ECOSYSTEMS BIOLOGY – GLOBAL ISSUES

DKN
How have microbes impacted large scale biogeochemical cycles?
How does microbial metabolism change the game so dramatically?
How could microbes impact future global climate change?

Break – short movie

MMN – A case study
What are the constraints on the form, function and distribution of coral reefs?
How are global, anthropogenic environmental changes affecting the health of the world’s coral reef habitats?

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Where have we been, where are we, and where are we going?

1. Introduction
2. Existence
3. Persistence
4. Communities/Ecology
5. Co-evolution
6. Molecular basis for reproduction
7. Cell cycle & development
8. Living with Others
9. Ecosystems biology
10. Co-evolution
How have microbes impacted large scale biogeochemical cycles?

• Example 1 – Microbial mats and the atmosphere
• Example 2 – Evolution of photosynthesis and ore deposits
• Example 3 – The biological pump in the oceans sequesters carbon (which affects our atmosphere)
Example 1: Intertidal Cyanobacterial Mats
Guerrero Negro, Baja California Sur, Mexico

The role of microbial mats in the production of reduced gases on the early Earth

Tori M. Hoehler, Brad M. Bebout & David J. Des Marais
Exobiology Branch, NASA Ames Research Center, MS 239-4, Moffett Field, California 94035-1000, USA
Example 2: Banded Iron Formations

Scenario 1 (*anoxygeneic photosynthesis*):
\[ 4Fe^{2+} + CO_2 + 4H^+ = 4Fe^{3+} + CH_2O + H_2O \]

Scenario 2 (*oxygeneic photosynthesis*):
i.) \[ H_2O + CO_2 = CH_2O + O_2 \]
ii.) \[ 4Fe^{2+} + O_2 + 4H^+ = 4Fe^{3+} + 2H_2O \]
Example 3: atmospheric O$_2$ produced (and maintained at high levels) by marine phytoplankton and the “biological pump”

Recall from Week 2: accumulation of O$_2$ in atmosphere due to reductant sequestration (e.g. carbon burial!)

3-year compression of NASA SeaWiFS satellite images
What is the BIOLOGICAL PUMP?

Primary production: $\text{CO}_2 \rightarrow \text{CH}_2\text{O}$

$\text{CH}_2\text{O} \rightarrow \text{CO}_2$

Bacterial decay (remineralization)

not 100% efficient

Sinking organic matter, burial
Example of the biological pump when dinosaurs roamed the Earth (Late Cretaceous, ~89 Ma)

White Cliffs of Dover, UK

Coccolithophores \( \text{CaCO}_3 \) shells
How does microbial metabolism change the game so dramatically?

(a.k.a. thermodynamic and kinetic underpinnings)

Example: AOM – primary production in the dark (chemoautotrophy)

→ 90% methane (greenhouse gas) originating from marine sediments is oxidized by AOM
→ CaCO₃ reef formation bottom of Black Sea
\[ \text{CH}_4 + \text{SO}_4^{2-} + \text{Ca}^{2+} = \text{CaCO}_3 + \text{H}_2\text{S} + \text{H}_2\text{O} \]

[Sulfate reducing bacteria]

[ANME-1]

Michaelis et al., Science 2002
Catabolic redox reaction:

$$A_{\text{red}} + B_{\text{ox}} = A_{\text{ox}} + B_{\text{red}}$$

$$\Delta G = -nF\Delta E \text{ (kJ)}$$

$$n = \text{number of } e^- \text{ transferred}$$

$$F = \text{Faraday constant}$$

$$\Delta E = \text{difference in redox potential}$$

**Low potential (-)**

Electron donor

**Reducant**

**Uphill unfavorable**

$$\Delta G -$$

**Downhill favorable**

$$\Delta G +$$

**High potential (+)**

Electron acceptor

**Oxidant**

**e- donor (A_{\text{red}})?**

**e- acceptor?**

**AOM:**

$$\text{CH}_4$$

$$H_2O? \text{ CO}_2?$$

**Sulfate reduction:**

$$H_2? \text{ CH}_2O?$$

$$\text{SO}_4^{2-}$$

**High potential (+)**

Electron acceptor

**Oxidant**
### Calculating Gibbs Free Energy from the Mass Law

**Generic reaction:** \( A + 3B \rightarrow C + D + 4E \)

\[
\Delta G = \Delta G^\circ + 2.3RT \log \frac{[C][D][E]^4}{[A][B]^3} \quad \text{pure solids, liquids} = 1
\]

**Specific case of H\(_2\)-exchange:**

<table>
<thead>
<tr>
<th>( \Delta G^\circ )</th>
<th>( \Delta G )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOM: ( \text{CH}_4 + 3\text{H}_2\text{O} \rightarrow \text{HCO}_3^- + \text{H}^+ + 4\text{H}_2 )</td>
<td>+</td>
</tr>
<tr>
<td>SRB: ( \text{SO}_4^{2-} + 4\text{H}_2 + \text{H}^+ \rightarrow \text{HS}^- + 4\text{H}_2\text{O} )</td>
<td>-</td>
</tr>
</tbody>
</table>

**Net rxn:** \( \text{CH}_4 + \text{SO}_4^{2-} \rightarrow \text{HCO}_3^- + \text{HS}^- + \text{H}_2\text{O} \)

\[
\Delta G = \Delta G^\circ + 2.3RT \log \frac{[\text{HCO}_3^-][\text{H}^+][\text{H}_2]^4}{[\text{CH}_4]}
\]

→ Drive AOM rxn forward by SRB consuming H\(_2\) (or other intermediate)
How does this promote reef formation?

Net AOM rxn: \[ \text{CH}_4 + \text{SO}_4^{2-} \rightarrow \text{HCO}_3^- + \text{HS}^- + \text{H}_2\text{O} \]

Bicarb/carbonate equilibrium: \[ \text{HCO}_3^- \rightarrow \text{CO}_3^{2-} + \text{H}^+ \]

Mineral formation: \[ \text{Ca}^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3 \text{ (s)} \]

\[ \text{CH}_4 + \text{Ca}^{2+} + \text{SO}_4^{2-} \rightarrow \text{CaCO}_3 \text{ (s)} + \text{H}_2\text{S} + \text{H}_2\text{O} \]

\[ \text{HS}^- + \text{H}^+ \]
How could microbes impact future global climate change?

- Example 1 – Marine iron fertilization experiments
- Example 2 – GAIA and the CLAW hypothesis
- Example 3 – CO$_2$ and warming of the permafrost
Example 1: Iron fertilization experiments (Boyd et al, 2007)

- Natural nutrient upwelling zones, aolian dust
- Man-made (targetting HNLC regions)
  - high nutrient, low chlorophyll
    - Missing trace metals (e.g. Fe)
    - cofactors in essential enzymes necessary for phytoplankton growth
- Potential impact for climate?
  - Draw down Atm CO$_2$ (stimulate phytoplankton growth)

→ But is it so simple? How else can phytoplankton affect climate?
Example 2: The GAIA hypothesis: Earth is like an organism, which maintains planetary homeostasis

A revolutionary, but controversial idea

Oxford University Press, Oxford, 1979
CLAW hypothesis

R.J. Charlson
J.E. Lovelock
M.O. Andreae
S.G. Warren

Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate

*Nature* 1987
CLAW hypothesis

Negative feedback loop

- More cloud condensation nuclei
- Elevated SO₂ concentration
- Elevated DMS concentration

Enhanced:
- Droplet number
- Liquid water content
- Cloud area

Increased Earth albedo
- More sunlight reflected

Enhanced DMS production
Enhanced phytoplankton growth
Ocean warms
Decreased Earth albedo
less sunlight reflected

Decreased:
droplet number
liquid water content
cloud area

Anti-CLAW hypothesis
Positive feedback loop

Decreased DMS production

Decreased phytoplankton growth

Ocean warms
The take-home message is that complex feedback loops are at play that complicate our ability to predict!
Example 3: Rising atmospheric CO$_2$, The Keeling Curve

Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii

Seasonal CO$_2$-draw down when photosynthetic activity is maximal (summer)
What do you think will happen when permafrost at high latitudes warms?

Positive feedback:
Stimulation of microbial respiration $\text{CH}_2\text{O} \rightarrow \text{CO}_2, \text{CH}_4$
Release of greenhouse gases will promote warming
ECOSYSTEMS BIOLOGY – GLOBAL ISSUES

How have microbes impacted large scale biogeochemical cycles? *The have shaped all aspects of the planet throughout Earth history, from the atmosphere to the oceans to the lithosphere.*

How is it that microbial metabolism changes the game so dramatically?
*By altering local conditions such that processes become favorable that otherwise would not be (either thermodynamically or kinetically).*

What do we need to think about when debating options for controlling global climate change?
*Biogeochemical cycles are highly complex and difficult to predict without knowing all the feedback-loops! “Geoengineering” is a VERY DANGEROUS GAME. Our understanding of these systems isn’t good enough yet to roll the dice.*
ECOSYSTEMS BIOLOGY – GLOBAL ISSUES

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Break

MMN – A case study
What are the constraints on the form, function and distribution of coral reefs?
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One system dramatically affected by anthropogenic activity

CORAL REEFS: Canary in the Coalmine
Colony

Individual animals of the clone derived from asexual reproduction

CORALS ALSO HAVE SEXUAL REPRODUCTION
Coral – solitary or colonial animal with two tissue layers
1) interfaces with environment/secretes exoskeleton
2) interfaces with ‘gut’ cavity

Calcium carbonate exoskeleton

\[
Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O
\]
Coral reefs are large marine features restricted to 30°N and 30°S of the equator.

Great Barrier Reef stretches 2600 km off the east coast of Australia.

Largest single structure made from living organisms.
Some non-reef-building corals of Southern California
**pH**

Solubility, g/10g water

Temperature

CO₂ solubility in water

Solubility, kg/m³

Temperature (°C)

Ocean pH and CO₂ solubility graphs showing the relationship between pH, temperature, and solubility.
PRODUCTIVITY

- high
- high
- low
- high
- high

Nutrient concentrations measured as chlorophyll concentration
“The [tropical] ocean is a desert, with it's life underground,  
And a perfect disguise above.”  
{America, ‘Horse with No Name’}

Tropical waters are clear due to lack of nutrients, low numbers of small plants and animals.

Low visibility in temperate waters is due to high nutrient levels supporting large number of small plants/animals.
So…the tropical regions are ‘deserts’, yet…

Coral reefs that are restricted to these regions.

Coral reef systems are highly diverse; the corals provide a complex set of niches in the 3-D structure of the reef.

1) cover only 0.01% of the earth surface

2) 1/4 of all of the ocean’s species life with corals.

HOW DO THEY DO IT?
Zooxanthellae are unicellular algae that live in the gut-tissue layer of the coral.
Coral gut-tissue cell

- Host tissue amino acids
- Host cytoplasm
- Host vacuolar membrane
- Zooxanthella photosynthesis
- Chloroplast
- Zoox. cytoplasm
- Cell wall
- CO₂
- HCO₃⁻
- Carbonic anhydrase
- Carbohydrates

Diagram shows the interaction between the host tissue and the Zooxanthella, highlighting the process of photosynthesis and the exchange of nutrients and gases.
Prey capture

Light capture (symbiosis)

DAY
1° autotrophic

NIGHT
1° heterotrophic
Coral reefs also have a depth restriction largely due to light absorption with depth.

The compensation point is the amount of light intensity on the light curve where the rate of photosynthesis exactly matches the rate of respiration.
Destruction of the coral reefs

Overfishing
Destructive fishing methods

Southeast Asia

Destruction of the coastline
Imbalanced exchange between land and sea

Chitales, Yucatan Peninsula, Mexico
Coral bleaching
Coral Bleaching – loss of pigmentation of the corals

*Proximate cause* – loss of the symbiosis

Since the 1970’s we have lost over 30% of our corals due to bleaching resulting from elevated temperatures

How and why is the symbiosis compromised?

Five different types of cellular mechanisms of symbiont loss from coral host tissues.
Movie on
1) global temperature change
2) ocean acidification –

OVER YOUR LIFETIME

NO TIME FOR RECOVERY

\[ \text{Ca}^{2+} + 2\text{HCO}_3^- \leftrightarrow \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \]
Marine bacteria going to the dark side with higher temperatures.

Occurrence of *Vibrio shiloi* in coral tissues.

pre 2003
THERE’S HOPE, BUT WE NEED TO ACT NOW!!!
What are the constraints on the form, function and distribution of coral reefs?
Coral reefs are ecosystems in which corals are the major physical and biological elements. Reef-building corals are colonial animals with calcium carbonate exoskeletons. These reefs support much of the ocean’s diversity.

Coral reefs are restricted to the tropics and subtropics, areas of low nutrients. They are able to live in such environments because they form a symbiotic relationship with photosynthetic, unicellular algae.

How are global, anthropogenic environmental changes affecting the health of the world’s coral reef habitats? Global climate change and ocean acidification severely threaten the world’s coral reefs.

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