Ocean life, bioenergetics and metabolism

Biological Oceanography (OCN 621)

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(MSB 612)
Ecosystems are hierarchically organized

- **Atoms → Molecules → Cells → Organisms → Populations → Communities**

- This organizational system dictates the pathways that energy and material travel through a system.

- Cells are the lowest level of structure capable of performing ALL the functions of life.
Two primary cellular forms

- **Prokaryotes**: lack internal membrane-bound organelles. Genetic information is not separated from other cell functions. Bacteria and Archaea are prokaryotes. Note however this does not imply these divisions of life are closely related.

- **Eukaryotes**: membrane-bound organelles (nucleus, mitochondrion, etc.). Compartmentalization (organization) of different cellular functions allows sequential intracellular activities.
Most Life on the planet is Microscopic!

In the ocean, microscopic organisms account for >50% of the living biomass.
Controls on types of organisms, abundances, distributions

- **Habitat**: The physical/chemical setting or characteristics of a particular environment, e.g., light vs. dark, cold vs. warm, high vs. low pressure
- Each marine habitat supports a somewhat predictable assemblage of organisms that collectively make up the community, e.g., rocky intertidal community, coral reef community, abyssobenthic community
- The structure and function of the individuals/populations in these communities arise from evolution and selective adaptations in response to the habitat characteristics

- **Niche**: The role of a particular organism in an integrated community
• The ocean is not homogenous: spatial and temporal variability in habitats

• Most of the Earth’s living space is cold, dark, and under high pressure.
Clearly distinguishable ocean habitats with elevated “plant” biomass in regions where nutrients are elevated.
The ocean is stirred more than mixed.

Sea Surface Temperature (°C)  Chl a (mg m⁻³)
Spatial discontinuities at various scales (basin, mesoscale, microscale) in ocean habitats play important roles in controlling plankton growth and distributions.
LIFE IS MULTI-VARIATE
Numerous environmental factors control where organisms live:
- temperature
- salt
- pressure
- oxygen
- biology (predation, disease)
What do cells require?

• Energy

• Electron acceptors and donors

• Nutrients (C, N, P, S, Fe, etc.)
Energy flows, matter cycles

Matter (C, N, P)
- regeneration
- uptake
- growth
- death

Cycles

Energy
- light
- chemical
- heat

Unidirectional
Classification of life by types of cellular metabolism

• **Energy source**
  – Sun: **Photo**
  – Chemical: **Chemo**

• **Reduction source**
  – Organic: **organo**
  – Inorganic: **litho**

• **Carbon source**
  – Inorganic molecules: **auto**
  – Organic molecules: **hetero**

Thus, an organism that utilizes light for energy, water for reducing power, and CO₂ for carbon is a **photolithoautotroph**. An organism that utilizes organic matter for energy, reducing power, and carbon is a **chemoorganoheterotroph**.
Where do cells acquire energy?

• Sources of Energy in the sea:
  • Light-aside from hydrothermal vents, sunlight is the ultimate energy source for life in the sea (phototrophy).
  • Chemical-both organic and inorganic molecules (chemotrophy).
ATP: universal cellular energy currency

Cells store chemical energy by adding phosphate to ADP; breaking these phosphate groups off of ATP yields energy. The phosphate groups can be transferred to other molecules (e.g. amino acids) and these receptor molecules are more reactive than ATP. This provides a means for the cell to fuel cellular biosynthesis or transport solutes into or out of the cell.

(a) ATP consists of three phosphate groups, ribose, and adenine.
NADH : electron carriers

- The harvesting and storage of energy by cells is mediated by a series of redox reactions.
- Synthesis of reduced material (organic molecules) requires energy (in the form of electrons). Biochemical consumption of reduced material releases energy.
- NAD+ serves as the primary intermediate electron acceptor, forming NADH. When NADH transfers its electrons to an acceptor, energy is released.

\[
\text{NAD}^+ + H^+ + 2e^- \rightarrow \text{NADH}
\]
Photosynthetic organisms capture energy from sunlight and convert this to chemical energy (ATP) and reducing power (NADH). Energy and reductant are required for fixing CO$_2$ into sugar.

Cells are more than sugar. Other compounds are built from simple sugars plus nutrients (Nitrogen, Phosphorous & trace metals)
Energy generation by aerobic respiration of organic matter includes several linked biochemical pathways:

- Glycolysis
- Krebs cycle or Citric acid cycle
- Electron transport phosphorylation

All living things respire...including plants!
## Alternate electron Acceptors for Respiration

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\Delta G^\circ$ (kcal/mole)</th>
<th>$\Delta G^\circ$ (kcal/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$</td>
<td>-686</td>
<td></td>
</tr>
<tr>
<td>$5 \text{CH}_2\text{O} + 4 \text{NO}_3^- \rightarrow 4 \text{HCO}_3^- + \text{CO}_2 + 3 \text{H}_2\text{O} + 2 \text{N}_2$</td>
<td>-570</td>
<td></td>
</tr>
<tr>
<td>$\text{CH}_2\text{O} + 3 \text{CO}_2 + \text{H}_2\text{O} + 2 \text{MnO}_2 \rightarrow 4 \text{HCO}_3^- + 2 \text{Mn}^{2+}$</td>
<td>-349</td>
<td></td>
</tr>
<tr>
<td>$\text{CH}_2\text{O} + 7 \text{CO}_2 + 4 \text{Fe(OH)}_3 \rightarrow 8 \text{HCO}_3^- + 3 \text{H}_2\text{O} + 4 \text{Fe}^{2+}$</td>
<td>-114</td>
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</tr>
<tr>
<td>$2\text{CH}_2\text{O} + \text{SO}_4^- \rightarrow 2 \text{HCO}_3^- + \text{H}_2\text{S}$</td>
<td>-77</td>
<td></td>
</tr>
<tr>
<td>$\text{CH}_2\text{O} \rightarrow \text{CO}_2 + \text{CH}_4$</td>
<td>-58</td>
<td></td>
</tr>
</tbody>
</table>

$\Delta G^\circ$ (kcal/mole) = free energy released per mole of glucose oxidized

**CONCEPT:** Some energetic transformations are more energetically favorable than others. These will usually occur first under natural conditions - i.e., the most energetically favorable terminal electron acceptor ($\text{O}_2$) will be used until it is no longer available, then the environment will favor organisms (bacteria) capable of utilizing alternative electron acceptor to oxidize organic matter.
Some Important Energy Generating Metabolisms

• Oxygenic Photosynthesis
  ATP and NADPH are made in large amounts
  Produces oxygen as a bi-product during splitting of water for reducing power

• Anoxygenic Photosynthesis
  ATP made in large amounts
  Reduction of NADP does not involve water; hence no oxygen produced

• Aerobic Respiration
  ATP and NADH are made in abundance
  Requires oxygen

• Anaerobic Respiration
  Lower ATP yield than aerobic respiration; NAD easily reduced
  Requires electron acceptor other than oxygen

Fermentation
Little ATP, no net NAD reduction, MOST SIMPLE SYSTEM
Aerobic Respiration:

\[ + \text{O}_2 \]

Oxygenic Photosynthesis:

\[ + \text{CO}_2 + \text{H}_2\text{O} = \]

ATP and NADH are created via series of redox reactions. Both ATP and NADH are required for creation of new cellular material – primary production.

\[ + \text{O}_2 \]

ATP and NADH are formed during oxidation of cellular material; some energy lost as heat.
Overall chemical equation describing oxygenic photosynthesis:

Electron donor (reductant) Sunlight

\[ 6\text{CO}_2 + 12\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 + 6\text{H}_2\text{O} + \text{heat} \]

Overall chemical equation describing aerobic respiration:

Electron acceptor

\[ \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + 686 \text{ kcal (ATP + heat)} \]
Coincidentally….

• Ocean plankton produce ~50% of all organic matter (and hence oxygen) on the planet.

• The amount of organic matter (and hence oxygen) in the biosphere is determined by the balance between primary production (oxygen producing) and respiration (oxygen consuming).

• In the ocean, this balance is almost always close to even; production of organic matter is closely linked (in time and space) to its consumption.

• We will revisit this in later lectures…. 
Other reduced compounds that contain bioavailable energy

• Sources of chemical energy:
  – CH$_4$, H$_2$, NH$_4^+$, NO$_2^-$, H$_2$S, Fe$^{2+}$
  – These substrates fuel energy demands of mostly chemolithautotrophic organisms (bacteria and archaea).

When oxidizing these compounds, organisms can obtain reductant and ATP.
What are cells doing with energy harvested from the environment?

- Growing and producing: creation of new cells/cell constituents (requires synthesis of specific biomolecules)
- Transporting material against concentration gradients (active transport)
- Moving (motility)
- Homeostasis (keep intracellular conditions stable)