Breathing of the Biosphere: Metabolism and Energetics of Cells, Microbes, Plants and Animals

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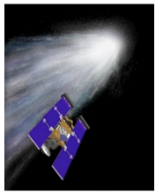
ESPM 2, the Biosphere
Fall 2017

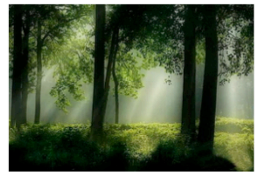
12/2/17 ESPM 2, Biosphere

The flows of energy are key to how the biosphere works, heralding back to the days of Vernadsky. This lecture will discuss energy and the routes it flows through the biosphere as used by plants, microbes and higher organisms. Capture of solar energy is key, but some microbial life are able to extract chemical energy from their environment by redox. Energy fixed and stored as carbon compounds is eventually cycled through food webs feeding lower and lower trophic levels.

Outline

- Energy
  - Forms, Units
- Metabolism
- Extracting Energy from the Environment
- Available Energy
  - Redox
  - Sunlight





'Our bodies are stardust;
Our lives are sunlight'

Oliver Morton, 2008 Eating the Sun: How Plants Power the Planet

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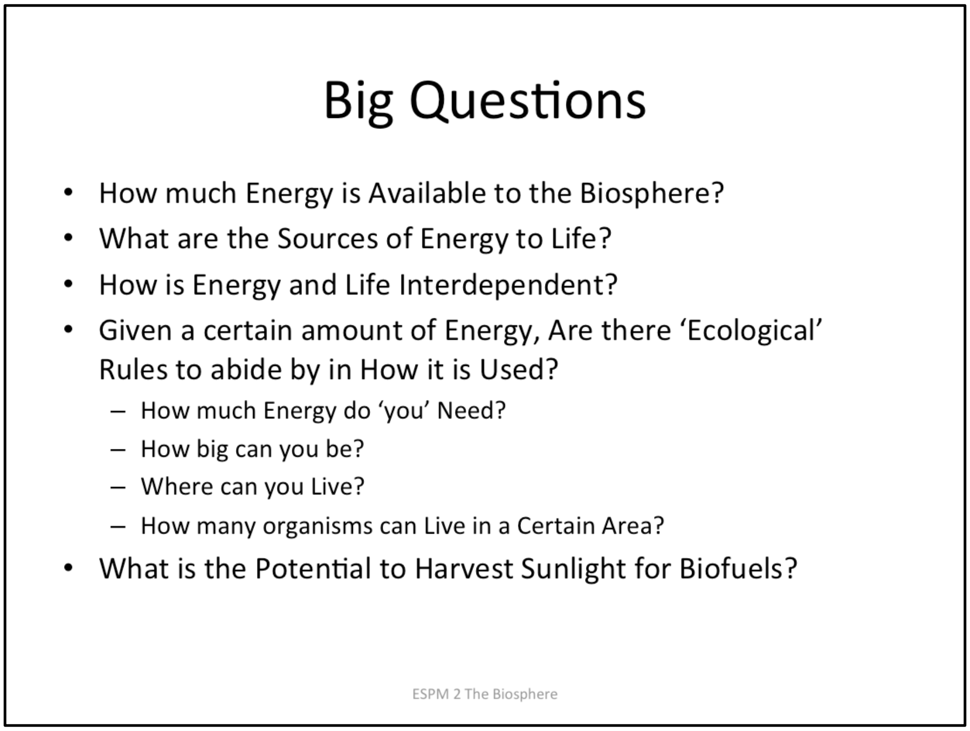
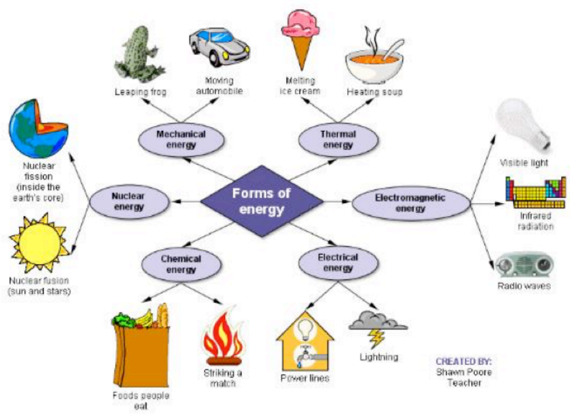
Wonderful book. If you have time to read for pleasure and curiosity sake I recommend this book for all biospherians.



These are some of the overarching questions associated with the links between Energy and the Biosphere. Can you think of others that come from your life experiences or interests?

Forms of Energy



Mechanical
Chemical
Electrical
Electromagnetic (Light)
Thermal/Heat
Nuclear
Sound

http://www.phibetaiota.net/wp-content/uploads/2014/04/energy-six-forms.jpg

The Baldocchi-Biometeorology Perspective,
With Apologies to Erwin Schrodinger

Physics ‘wins’, or ‘Sets the Limits’

‘Biology is How It’s Done’

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It is a ‘tongue in check’ statement to get your attention. But there are many truths to it, especially by linking Physics and Biology.

Modern science cannot afford to work in silos of only physics or only biology. The two fields of biology and physics must interact, to get a better appreciation about how the biosphere works. Life is sustainable because it re-cycles material and is able to extract as much energy out of the system as possible, through multiple trophic levels. Evolution is powerful as it enables organisms to develop structures and functions that are optimized for their environment. This is not to say multiple ways are viable, just walk through the desert. But it does say that certain forms and functions are not viable. 100 m tall redwood trees don’t grow in the desert, for example.

The first part of this statement came to mind when I was in India riding a jitney. Observing automotive chaos everywhere I asked the driver where I could find the seat belt. The taxi driver seemed insulted and questioned my trust in his driving ability. I retorted ‘*I want to be restrained because in the case of an accident, because ‘Physics wins’* ‘; I surely did not want to get projected through the wind shield if he came to an abrupt stop.

Seriously, the basis for this statement comes from observation, research and

The Baldocchi-Biometeorology Perspective

- Physics ‘wins’, or sets the Limits
  - Plants, and Ecosystems, function by capturing solar energy
  - Plants convert solar energy into high energy carbon compounds that is used for Work by Plants and consumed by Animals, Invertebrates and many microbes
  - There is only ‘so-much’ Solar Energy available to a given area of land; This limits the number and size of plants, animals, invertebrates, and microbes
  - Plants transfer nutrients and water between air, soil and plant pools to sustain their structure and function, via diffusion and mass transfer. Networks of veins are established to optimize the transfer of resources, and thereby set limits to size and density.

These examples clearly state the how physics sets limits on metabolism, form and function

The Baldocchi-Biometeorology Perspective

- Biology is how it's done
  - Information is transferred from generation to generation through DNA
  - Species differentiation (via evolution and competition) produces the structure and function of plants, invertebrates and vertebrates
  - In turn, structure and function provides the mechanisms for competing for and capturing light energy and transferring matter,
  - Reproductive success that passes genes through the gene pool.
  - Microbes break down and recycle biological material
  - Microbes extract energy by exploiting electron gradients possessed in biomass and their environment
  - We are effectively 'Bags of Differentiated and highly evolved Microbes'
  - If we want to develop a sustainable World, listen and learn lessons from the Environment. They have had several Billions years to evolve and get it as right as possible

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Examples on how Biology does it…otherwise all you have is dead rocks rolling down hills. This is not life.

Joule

ENERGY = WORK

WORK = FORCE times DISTANCE (m)

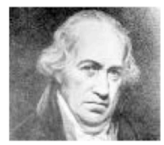
Newton

UNITS: Joule = N-m = kg m^2 s^{-2}

FORCE (kg m s^{-2}) = MASS (kg) times ACCELERATION (m s^{-2})

ENERGY FLUX DENSITY (W m^{-2} =J m^{-2} s^{-1})

Watt = J s^{-1}



Watt

Examples of the links between Energy and Work and the Units associated with these terms. If you forget, go back to first principles. Work is force times distance. We know from dropping a rock that a force is mass times acceleration. And we know that an acceleration is the change in velocity with time (meter per second per second)

What is Metabolism?
Why should we Care?

- **Metabolism** (from Greek: μεταβολή metabolē, "change") is the set of life-sustaining chemical transformations within the cells of living organisms. These enzyme-catalyzed reactions allow organisms to grow and reproduce, maintain their structures, and respond to their environments.
- These reactions involve Work and it Takes Energy to do Work

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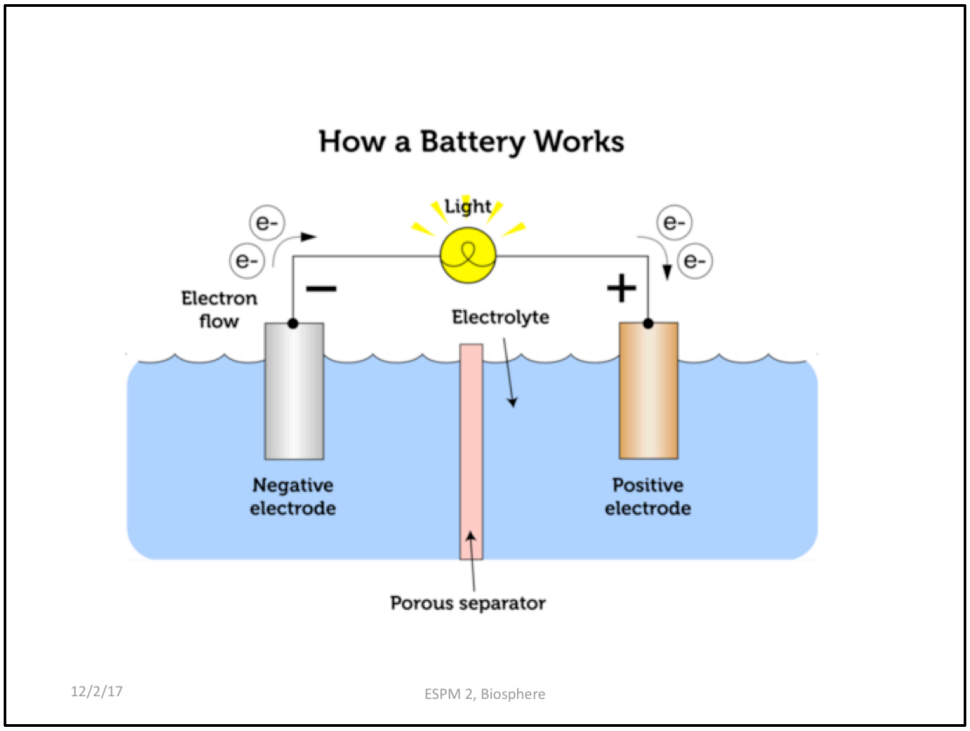
Energy Fuels Metabolism

Electrical Potential

- The difference in Electrical Potential is a measure of the amount of Electrical Work involved in moving a Charge from one location to another
- Remember, it Takes Energy to do Work
- Principle by Which Batteries Work
  - Cation is reduced as electrons migrate towards it and are added
  - Anion is Oxidized as electrons are removed

Park Nobel



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Energy from Redox, e.g. Microbial Battery

Reduction, Gain of Electrons (GER)
Oxidant + e- ==> Product

Oxidation, Loss of Electrons, (LEO)
Reductant ==> Product + e-

OIL (Oxidation is Loss) RIG (Reduction is Gain)

Oxidizing agent (an Oxidant) is Reduced and gains Electrons, so it is also the Electron Acceptor, e.g. O_2 and SO_4--

A Reducing agent (a Reductant) is Oxidized and looses Electrons, so it is also the Electron Donor, e.g. $(CH_2O)_n$

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I've come to view the process of life, like a battery. The flow of electrons from chemical energy drives this battery and the flows, gains and losses of electrons are associated with REDOX. Whendee is more expert on this topic and will cover it more and better with decomposition.

Nerst Equation
Electrical Potential of ions across a membrane
Computes Redox Cell Potential

$$E_i - E_0 = \frac{RT}{nF} \ln\left(\frac{[oxidant]}{[reduc\tan t]}\right)$$

(Voltage, or Electromotive Force)

Change in Gibbs Free Energy, ΔG, the Energy that
Equilibrium Chemical Reactions can Store or Release

$$\Delta G = -(E_i - E_0)\ n\ F$$

n is charge number
F is Faraday constant, 96840 J per volt gram-equivalent (J s^{-1} A^{-1}) or (C $mol^{=1}$)
R = 8.314 J K^{-1} mo^{l-1}

Units

$$E_i - E_0 = \frac{RT}{nF}\ln\left(\frac{[oxidant]}{[reduc\tan t]}\right)$$

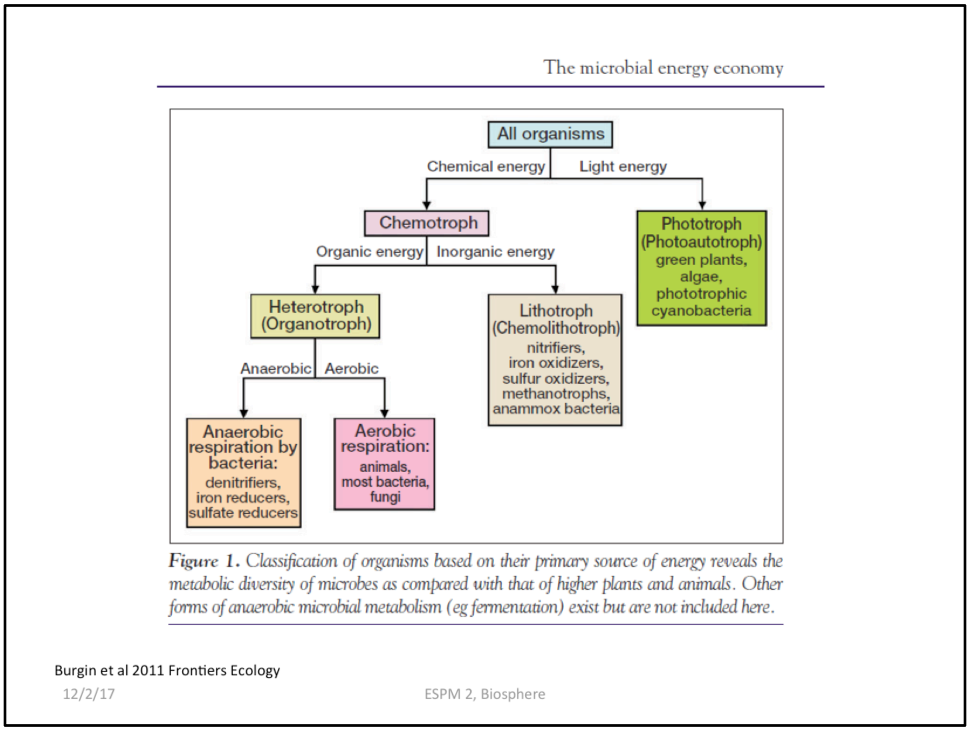
K x (J K^{-1} mol^{-1})/ n J V^{-1} g mol^{-1} n^{-1} = V g^{-1}

g-equival = g mol-1 n-1; n is number of charge

$$\Delta G = -\ (E_i\text{-}E_0)\ \ n\ F$$

V g^{-1} n J V^{-1} g mol^{-1} n^{-1} = J mol^{-1}

Question in class about units, per molecule or per mole. Working through the computations we find Gibbs Free energy is Joules per mole



Here it is enough to show how adept life is at extracting energy from its environment. Knowing these different routes and how acts within each box is important

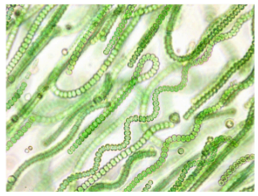
One fraction of the biosphere is dominated by the phototrophs, those who eat sunlight. The other fraction is dominated by Chemotrophs. They either derive energy from organic matter or are Lithotrophs and able to 'eat' chemical energy stored in minerals.

It is important to Recall and Remember the Chemical Energy used by OrganoTrophs Ultimately came from PhotoTrophs and the Sun.

Burgin et al 2011 Frontiers Ecology

Phototrophs

Leaves



Cyanobacteria

Algae

Redox of Carbon Fixation

Oxidation: 2 H_2O -> O_2 + 4 e- + 4 H+
Electron Donor: -78 kJ/e- x 4 e- = -312 kJ

Reduction: CO_2 + 4H+ + 4 e- -> CH_2O + H_2O
Electron Acceptor: 47 kJ/e- x 4 e- = 188 kJ

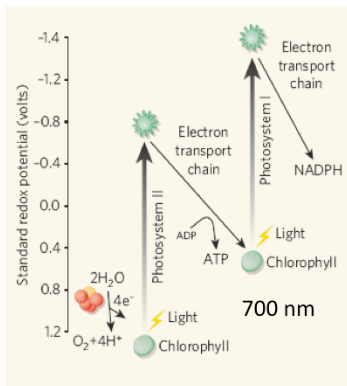
Net: CO_2 + H_2O -> CH_2O + O_2

500 kJ per carbohydrate (CH_2O)

3000 kJ per $C_6H_{12}O_6$ (glucose)

PhotoTrophs: Using Solar Energy for Life

Light ('Hill') Z Reactions:
PS II and Ps I



680 nm

Allen and Martin, 2007 Nature

- Visible solar energy (400 to 700 nm) is absorbed by pigments and this energy is converted into high energy compounds, ATP and NADPH, by photosystems II and I (PS II and I)
  - Photosystem II uses 680 nm energy to generate ATP (non-cyclic electron transport)
  - PS I uses 700 nm solar energy to generate NADPH (cyclic electron transport).
  - Excess energy is lost as heat or fluorescence.
- **8 Photons per CO_2 molecule fixed**

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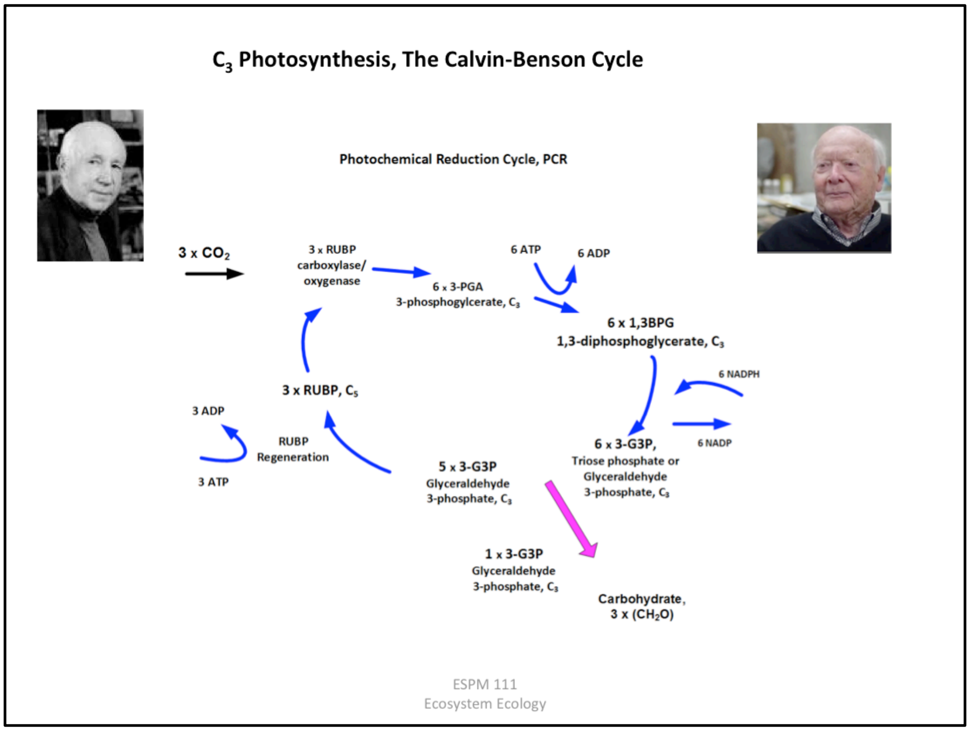
Prof Banfield will cover this topic in great detail on her lecture on Carbon Metabolism. Light Energy splits water and electrons are released, and oxygen is formed

General lessons at this stage are: light energy is used to split water releasing 4 electrons and producing Oxygen. These electrons are transported and inter-converted into biochemical energy compounds, ATP and NADPH, that ultimately lead to the fixation of CO2; energy is stored in chemical compounds, sugars, and the respiration (oxidation) of these sugars provide energy for metabolism and the food changes of primary, secondary and tertiary consumers.



An example of the stoichiometry of the photosynthetic carbon reduction (PCR) and the photosynthetic carbon oxidation (photorespiration cycles). In this case, it is scaled with in an input of 3 CO2 molecules

The enzyme ribulose-1,5-bisphosphate carboxylase (Rubisco) catalyzes the reaction between gaseous carbon dioxide and ribulose-1,5-bisphosphate (RuBP).

Product of the reaction are two molecules of 3-phosphoglyceric acid for each CO2 molecule

$C_5O_3H_8(PO_4^{2-})_2 + CO_2 \rightarrow 2\ C_3O_3H_4PO_4^{2-}$

RUBISCO has an affinity for both CO_2 and O_2, with the later leading to photorespiration, a loss of CO_2. The rate of competitive oxygen fixation is a proportional to the oxygen concentration time the ratio of oxygenation (Vo) to carboxylation (Vc). At ambient conditions Vo/Vc is about 0.27 (2 times the CO2 compensation point divided by CO2; ~ 2 x 38/280). In practice for each CO2 consumed by carboxylation 0.5 CO2 times Vo/Vc are lost by photorespiration;

Aerobic Heterotrophs

Respiration

Mole basis

Oxidation: $CH_2O + H_2O = CO_2 + 4\ H^+ + 4\ e^-$: Electron Donor

ΔG_2: 4 e- * -47 kJ/e- = -188 kJ

Reduction: $O_2 + 4\ H^+ + 4\ e^- = 2\ H_2O$: Electron Acceptor

ΔG_1: 4 e- * 78 kJ/e- = 312 kJ

Net: $CH_2O + O_2 = CO_2 + H_2O$:

$\Delta G_1 - \Delta G_2$: 4 e- * (78 - -47) kJ/e- = 312 - - 188 kJ=

500 kJ/CH_2O

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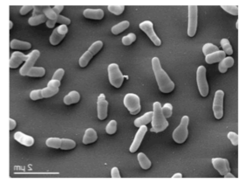
We always see the Net reactions, eg CH2O + O2 = CO2 + H2O. But it is important to explore the Redox Half reactions and see how many electrons are being shuttled back and forth, as these drive the ultimate energetics. We see we release 500 kJ per carbon hydrate and 3000 kJ per glucose molecule, the sugar fixed by photosynthesis.

Anaerobic Heterotrophs

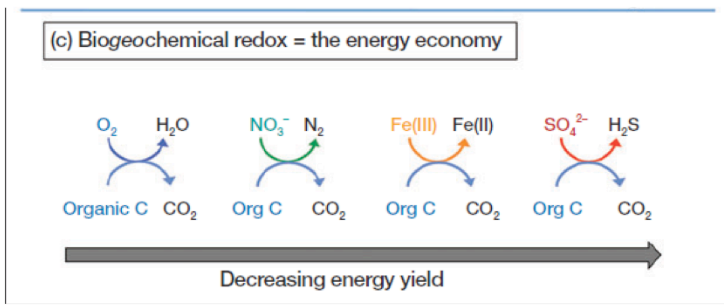
Iron Reducers

Sulfate Reducers



Denitrifying Bacteria

Anaerobic Respiration by Anaerobic Heterotrophs
Microbes Can 'Breathe' without Oxygen
Using Alternative Electron Acceptors



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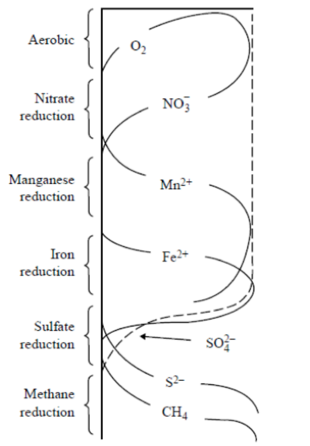
Adapted from Burgin. With ample oxygen, Organic C is consumed and CO2 and H2O are produced. If O2 is depleted, Nitrate becomes the electron acceptor and N2 gas and CO2 is produced. Next Fe(III) gains an electron, forming Fe(II) and CO2. Lowest in Energy yield is SO4– as an electron acceptor. H2S and CO2 are formed



gure 1 Vertical biogeochemical zones in sediments.

The Redox Ladder

Exemplified by the Vertical Variation in Microbial Activity and the Terminal Electron Acceptors they use in Sediments

O2 > NO3- > Mn++ > Fe++ > SO4--

Megonigal and Hines

Redox Ladder for Aerobic and Anaerobic Respiration

	Electron Donor	Electron Acceptor	ΔG kJ e^- eq^{-1}	Energy, kJ
Aerobic respiration	CH_2O	O_2	-125	3000 kJ/mole $C_6H_{12}O_6$
Denitrification	CH_2O	NO_3-	-119	2856 kJ/ mole $C_6H_{12}O_6$
Nitrate reduction	CH_2O	NO_3-	-82	1968 kJ/mole $C_6H_{12}O_6$
Soluble Iron (Fe(II) production	CH_2O	FeOOH	-87	1248 kJ/ glucose
Fermentation	CH_2O	CH_2O	-30	240 kJ/mole $C_6H_{12}O_6$
Sulfate reduction	CH_2O	SO4=	-25	600 kJ/mole
Methane fermentation, via CO2 reduction	CH_2O -> H2	CO_2	-24	576 kJ/ mole $C_6H_{12}O_6$
Methane fermentation via acetate	CH_2O ->CH3OOH	CO_2	-38	

Denitrification

Electron basis

Reduction: 1/5 NO_3^- + 6/5 H+ + e- = 1/10 N_2 + 3/5 H_2O ; 72 kJ/e-

Oxidation: ¼ CH_2O + ¼ H_2O = ¼ CO_2 + H^+ + e^- : -47 kJ/e^-

Net: ¼ CH_2O + 1/5 NO_3^- + 1/5 H^+ = ¼ CO_2 + 1/10 N_2 + ½ H_2O: 72 - -47 = 119 kJ/e-

Mole basis (x 20 e-)

5 {CH_2O} + 4 {NO_3^-} + 4 H^+ = 5 CO_2 + 2N_2 + 10 H_2O

ΔG: 20 e- * 72 – 20 e- * -47 = 1440 - -940 = 2380 kJ

ΔG: X 6/5, per $C_6H_{12}O_6$ = 2856 kJ

5 {$C_6H_{12}O_6$} + 24 {NO_3^-} + 24 H^+ = 30 CO_2 + 12N_2 + 60 H_2O

Nitrate Reduction

Oxidation: ¼ CH_2O + ¼ H_2O = ¼ CO_2 + H^+ + e^-; -47 kJ/e-

Reduction: 1/8NO_3- + 5/4 H+ + e- = 1/8 NH_4+ + 3/8 H_2O; 35 kJ/e-

Net: ¼ CH_2O + 1/8 NO_3- +1/4H+ = ¼ CO_2 + 1/8 NH_4+ + 1/8 H_2O; -82 kJ/e-

Mole basis:

2 {CH_2O} + NO_3^- +2 H^+ = 2CO_2 + NH_4^+ + H_2O

8 e- x -82 kJ/e- = 656 kJ/ 2 CH2O = 328 kJ/CH2O

{$C_6H_{12}O_6$} + 3 NO_3^- +6 H^+ = 6 CO_2 + 3 NH_4^+ + 3 H_2O

6 x 328 = 1968 kJ/glucose

Production of soluble Fe(II)

Oxidation: ¼ CH_2O + ¼ H_2O = ¼ CO_2 + H^+ + e^-, oxidation, -47 kJ/e-

Reduction: FeOOH + 3H+ + e- = Fe++ + 2H2O, log K=11.3 , -5.6 KJ/e-

Net: ¼ CH_2O + FeOOH + 2H+ = 1/4CO2 +7/4 H2O + Fe++; -52 kJ/e-

Mole Basis

CH_2O + 4 FeOOH + 8 H+ = CO2 + 7 H_2O + 4 Fe+ +; 208 kJ/mole

Soluble Iron (Fe(II) production

$C_6H_{12}O_6$ + 24FeOOH + 48 H+ -> 24 Fe++ + 6CO2 + 42 H2O + energy

Fe+++ + e- -> Fe++

Sulfate Reduction

Electron basis

Oxidation: ¼ CH_2O + ¼ H_2O = ¼ CO_2 + H^+ + e^-

Oxidation: 1/8 CH_3OOH + 1/4 H_2O = 1/4 CO_2 + e- + H+

Reduction: 1/8 SO_4-- + 9/8 H+ + e- = 1/8 HS- + ½ H_2O

Net: 1/8 CH_3OOH + 1/8 SO_4-- = ¼ CO_2 + ¼ H_2O = 1/8 HS-

Net: ¼ CH_2O + 1/8 SO_4-- + 1/8 H+ = ¼ CO_2 + ¼ H_2O = 1/8 HS-

Mole basis, carbohydrate

Reduction: SO_4-- + 9 H+ + 8 e- = HS- + 4 H_2O

Oxidation: CH3OOH + 2 H2O = 2 CO2 + 8 e- + 8 H+

Oxidation: 2 CH_2O + 2 H_2O = 2 CO_2 + 8H+ + 8 e-

Net: 2 CH_2O + SO_4-- + H+ = HS- + 2 CO_2 + 2 H_2O
-> H_2S + H+ + HCO_3-

Per mole glucose

8e- x -25 kJ/e- = 200 kJ/(2 CH_2O)

600 kJ/$C_6H_{12}O_6$

Fermentation

Electron basis:

Oxidation: ¼ CH_2O + ¼ H_2O = ¼ CO_2 + H^+ + e^- : -47 kJ/e-

Reduction: ½ CH_2O + H^+ + e^- = ½ CH_3OH: -17 kJ/e-

Net: ¾ CH_2O + ¼ H_2O = ¼ CO_2 + ½ CH_3OH: 30 kJ/e-

Mole basis

Oxidation: CH_2O + H_2O = CO_2 + 4 H^+ +4 e^- : 4 * -47 kJ/e- = -188 kJ

Reduction: 2 {CH_2O} +4 H^+ +4 e^- = 2 {CH_3OH}: 4* -17 kJ/e- = 68 kJ

Net: 3 {CH_2O} + H_2O = CO_2 + 2 {CH_3OH}

4 e- * 30 = -120 kJ/ 3(CH_2O)

Carbohydrate basis, x2 =>

240 kJ/$C_6H_{12}O_6$

Methane Production

- Requires Breakdown of Organic Matter into
- Organic Acids and Alcohols
- Fermenting Bacteria produce Acetate, H2 and CO2 as intermediates
- Archaea use Acetate and H2 as energy sources to produce Methane

Methane Production by CO2 Reduction

Electron basis:

Oxidation: ¼ CH_2O + ¼ H_2O = ¼ CO_2 + H^+ + e^-: -47 kJ/e-

Reduction: 1/8 CO_2 + H^+ + e- = 1/8 CH_4 + ¼ H_2O: -23 kJ/e-

Net: ¼ CH_2O = 1/8 CO_2 + 1/8 CH_4: -24 kJ/e-

Mole basis, 8x:

4 H2 + CO_2 = CH_4 + 2 H_2O

ΔG = 8 e- * -23 kJ/e- = -184 kJ

2 CH_2O = CO_2 + CH_4

ΔG = 8 e- * -47 kJ/e- = -376 kJ

2 {CH_2O} = CO_2 + CH_4

ΔG = -184 - -376 = 192 kJ

Carbohydrate basis, x3

{$C_6H_{12}O_6$} = 3 CO_2 + 3 CH_4: ΔG = 192 kJ * 3 = 576 kJ/$C_6H_{12}O_6$

Anaerobic Methane production via Acetate, Acetotrophic methanogenesis

Reduction: 18 kJ/e- $$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$$

Oxidation: 22 kJ/e- $$CH_3OOH + 2H_2O \rightarrow 2CO_2 + 8e^- + 8H^+$$

Net $$CH_3OOH \rightarrow CO_2 + CH_4$$

ΔG = -38 kJ/e-

Take Home Points, p1

- Chemical Energy, through the flow of electrons, associated with Redox Reactions, and voltage differences, drives Metabolism
- Redox: LEO/GER or OIL/RIG
- PhotoTrophs convert solar energy to chemical energy
- Heterotrophs convert Organic energy to Energy for work and Metabolism
- Redox Ladder determines the amount of Energy Extracted, which depends upon the Terminal Electron Acceptor

ChemoLithoTrophs

They use Inorganic Sources of Energy (minerals) such as:

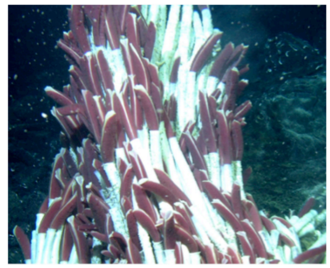
Hydrogen Sulfide

Elemental Sulfur

Ferrous Iron

Hydrogen and Ammonia

Methane (methanotrophs)



Iron Reducing Bacteria

Oxidation: Fe^{++} (Ferrous) -> Fe^{+++} (Ferric) + e^-

Reduction: O_2 + H^+ + e^- -> H_2O

ChemoLithoTroph

Ferrous Oxidation

Electron Basis

Reduction: ¼ O_2 + H^+ + e- = ½ H_20 : 78 kJ/e-

Oxidation: $FeCO_3$ + $2H_2O$ = FeOOH + HCO_3- + 2 H+ + e-: 4.5 kJ e-

G = -(78 + 4.5) = 82.5 kJ/e-

Nitrification

Electron basis:

Reduction: ¼ O_2 + H^+ + e- = ½ H_20 : 78 kJ/e-

Oxidation: 1/8 NH_4^+ + 3/8 H_2O-> 1/8 NO_3- + 5/4 H+ + e-: 35kJ/e-

Net:

Mole basis:

$2O_2$ + 8 H+ + 8 e- = 4 H_2O: 8 e- * 78 kJ/e- = 624 kJ

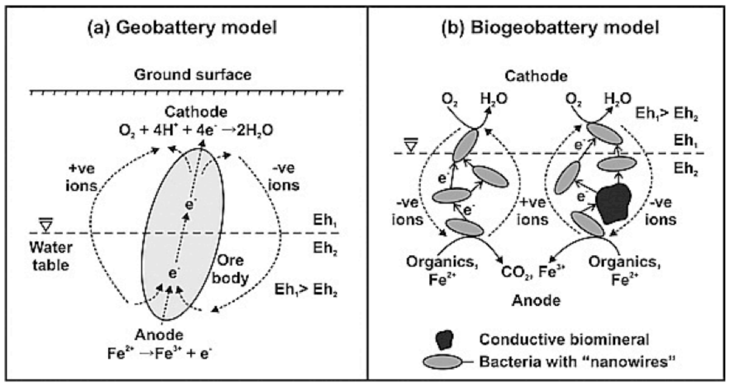
NH_4^+ + $3H_2O$ = NO_3- + $10H^+$ + 8 e^-: 8 e- * 35 kJ/e- = 280 kJ

Net

NH_4^+ + $2O_2$ = H_2O + NO^{-3} + 2 H^+:

ΔG: 624 kJ -280 kJ = 344 kJ

In search of experimental evidence for the biogeobattery



Journal of Geophysical Research: Biogeosciences
Volume 116, Issue G4, G04018, 15 NOV 2011 DOI: 10.1029/2011JG001713
http://onlinelibrary.wiley.com/doi/10.1029/2011JG001713/full#jgrg843-fig-0001

Conceptual models of redox-associated mechanisms for generating self-potentials: (a) classical geobattery model [after *Sato and Mooney*, 1960; *Revil et al.*, 2010] and (b) biogeobattery model [after *Naudet and Revil*, 2005; *Revil et al.*, 2010].

Take Home Points

- Electrons can be extracted from Minerals to power Chemolithotrophs in the absence of organic matter

Theoretical and Potential Photosynthetic Efficiencies

- 8 Photons per CO_2 molecule fixed
- 4 e- released with each water molecule that is split
- 496 kJ/mole CO_2, Energetics of photosynthesis
  - 4 e- times 125 kJ mole e-
- 13%, Maximum Efficiency of sunlight to stored carbon
- 9%, Ideal photosynthetic efficiency
  - Considering photorespiration and leaf absorptance
- 2%, Typical Maximum Efficiency Observed in the field
- Potential Gross Primary Productivity
  - 12 g/mole C * 0.02 mol C/mole quanta * Rg/2 *4.6 (mole quanta m^{-2})
  - 12 * 0.02 * 161/2 * 4.6e-6 * 12*3600*365=1401 gC m^{-2} y^{-1}

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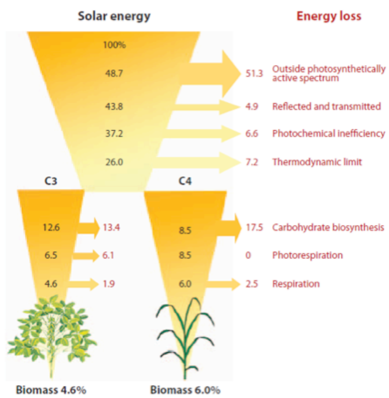
In this lesson we concentrate on the utilization of solar energy at field and farm scales. In essence, how may chemical energy is stored through field photosynthesis given the abundant amounts of energy discussed above? And, how much carbon can be extracted from the atmosphere by these processes?

These calculations are for solar radiation flux density averaged across the Earth's surface, 161 W m-2; simplistic as it is respect to the hemisphere that includes oceans, and does not consider the geographical distribution of land, sunlight and plants

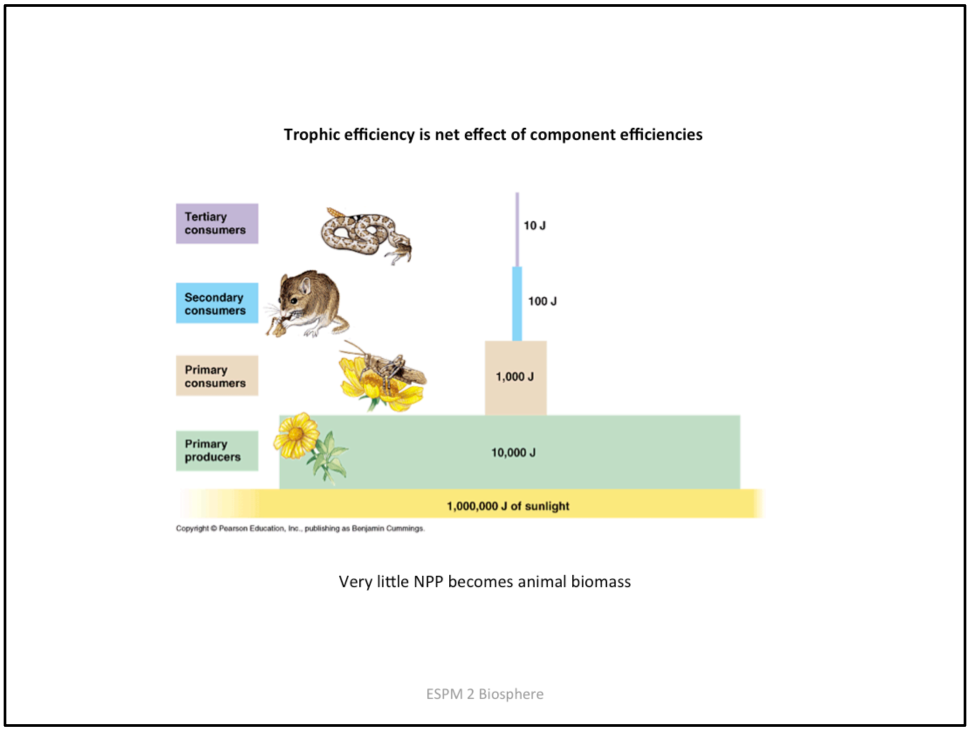
PS Efficiency, adapted from Bolton and Hall 1991

Eating the Sun: Converting Solar Energy to Biomass

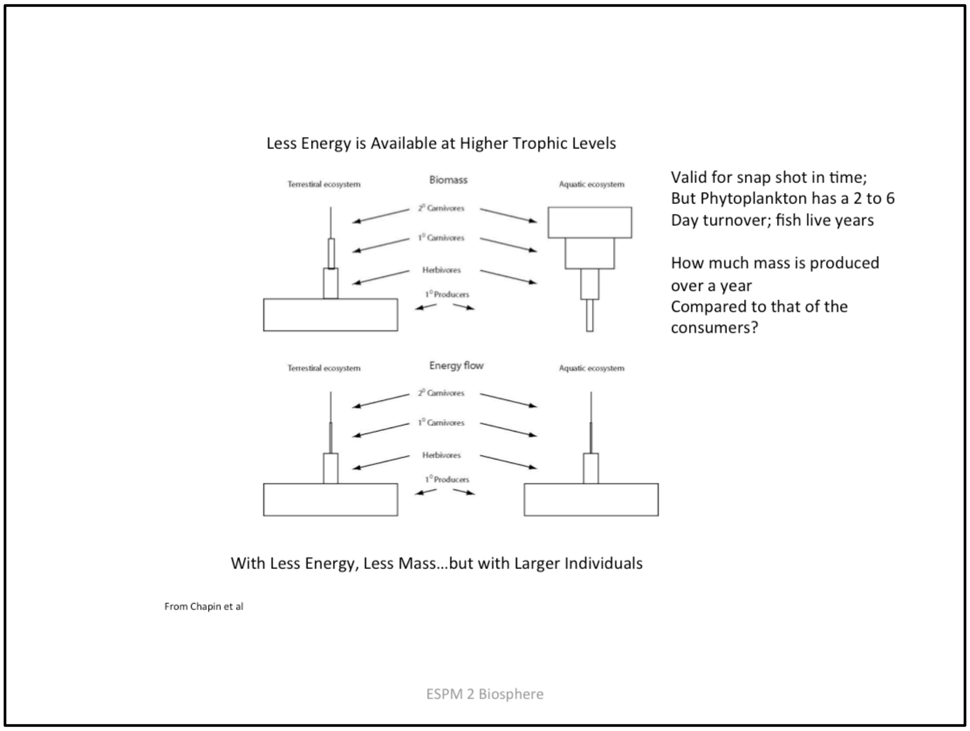


Zhu et al. 2010 Ann Rev Plant Biol

Only a small portion of incident sunlight is actually capture and converted to biomass. Hence, biofuels may be a less efficient alternative to capturing sunlight than solar panels. And this figure ignores the additional loss of respiration due to growth and maintanence.



For 1 MJ of sunlight about 1% of that energy will be produced into the biomass of primary producers. About 1 to 10% of this energy will be used by primary consumers, herbivores, like insects, cattle, grazers, etc. Even less energy is dispensed to secondary consumers who may eat the primary consumers and detritus. Even less energy is left for the tertiary consumers, who may reside at the top of the inverted food pyramid

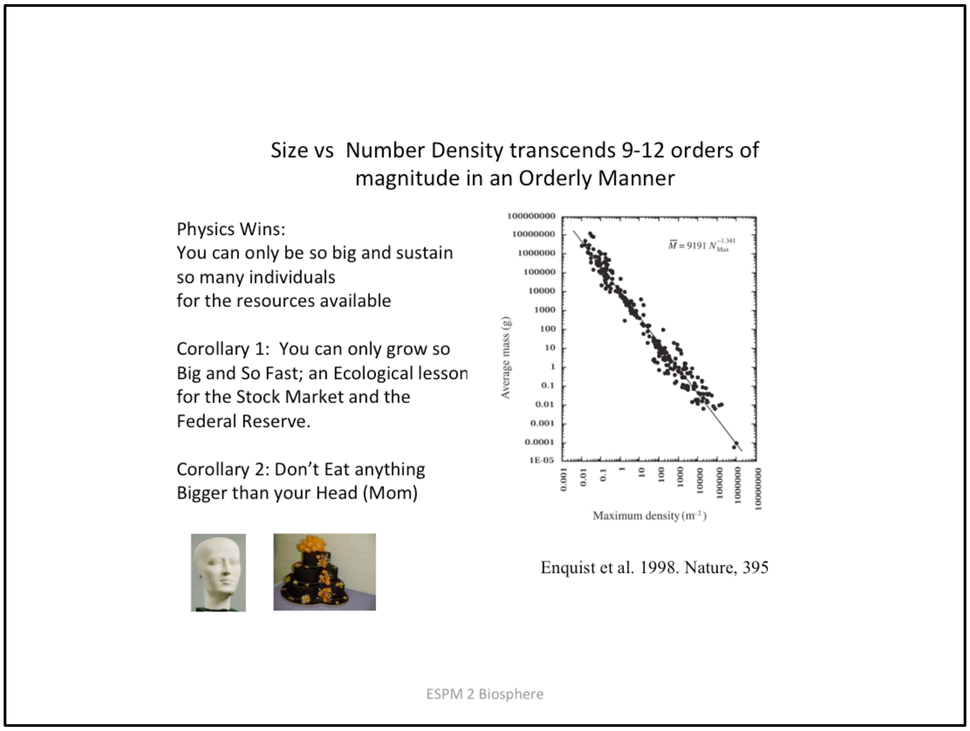


Less and Less energy is available at higher and higher Trophic Levels, Less energy, less mass…but larger individuals.

The classic textbook example of the inverted pyramid for aquatic systems is misleading. The large whales and sharks at the top are actually sustained by large pools of plankton and krill that have short life times and fast turn over (2 to 6 days). It is more appropriate to consider the mass of this primary productive over the course of a year than its mass at a give instant. And it is more appropriate to consider the mass of large carnivores and mass of small primary producers over a large area..then there is coherency between the pyramids of energy and the pyramids of biomass

Global integrated chlorophyll biomass is 4 to 5 Tg.. Phytoplankton turn over every 2 to 6 days! Ocean NPP is ~50 Pg/y

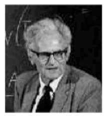
Behrenfeld, M. J., R. T. O/'Malley, D. A. Siegel, C. R. McClain, J. L. Sarmiento, G. C. Feldman, A. J. Milligan, P. G. Falkowski, R. M. Letelier, and E. S. Boss. 2006. Climate-driven trends in contemporary ocean productivity. N



The beauty of complex systems is that aspects of their behavior can be predicted by power laws. So there is 'order' and 'rules' among chaos.

In this case there are only so many individuals sustainable on a plot of land, give a certain size.

You can either have a lot of small individuals or a few large individuals for unit area of land. This is an example of the self-organizing and predictive aspect of complex systems. Predictions follows a power law, with log-log scaling, with a known slope, or power law exponent, in this case -4/3.



Kleiber's Law

Metabolic rate (B) of an organism scales to the 3/4 power of its mass (M)

$$B = M^{3/4}$$

The Metabolic Energy needed to Sustain an organism INCREASES with Mass, to the ¾ power

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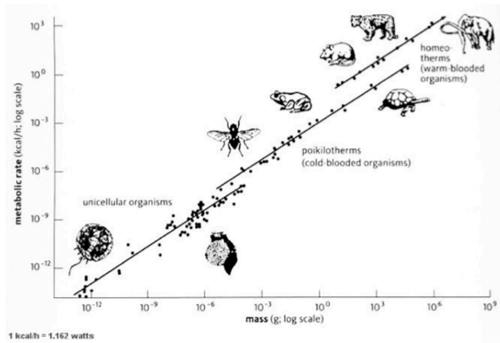
The metabolic energy, B, needed to sustain metabolism scales with the mass of the organism to the ¾ power

Max Kleiber was a zoologist at UC Davis. I took my courses on biology and botany, as an undergrad, in Kleiber Hall. Sadly, I don't recall we were told of his impact on science then.

Basal Metabolic Rate (B) of uni-cellular and multi-cellular organisms scales to the 3/4 power of their mass (M)



http://universe-review.ca/I10-83-metabolic.jpg

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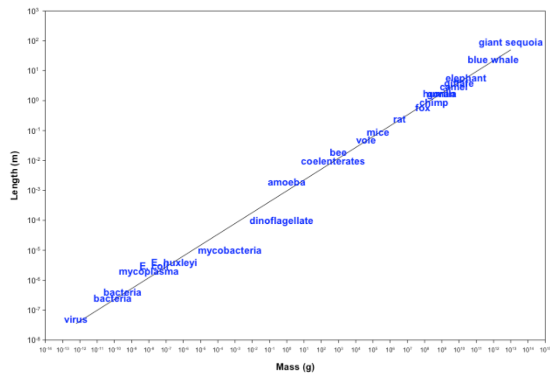
Example of the ‘Universality’ of Kleiber’s law over 21 orders of magnitude of mass

Size of Organisms Scales with Mass according to ~1/3 Power Law



adapted from Smil (2002)

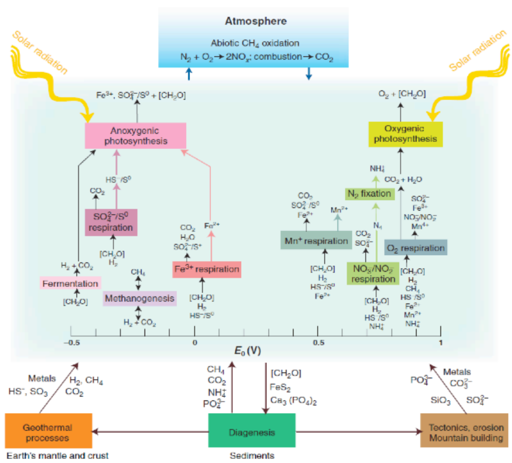
Example of the mutual constraints of size and mass, only large things can have much mass

Microbes make the BioGeoChemical Cycles Revolve

'bacteria are astonishingly good at finding energy that will let them make a living. More or less everywhere the earth brings together substances with different redox potentials, there's a bacterium that knows how to take advantage of the situation by passing electrons from one to the other and skimming off energy as it does'.

Oliver Morton, 2008 Eating the Sun: How Plants Power the Planet

(Falkowski et al., 2008)



Summary:

1.Chlorophyll is a light-absorbing plant molecule while chloroplasts are plant organelles.
2.Chlorophyll paves the way for light to create the process of photosynthesis, at the same time, it is the chloroplasts that organize and conduct the whole process.
3.Chlorophyll has two kinds. Chloroplasts have no kinds.
4.Chlorophyll enables the green pigment in plants while chloroplasts are colored green because of the chlorophyll.
5.Aside from the green pigment, chlorophyll also has carotenoids, which are red and yellow pigments. Chloroplasts do not produce pigments at all.
6.Chloroplasts are found in great concentrations in the plant's leaves. Chlorophylls are found inside the chloroplasts.
7.Chlorophylls are part of the chloroplasts while chloroplasts are part of the plant cell

Redox Equations for Life

	Reductions	Pe^0 (Water@pH=7) = log(K)	Eh(mv) = RT ln K/nF	$\Delta G = E_h\, nF$ kJ/e-
A	$\frac{1}{4} O_2 + H^+ + e^- = \frac{1}{2} H_20$	13.75	809	78
B	$1/5\ NO_{3-} + 6/5\ H^+ + e^- = 1/10\ N_2 + 3/5\ H_2O$	12.65	744	72
C				
D	$1/8NO_3- + 5/4\ H^+ + e^- = 1/8\ NH_4+ + 3/8\ H_2O$	6.15	362	35
E				
F	$\frac{1}{2} CH_2O + H^+ + e^- = \frac{1}{2} CH_3OH$	-3.01	-177	-17
G	$1/8\ SO_4^{--} + 9/8\ H^+ + e^- = 1/8\ HS^- + \frac{1}{2} H_2O$	-3.75	-221	-21
H	$1/8\ CO_2 + H^+ + e^- = 1/8\ CH_4 + \frac{1}{4} H_2O$	-4.13	-243	-23
J	$1/6\ N_2 + 4/3\ H^+ + e^- = 1/3\ NH_4^+$	-4.68	-275	-26.7
	Oxidation	Pe0 (Water @ pH=7) = -log(K)		
L	$\frac{1}{4} CH_2O + \frac{1}{4} H_2O = \frac{1}{4} CO_2 + H^+ + e^-$	-8.20	-482	-46.7
L1	$\frac{1}{2} HCOO- = \frac{1}{2} CO_2 + \frac{1}{2} H^+ + e^-$	-8.73	-513	-49.7
L2	$\frac{1}{2} CH_2O + \frac{1}{2} H_2O = \frac{1}{2} HCOO- + 3/2\ H^+ + e^-$	-7.68	-452	-43.8
L3				
L4	$\frac{1}{2} CH_4 + \frac{1}{2} H_2O = \frac{1}{2} CH_3OH + H^+ + e-$	2.88	169	16.4
M	$1/8\ HS- + \frac{1}{2} H_2O = 1/8\ SO_4^{--} + 9/8\ H^+ + e^-$	-3.75	-221	-21.4
N				
O	$1/8\ NH_4+ + 3/8\ H_2O => 1/8\ NO^{-3} + 5/4\ H^+ + e-$	6.15	-362	35
P				

Derived from Strumm and Morgan

	Redox Potential (mv)	Energy Release kJ (mole e-) $^{-1}$	Energy Release (Kcal/mol/e-)
Reduction of O_2			
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	812	125	-29.9
Reduction of NO_3^-			
$NO_3^- + 2H^+ + 2e^- \rightarrow NO_2^- + H_2O$	747	119	-28.4
Reduction of Mn^{4+} to Mn^{2+}			
$MnO_2 + 4H^+ + 2e^- \rightarrow Mn^{2+} + 2H_2O$	526	-97	-23.3
Reduction of Fe^{3+} to Fe^{2+}			
$Fe(OH) + 3H^+ + e^- \rightarrow Fe^{2+} + 3H_2O$	-47	42.2	-10.1
Reduction of SO_4^{2-} to H_2S			
$SO_4^{2+} + 10H^+ + 8e^- \rightarrow H_2S + 4H_2O$	-221	24.6	-5.9
Reduction of CO_2 to CH_4			
$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$	-244	-23	-5.6

From Schlesinger's book