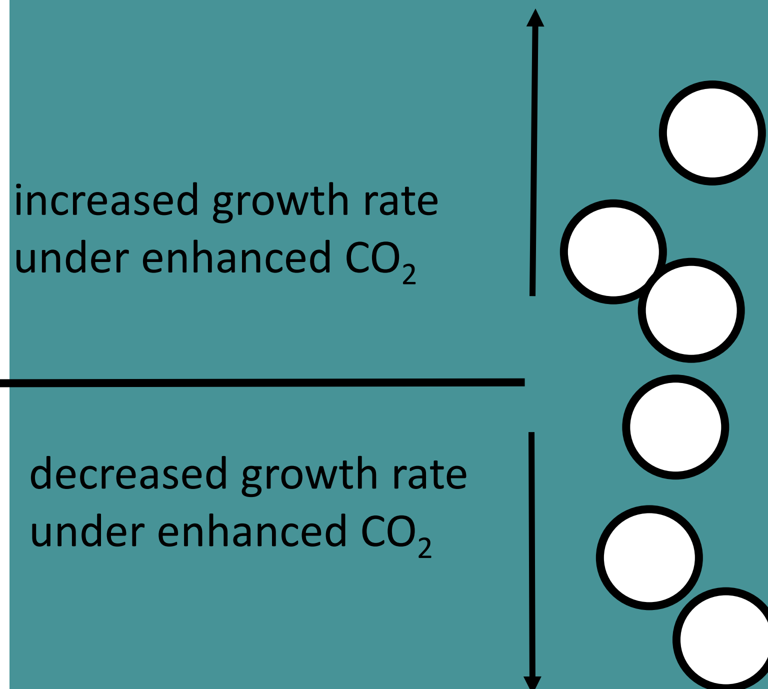
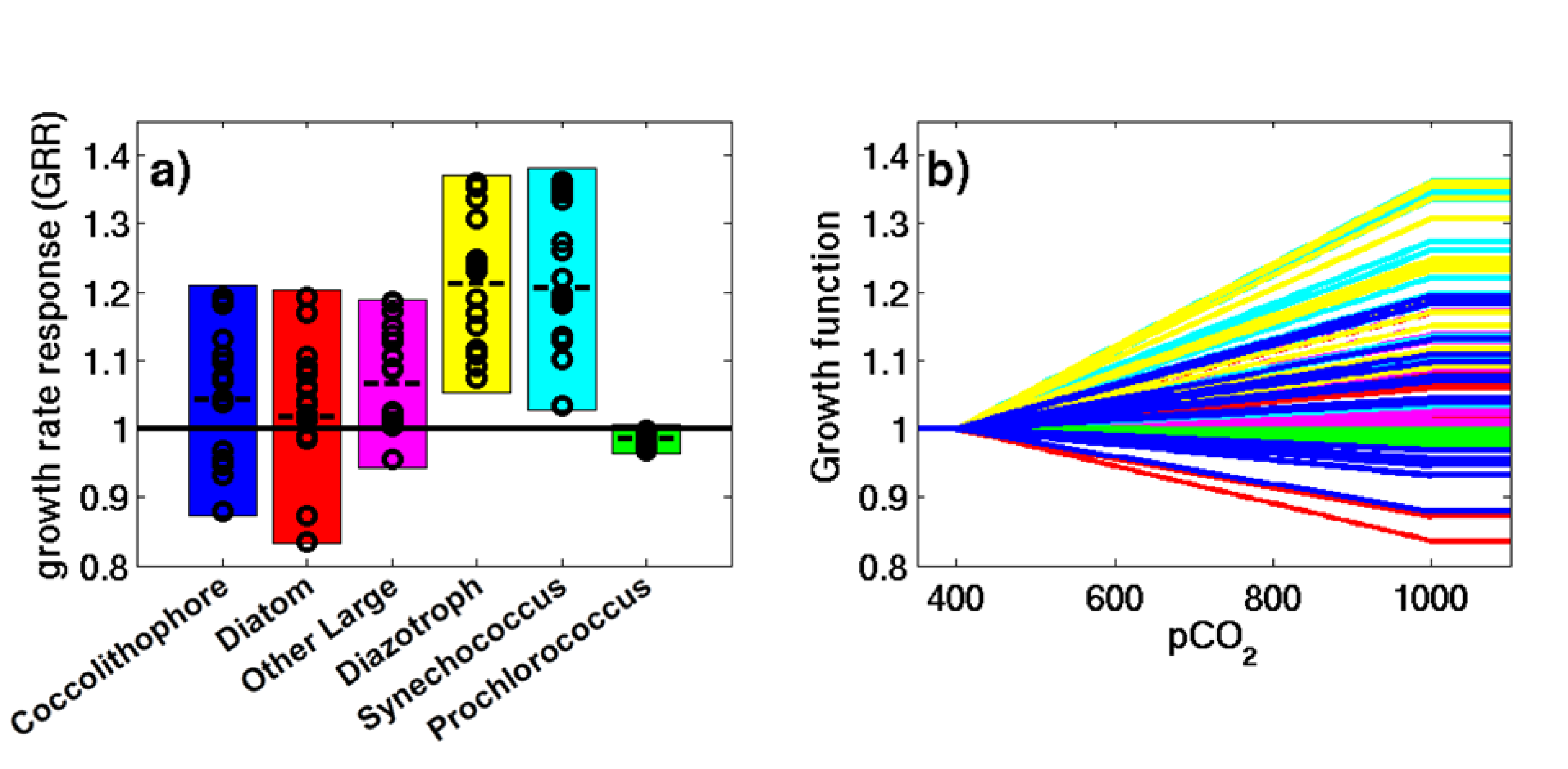



Randomly assign $CO_2$ response to model phytoplankton within bounds suggested by meta-analysis

*Dutkiewicz et al, in review*

# CLIMATE CHANGE EXAMPLE: OCEAN ACIDIFICATION

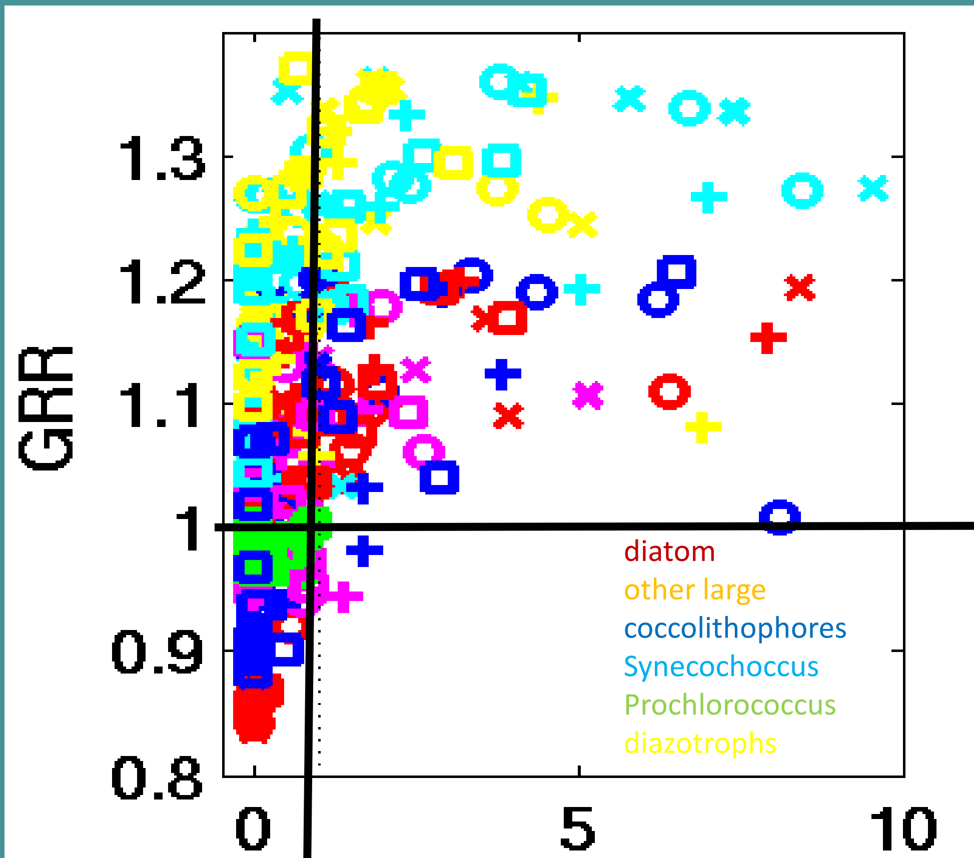



*Dutkiewicz et al, in review*

# CLIMATE CHANGE EXAMPLE: OCEAN ACIDIFICATION

**global biomass response at 2100 ($CO_2$ only)**

response (to environmental control) relative to competitor is important




increased growth rate under enhanced $CO_2$

decreased growth rate under enhanced $CO_2$

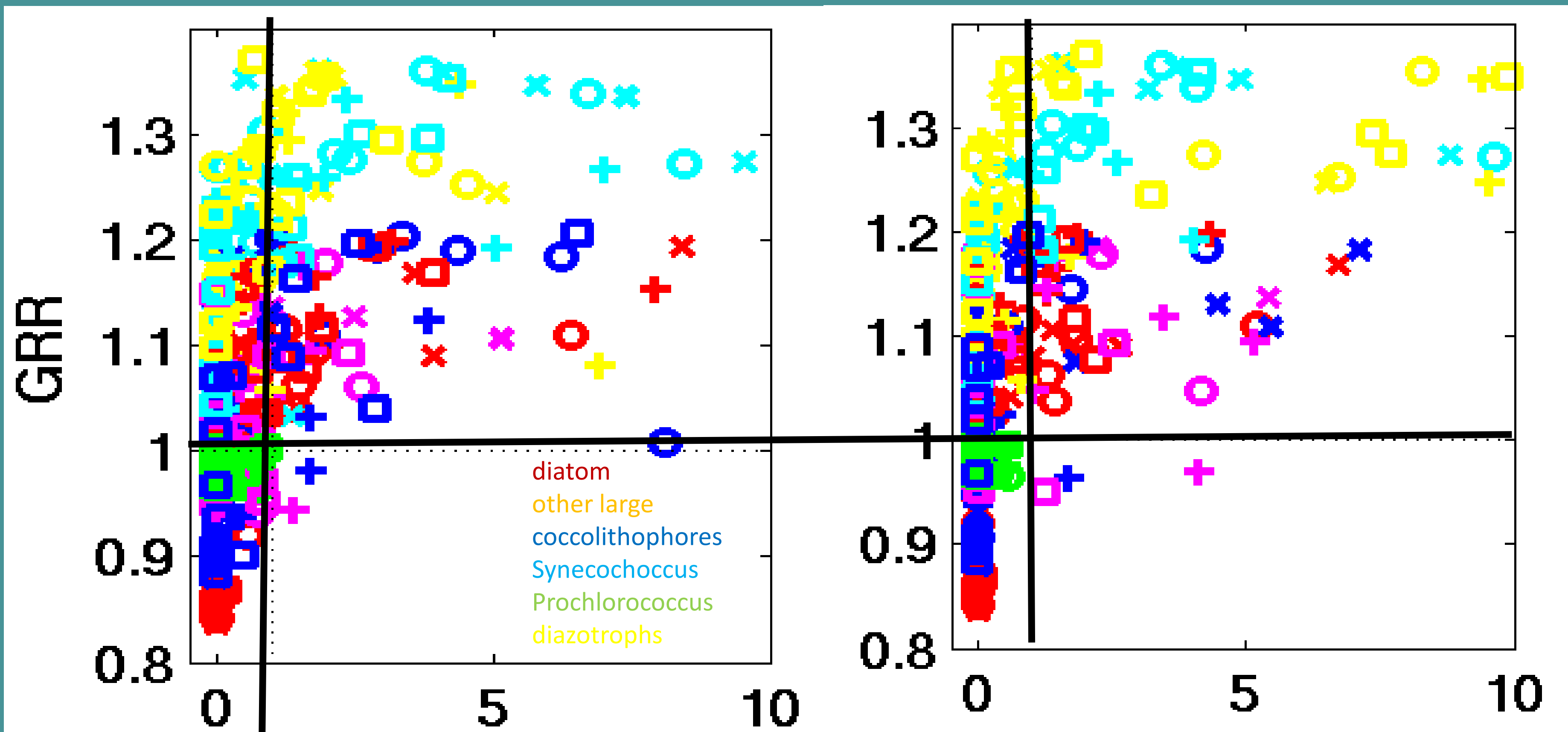
*biomass 2100 / biomass 2000*

decrease ← | increase →

*Dutkiewicz et al, in review*

# CLIMATE CHANGE EXAMPLE: OCEAN ACIDIFICATION

**$CO_2$ only** | **$CO_2$ , temperature, light and nutrient changes**




*biomass 2100*
*biomass 2000*

decrease ← | increase →

response of different traits to different environmental control also important

*Dutkiewicz et al, in review*

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# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

1. Identify key traits and trade-offs

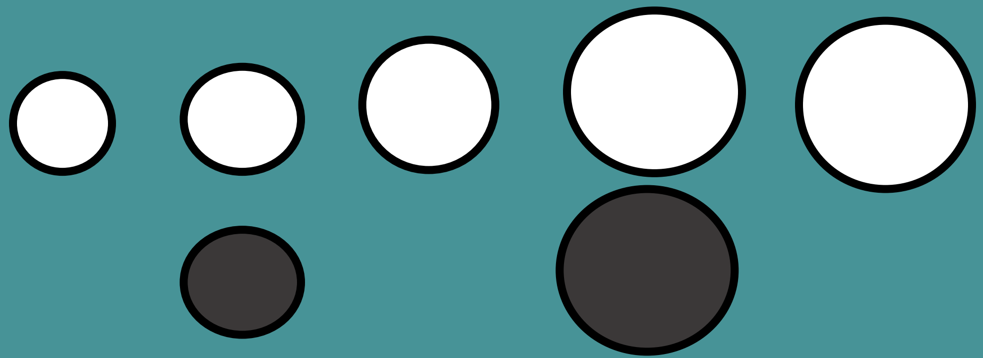
2. Understand the specific environmental control that selects for those traits

3. Understand how that environmental control changes with time

4. Caveats: - phytoplankton types response is determined by change in fitness <u>relative</u> to competitors
   - multiple stressors may affect different traits differently

# NAÏVE THOUGHTS ON HOW TO USE THIS APPROACH FOR HABS

1. Identify key traits and trade-offs of HABs



*non-HAB*

*HAB*

**toxin production** - is there an evolutionary reason?
- in there a cost?

**massive blooms** - maximize(growth-loss)?
- exclude others (shading)?

# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

1. Identify key traits and trade-offs
   **complex!**
   **toxicity?**

2. Understand the specific environmental control that selects for those traits
   **could we use knowledge of environments to help identify the main traits?**

# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

1. Identify key traits and trade-offs
   **complex!**
   **Is there a fundamental trait, or are each HAB species too specific?**

2. Understand the specific environmental control that selects for those traits
   **could we use knowledge of environments to help identify the main traits?**

3. Understand how that environmental control changes with time
   **need understanding of controls first!**

# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

1. Identify key traits and trade-offs

   **complex!**

   **Is there a fundamental trait, or are each HAB species too specific?**

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   **could we use knowledge of environments to help identify the main traits?**

3. Understand how that environmental control changes with time

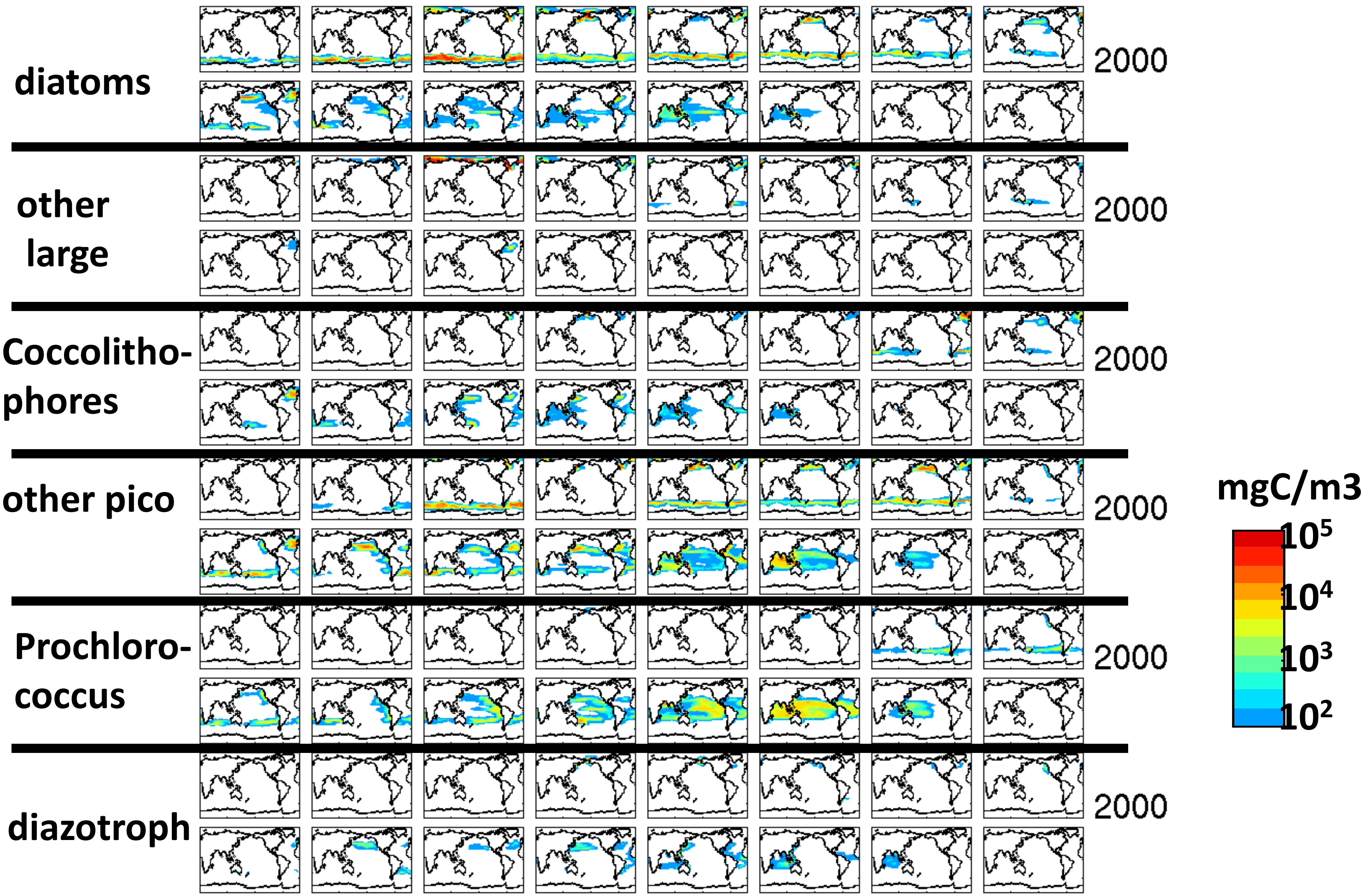
   **need understanding of controls first!**

4. Caveats: - phytoplankton types response is determined by change in fitness <u>relative</u> to competitors

   **need competition experiments (HAB vs non-HAB)**

   - multiple stressors may affect different traits differently

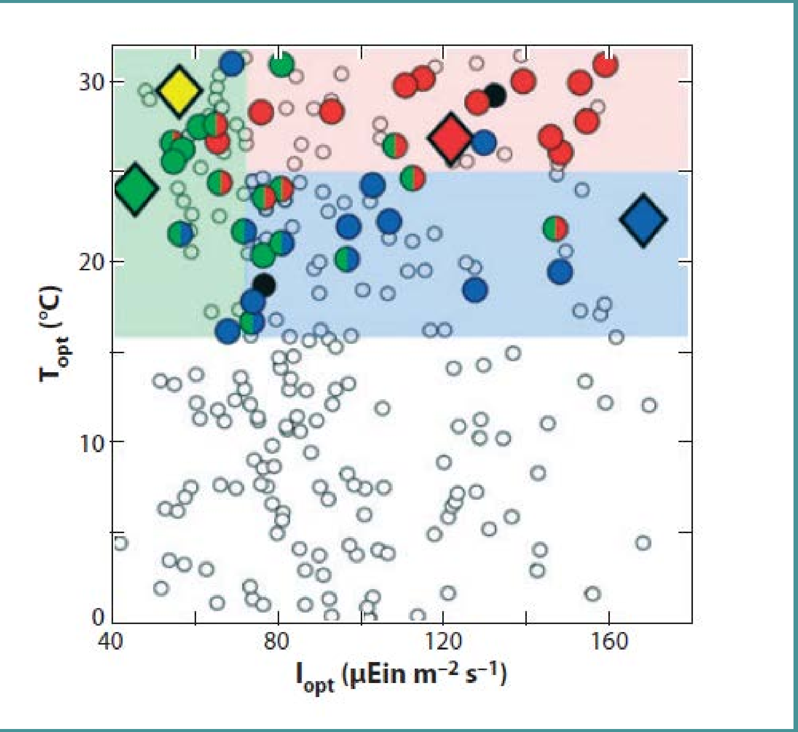
   **need multi-factorial experiments**


diatoms
2000
other large
2000
Coccolitho-phores
2000
other pico
2000
Prochloro-coccus
2000
diazotroph
2000
mgC/m3
$10^5$
$10^4$
$10^3$
$10^2$

# TRAIT BASED APPROACH TO MODELLING PHYTOPLANKTON

**Initialize model with 78 phytoplankton types with random assignments of traits**

(nutrient-acquisition ability, optimum light, optimum temperature)



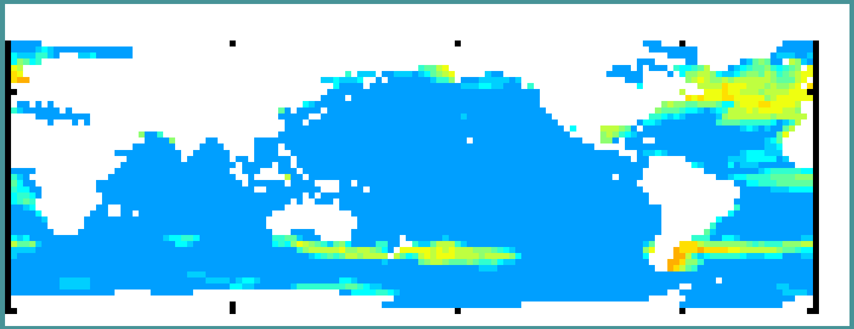

all initialized *Prochlorococcus*

environment selects which survive

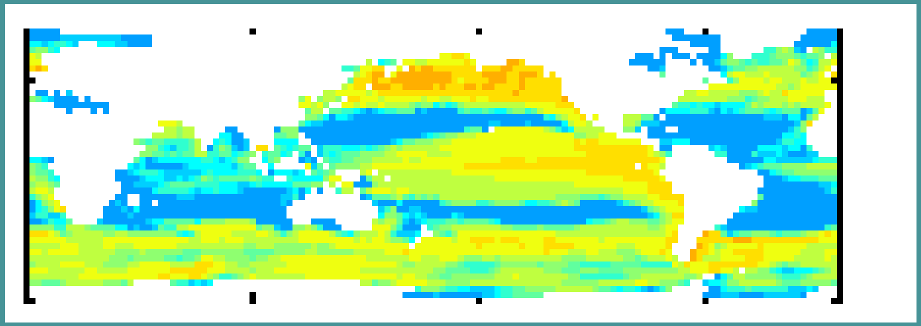
**MODEL CAN ALSO SUGGESTS WHAT TRAITS ARE NOT OPTIMAL**

# NAÏVE THOUGHTS ON HOW TO USE THIS APPROACH FOR HABS

mixotroph (fixed elemental ratios)



mixotroph (variable Fe quota)



allowed to fill quota by different strategies:
useful when Fe:other nutrient supply imbalanced

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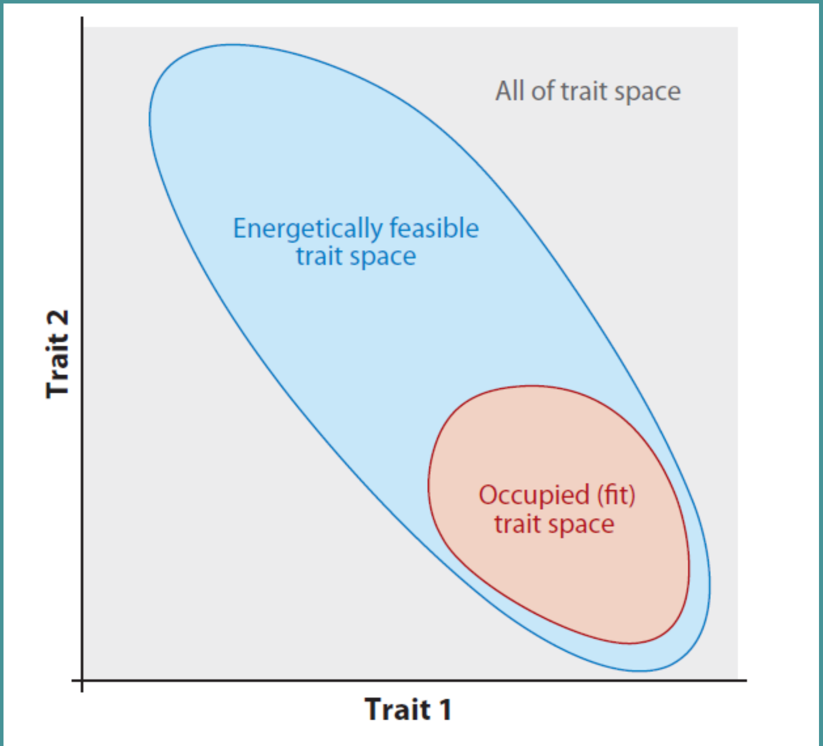


*Follows and Dutkiewicz, Ann Rev Mar Sci, 2011*