ENERGY & ECOSYSYEM ECOLOGY

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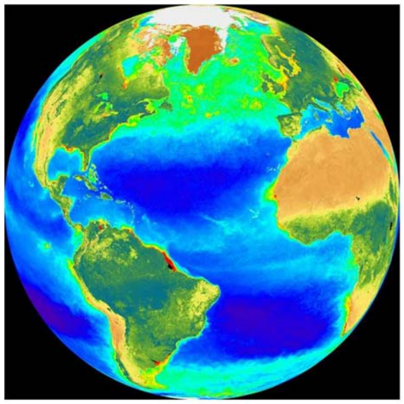

Energy is the currency of life and is the currency that drives the metabolism of ecosystems.

Overview

- Concepts and Units of Work and Energy
- Solar Energy
  - How Much, When and Where
- Net Radiation Balance
  - shortwave and longwave energy
- Energy Partitioning
  - Sensible and Latent Heat Exchange
- Radiation Transfer through Vegetation

'Our bodies are stardust;
Our lives are sunlight'

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

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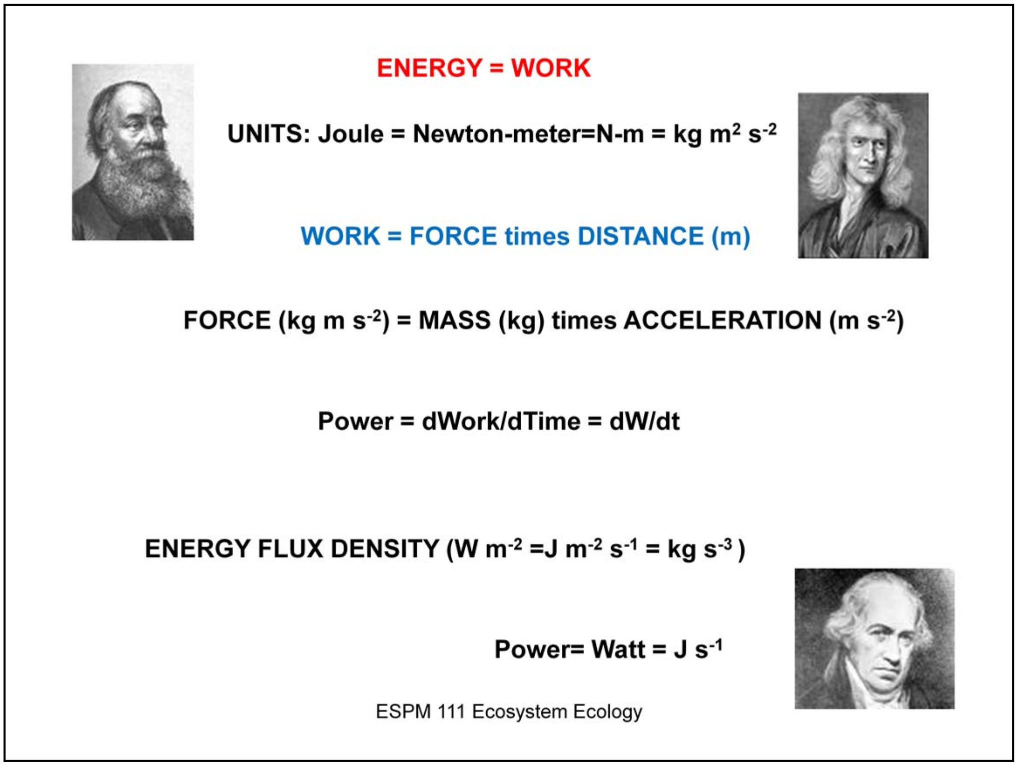
Our lives and the world around us functions with energy, most coming from the sun.



To understand energy, we need to understand the units. To understand the units we must understand the physics and terms. So with this information in hand, we can always remember the units of energy, as ideas of force and its derived variable work, are intuititve.

First Law of Thermodynamics:

- The **change in internal energy** (ΔU) is a function of the change in the amount of **heat** absorbed or lost (ΔQ) and the change in amount of **work** done on the system (ΔW)

$$U_2 - U_1 = \Delta U = \Delta Q + \Delta W$$

  - *Energy cannot be created, nor destroyed; it can only be transferred from one state to another.*
  - *The total amount of energy in a closed system is constant*
  - *Life and Ecosystems are Open Systems*

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Why are work and energy important? They are part of the first laws of thermodynamics. Just like an English major should know Shakespeare, a scientist should know the laws of thermodynamics.

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 is Reduced and gains Electrons, so it is also the Electron Acceptor, e.g. O_2 and SO_4--

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

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.

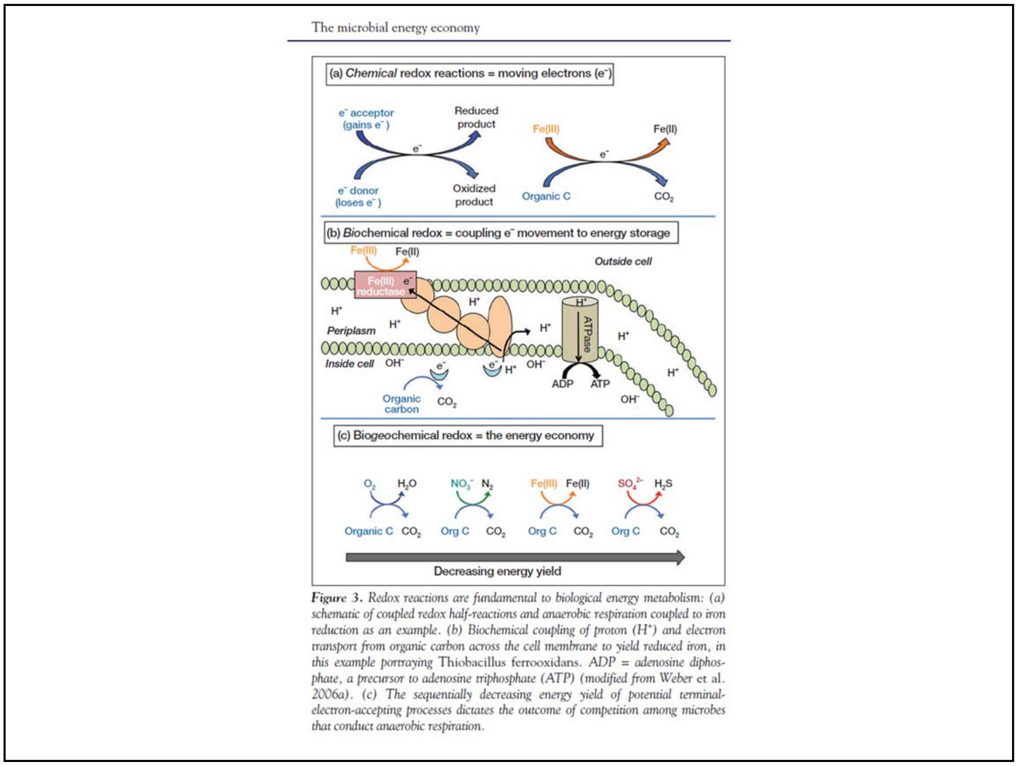

Figure 3. Redox reactions are fundamental to biological energy metabolism: (a) schematic of coupled redox half-reactions and anaerobic respiration coupled to iron reduction as an example. (b) Biochemical coupling of proton (H^+) and electron transport from organic carbon across the cell membrane to yield reduced iron, in this example portraying Thiobacillus ferrooxidans. ADP = adenosine diphosphate, a precursor to adenosine triphosphate (ATP) (modified from Weber et al. 2006a). (c) The sequentially decreasing energy yield of potential terminal-electron-accepting processes dictates the outcome of competition among microbes that conduct anaerobic respiration.

This paper and schematic by Whendee's colleague is a great primer on the flows of electrons and the energy that flows from organic matter, that is stored energy from the sun. Burgin et al 2011 Frontiers Ecology

Nerst Equation

Computes Redox Cell Potential

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

(voltage, or Electromotive Force)

Gibbs Free Energy, ΔG

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

n is charge number
F is Faraday constant, 96.84 kJ per volt gram equivalent

The microbial energy economy

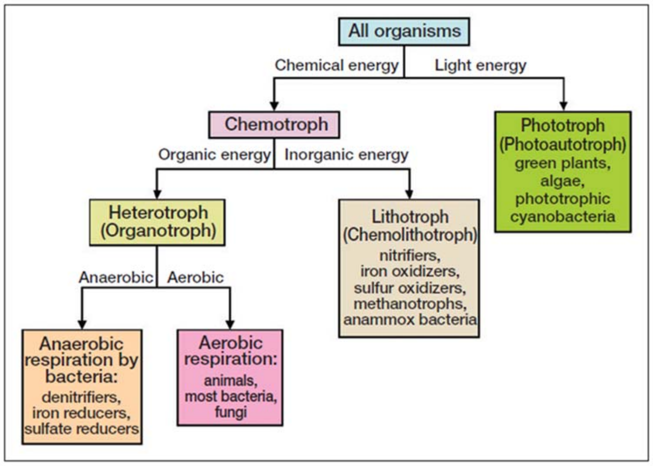

Figure 1. *Classification of organisms based on their primary source of energy reveals the metabolic diversity of microbes as compared with that of higher plants and animals. Other forms of anaerobic microbial metabolism (eg fermentation) exist but are not included here.*

Burgin et al 2011 Frontiers Ecology

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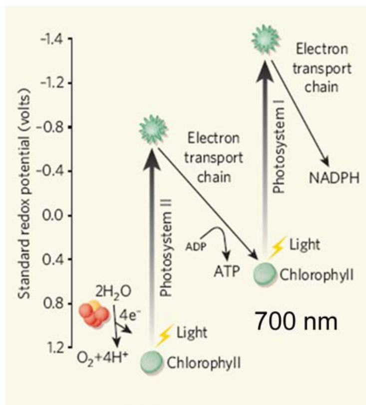
While most energy is consumed by photo-autotrophs in the form of sunlight, microbes are adroit at extracting chemical energy in their environment using stored energy in the form of organic matter, or via inorganic pathways by exploint redox potentials.

Burgin et al 2011 Frontiers Ecology

Solar Energy Produces Chemical Energy Used by Life

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



680 nm

Allen and Martin, 2007 Nature

- Light Energy (400 to 700 nm) is absorbed by pigments
- This energy splits water and releases 4 electrons, e-
- These Electrons produce biochemical energy compounds, ATP and NADPH
  - 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).
- 8 Photons per CO_2 molecule are fixed
- Excess energy is lost as heat or fluorescence.

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The sun's energy is captured through the light reactions of photosynthesis.

Aerobic Respiration of CarboHydrates Produce Energy for Life

CarboHydrate is an electron donor

$CH_2O \Rightarrow C^{4+} + 4\ e^- + H_2O$

Oxygen is an electron acceptor

$O_2 + 4e^- + 4H^+ \Rightarrow H_2O + \text{energy}$

Change in Gibbs free Energy, $\Delta G = -125\ \text{kJ mole}^{-1}\ e^-$

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	$1/8 NO_3- + 5/4\ H^+ + e^- = 1/8\ NH_4+ + 3/8\ H_2O$	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	$1/8\ NH_4+ + 3/8\ H_2O \Rightarrow 1/8\ NO^{-3} + 5/4\ H^+ + e-$	6.15	-362	35
P				

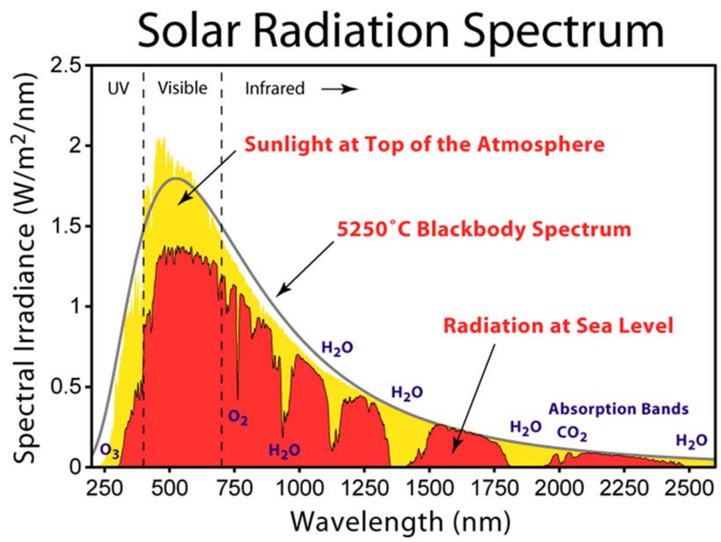
Derived from Strumm and Morgan

Energy Yields from CarboHydrates

		E(red)-E(ox)	ΔG kJ e^- eq^{-1}	Energy, kJ
Aerobic respiration	A + L	-(78 - -47)	-125	3000 kJ/mole $C_6H_{12}O_6$
Denitrification	B + L	-(72 - -47)	-119	2856 kJ/ mole $C_6H_{12}O_6$
Nitrate reduction	D + L	-(35 - -47)	-82	
Fermentation	F + L	-(-17 - -47)	-30	240 kJ/mole $C_6H_{12}O_6$
Sulfate reduction	G + L	-(-21 - -47)	-25	
Methane fermentation	H + L	-(-23 - -47)	-24	576 kJ/ mole $C_6H_{12}O_6$
N fixation	J + L	-(-27 - -47)	-20	
Sulfide oxidation	A + M	-(78 - -21)	-100	
Nitrification	A + O	-(78 – 35)	-43	344 kJ/mole NH_4^+

Solar Facts

- Solar Constant: 1366 W m^{-2}
- Solar Radiative Temperature: 5770 K



http://www.globalwarmingart.com/images/4/4c/Solar_Spectrum.png

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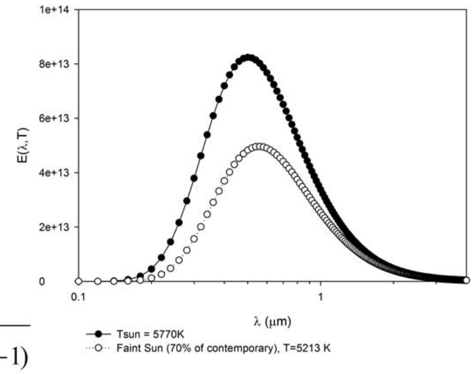
The solar spectrum defines the amount of energy emitted by the sun across a range of wavelengths. Most energy received at the Earth's surface ranges between the ultraviolet (250 nm), through the visible (400-700 nm) and out to the near infrared (700-3000 nm). The peak wavelength is in the blue region and the shape of this spectrum is a function of the Sun's surface temperature

Planck's Law



$$\frac{dE(T,\lambda)}{d\lambda} = E^*(\lambda,T) = \frac{2\pi hc^2}{\lambda^5(\exp(\frac{hc}{\lambda kT})-1)}$$

k is the Boltzmann constant, 1.381 10^{-23} J molecule^{-1} K^{-1}

h is Planck's constant, 6.626 10^{-34} J s

c is speed of light, 2.99972 * 10^8 m s^{-1}

Planck's Law defines the spectral distribution of energy emitted by any black body and is a function of its surface temperature and the wavelength.

Distribution of Solar Energy by Waveband: Color is a function of the Black Body Temperature

Waveband (nm)	Energy %	
0-300	1.2	
300-400, ultra-violet	7.8	SUNBURN
400-700, visible/PAR	39.8	PHOTOSYNTHESIS
700-1500, near infrared	38.8	SUNSTROKE/ OVERHEATING
1500 to infinity	12.4	Heat Emission

Monteith and Unsworth

Shorter wavelengths have more energy, hence Ultraviolet light causes skin cancer and sunburns. The co-evolution of the production of oxygen via photosynthesis, enabled the ozone layer to form a protective layer and enhanced the evolution of higher forms of life.

LONGWAVE ENERGY EMISSION
is a Function of Temperature to the 4th power

$$L^{\uparrow} = \varepsilon\sigma T_k^{\ 4}$$

Area under the Curve of Planck's Law

$$\int E(\lambda, T)d\lambda = L = \sigma T^4$$

σ is the Stefan-Bolztmann constant, 5.67 10^{-8} W m^{-2} K^{-4}.

ε is emissivity, 0 to 1; ε~ 0.98 for leaves

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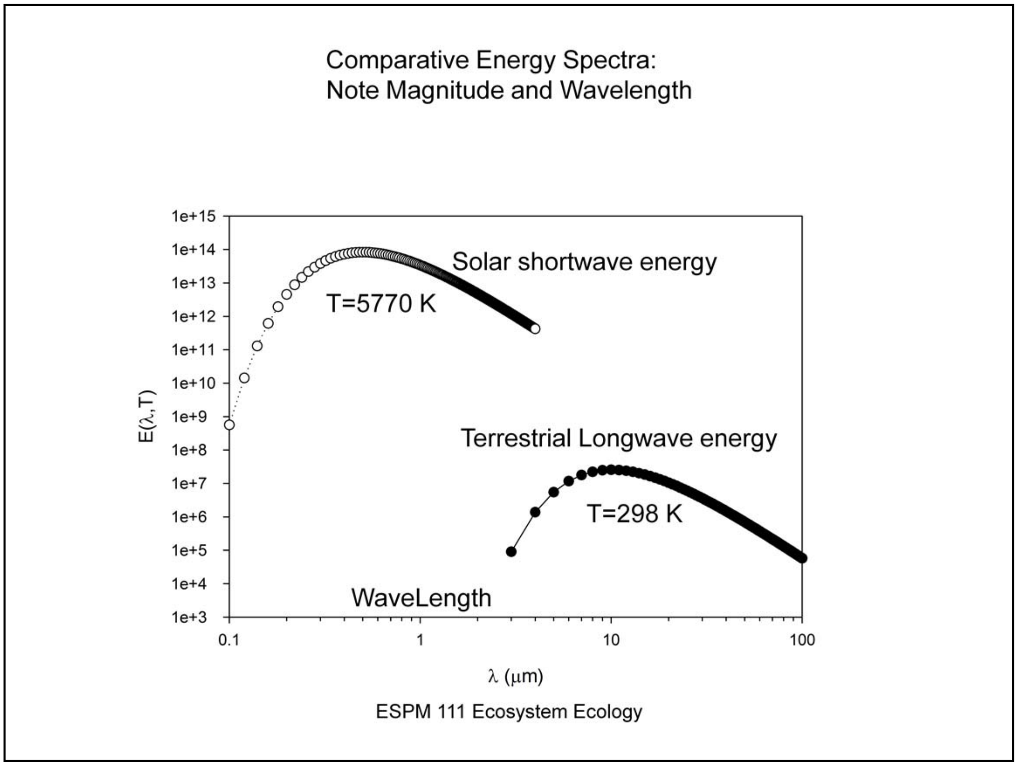
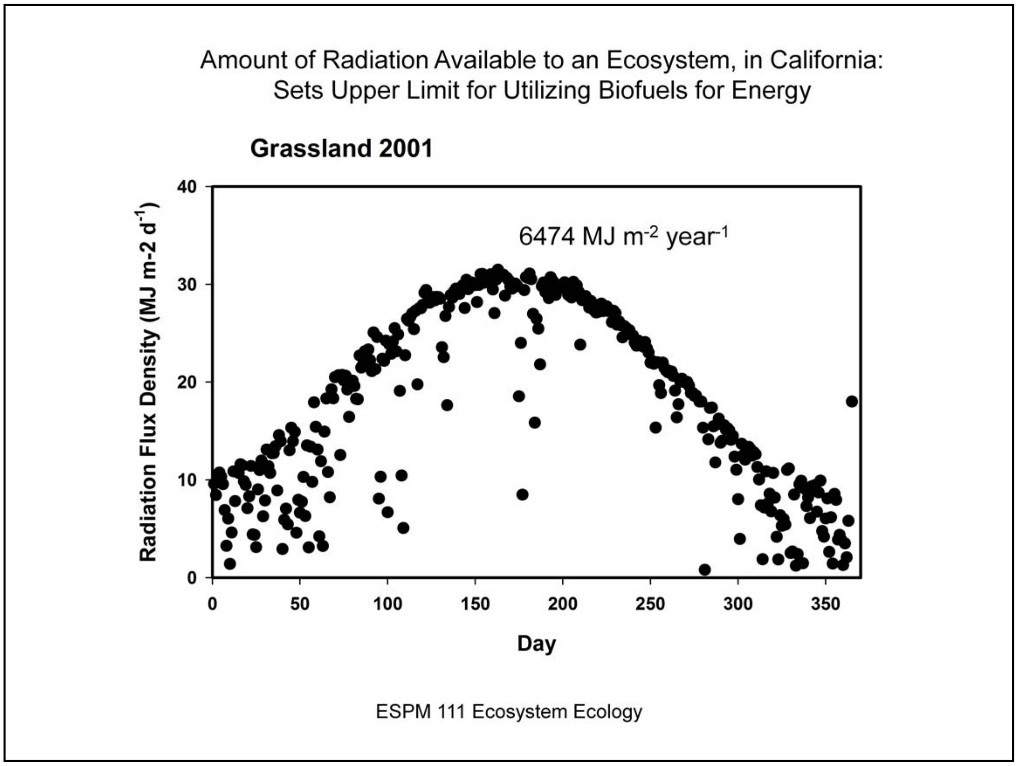
Integration of Planck's law with respect of wavelength yields the amount of energy under the curve. It simplifies to the Stefan Bolzmann law which says the amount of energy emitted is a function of the surface temperature to the 4th power..Here is a highly non linear function, one that has a profound effect on the surface energy balance of an organism, including you!



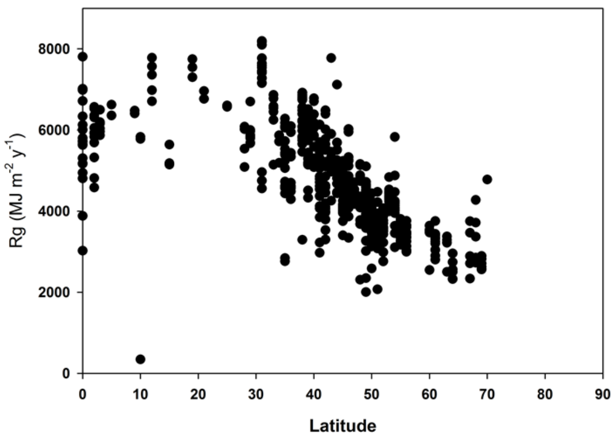
The earth is at a much cooler temperature than the sun, so its spectrum is shifted towards longer wavelengths and the spectral density at a given wavelength is low. The earth emits long wave, infrared energy. This energy also corresponds to wavelengths absorbed and re emitted by many greenhouse gases, like CO2, CH4, N2O, enabling a warm surface and liquid water for life.



How much energy does an ecosystem receive. At my field sites, and across Fluxnet, we measure incident solar energy. Near Ione, we measure over 6000 MJ m-2 y-1 of sunlight per year.

Energy Drives Metabolism:
How Much Energy is Available and Where

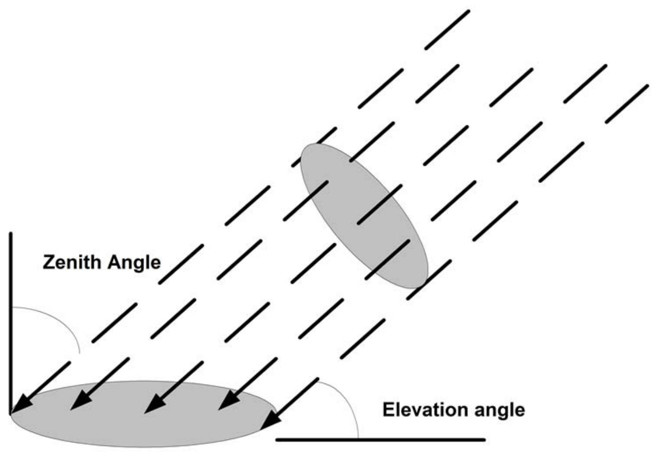
FLUXNET database



Solar Radiation Decreases with increaseing Latitude,
except near the Tropics due to Clouds

The amount of sunlight received is a strong function of latitude. Why may this happen? And if it is a function of latitude why may there be less sunlight at the tropics and equator?

The radiation normal to a surface is a function of the projection of area normal to incident rays on a flat surface: Lambert's Cosine Law



Sunlight is directional, hence the observation of microclimates. So the incident amount of sunlight on a flat plane is a function of the cosine of the solar zenith angle, or the sine of the solar elevation angle.

- Net Radiation (Rn) is comprised of the balance between incoming and outgoing Solar (shortwave, Rg) and Terrestrial (Longwave) Radiation (L)

$$R_n = (1 - \overline{\alpha})R_g + L\downarrow - L\uparrow$$

$$R_n = (1 - \overline{\alpha})R_g + \varepsilon L\downarrow - \varepsilon\sigma T_s^4$$

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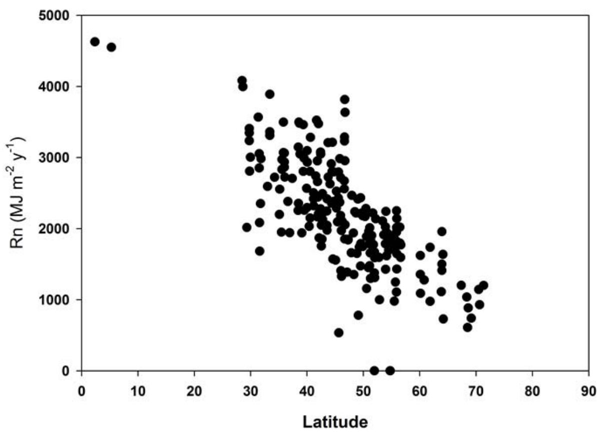
The energy balance is a KEY concept of ecosystem ecology, as well as biometeorology. Do understand the differences between incoming solar radiation and incoming and outgoing Longwave or terrestrial energy.

Net Radiation Budgets across the Globe: Affected by Vegetation, Albedo, Surface and Air Temperature

FLUXNET database



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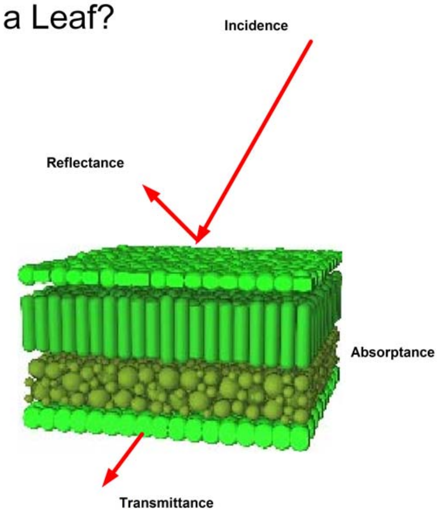
What Happens to Photons Hitting a Leaf?

Absorption + Reflectance + Transmission = 1

$$\alpha(\lambda) + \rho(\lambda) + \tau(\lambda) = 1$$



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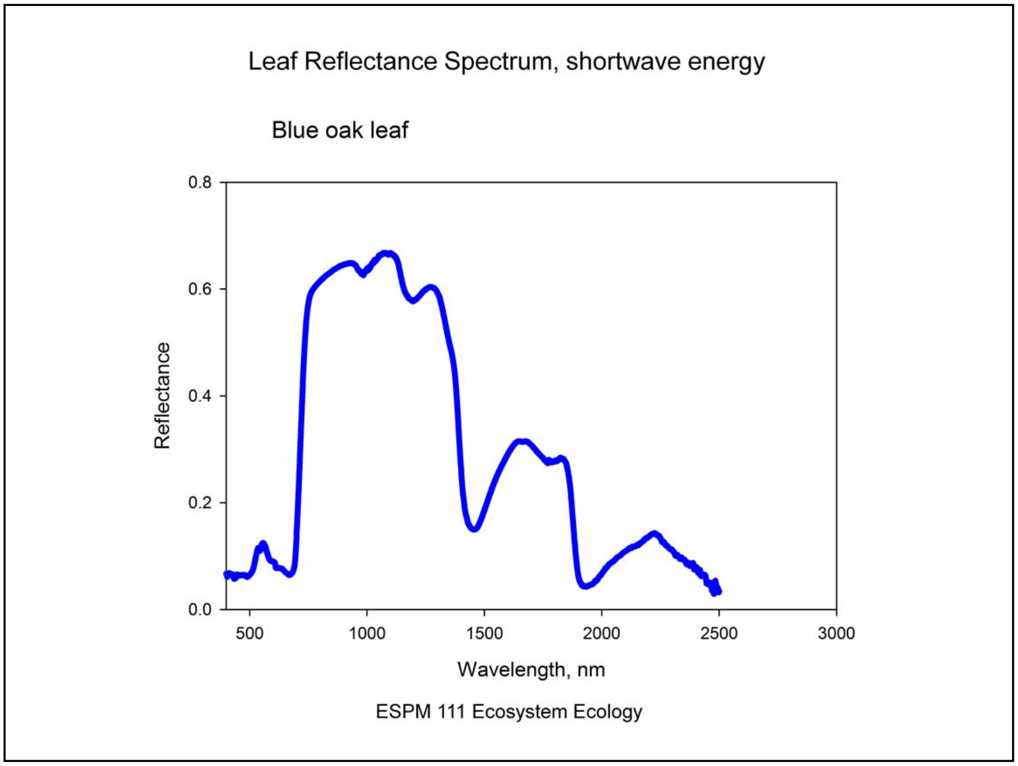
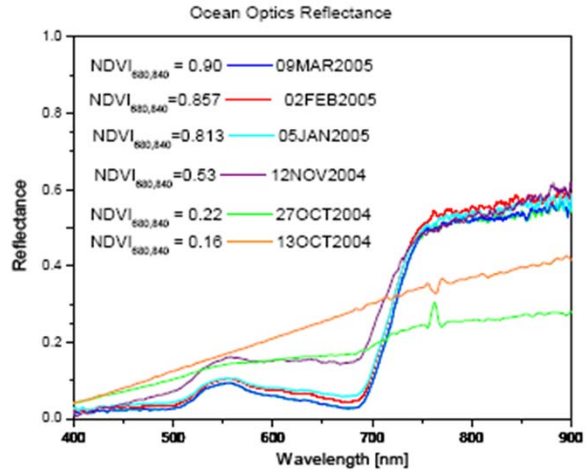
Photons are either absorbed, reflected or transmitted by a leaf. The ratios add to one and are dependent upon wavelength of the light. Leaves are darker in the visible as they use that energy for photosynthesis. They are highly reflective in the near infrared as they want to reduce their heat load.



Classic spectrum of an oak leaf. Leaves are darker in the visible as they use that energy for photosynthesis. They are highly reflective in the near infrared as they want to reduce their heat load.

Reflectance spectra of an annual grassland



Data collected by M. Falk, Ma, Baldocchi

The spectral reflectance of a landscape varies with time with physiological activity and the abundance of green leaf material.

Planetary ALBEDO

Earth ~ 30%

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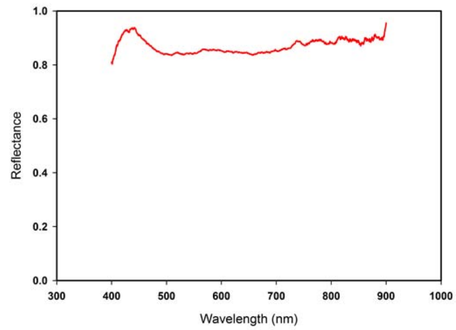
At the landscape and global scale we also are concerned with albedo, the reflectance of the surface with regards to incoming solar energy

The Real 'ALBEDO'



His Spectral Reflectance

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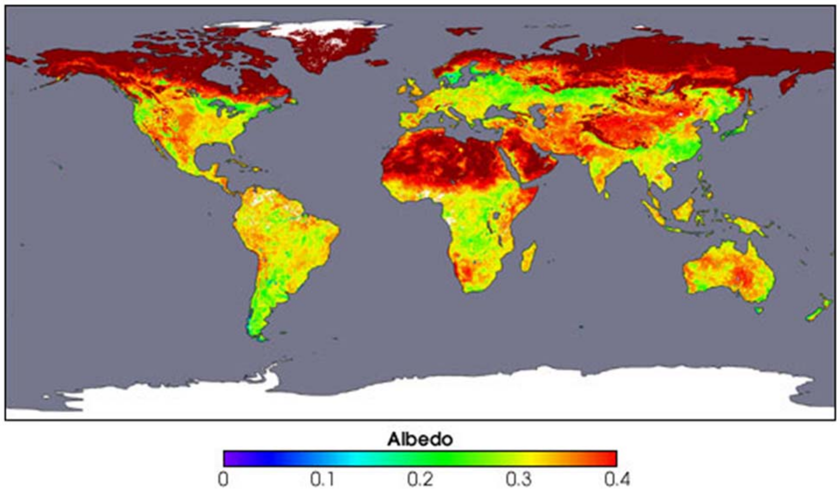
Love the word Albedo and convinced my wife to name our late puppy Albedo. A Maltese/Bichon mix, he was truly reflective; note he has been replaced with a highly reflective puppy named Tule Fog and her darker brother Zephyr, a King Charles-Coton de Tulear mix.

GLOBAL ALBEDO



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Albedo varies globally with season and type of vegetation.

Vegetation Albedo differs with Canopy Structure

Dark, Old Growth Redwoods and Brighter Logged and Regrowth Patches

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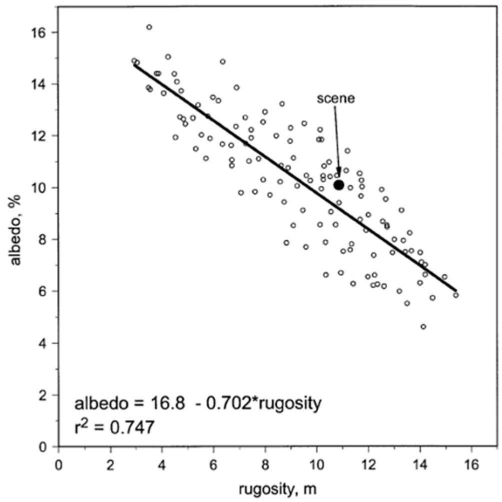
Orick, CA

Tall primal forests are dark. Secondary forests are much brigher.

Tall, Rough, Forests Trap more Sunlight:
Douglas fir Forest, Pacific Northwest



Ogunjemiyo et al., 2005

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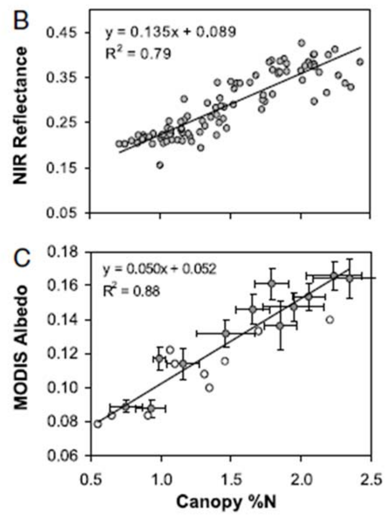
Tall forests in the northwest possess some of the lowest albedos in the world, below 6%

Albedo varies with canopy Nutrition



Ollinger et al. 2008 PNAS

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Albedo can vary with nutrition. This work is controversial, but it is functional.

Snow Reflectance Differs with the Presence and Absence of Trees

Notice the dark spots from the interception of light by the boreal forest, even though the landscape is covered with snow, a larger scale example of the one demonstrated in the previous figure

http://modland.nascom.nasa.gov/gallery/?JamesBay.A2000055.1645.1110x840.jpg

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Snow is bright, but boreal forests are darker than previously thought because they stick up above the snow

Radiation Budget

$$R_n = H + \lambda E + G + S + P_s$$

- Net Radiation is partitioned into
  - Sensible Heat Exchange (H)
  - Latent Heat Exchange (λE)
  - Soil Heat Exchange (G)
  - Heat Storage in the Air and Vegetation (S)
  - Photosynthesis (Ps)

Units: J m^{-2} s^{-1} = W m^{-2}

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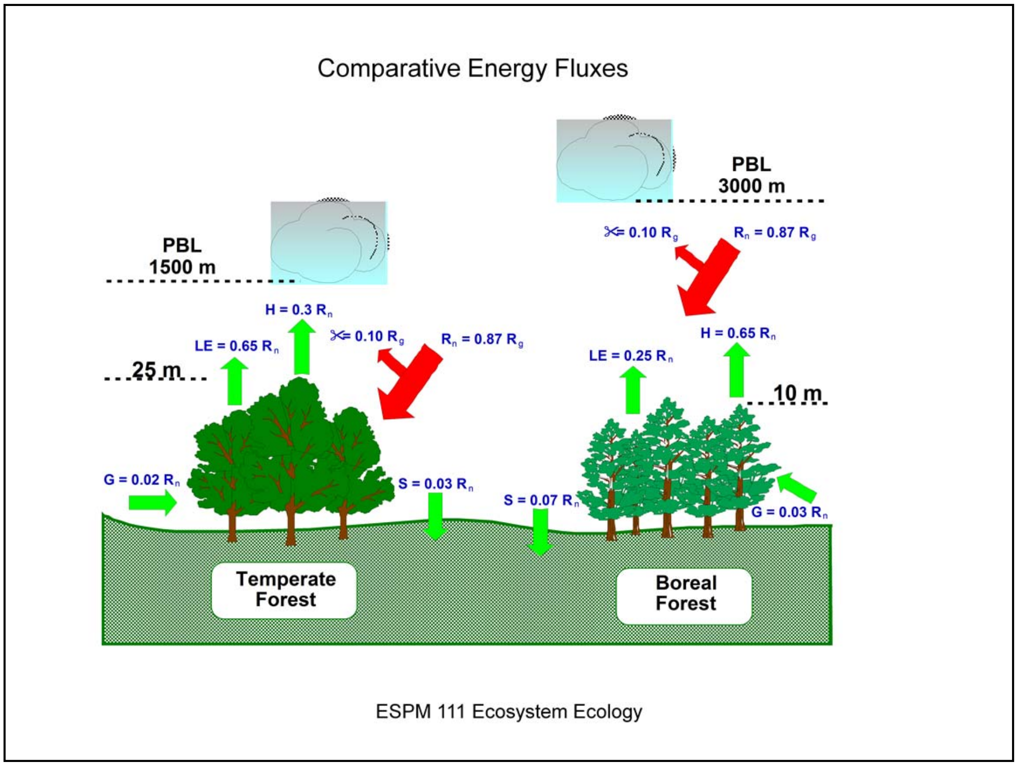
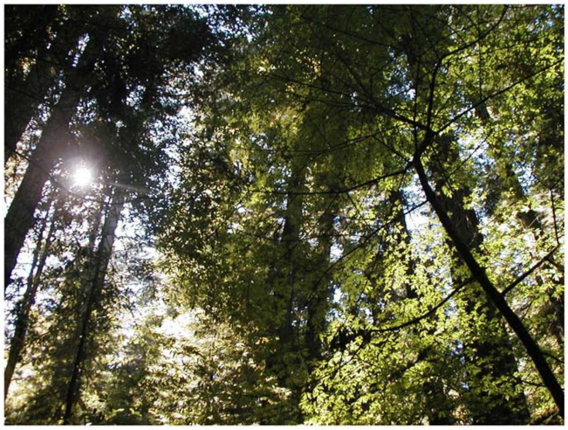
What happens to net radiation? It drives evaporation in the form of latent heat exchange, heats the air in the form of sensible heat exchange and warms the soil and plants through heat conduction. Less then 2% drives photosynthesis.



The energy balance of landscapes differ from one another. These are figures derived from studies I produced in the 1990s over boreal forest in Canada and an oak forest in Tennessee

Light transmission through a forest canopy

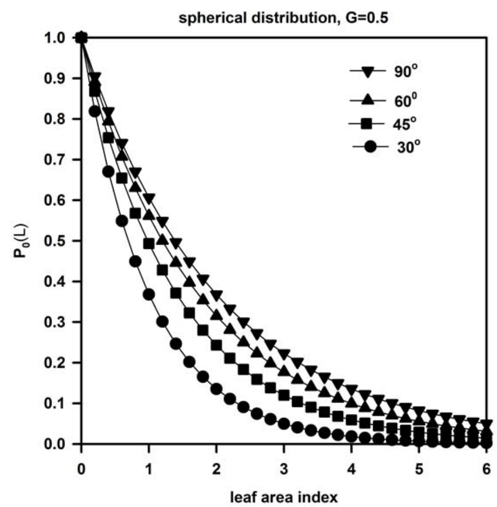


Sunlight passing through gaps comes from the sun and from the sky. Leaves intercept, absorb, reflect and transmit light. This causes complementary radiation

Pt. Reyes National Seashore, Allomere Falls trail, August 2002

We need to know about how light is transmitted through vegetation to illuminate leaves at different layers.

Sun Angles and the probability of beam penetration, P_0



Beer's Law

$$P_0 = \exp(-kL)$$

$$P_0 = \exp(-\frac{LG}{\cos\theta_{sun}}) = \exp(-\frac{LG}{\sin\beta_{sun}})$$

L: Leaf area Index
G: direction cosine, leaf normal vs solar zenith angle

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Beers law is a powerful idea on the probability light will transmit through vegetation. It is a function of leaf area index, the angle of the sun and the angle of the leaves.

Gap Fraction, Probability of Beam Penetration, P_0

Patterns of Sunflecks, Umbra and Penumbra

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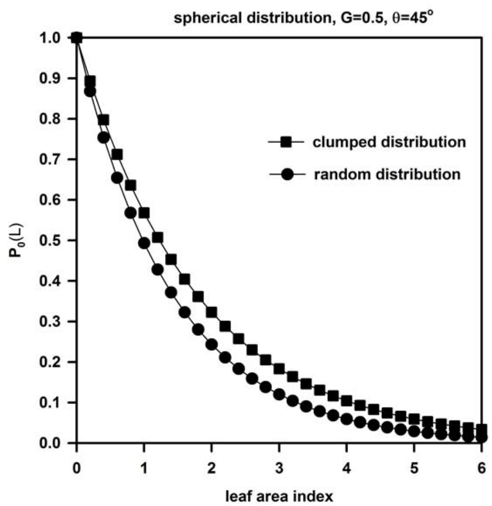
We use statistical theory to model light transmission

Probability of beam penetration with clumped and randomly distributed foliage



Ecology

Beer's Law

$$P_0 = \exp(-kL)$$

$$P_0 = exp\left(-\frac{L\,G\Omega}{\sin\beta}\right)$$

Ω, clumping coef

Points To Ponder

- How much Energy is Available to a square meter of soil over a Year?
- How does this integrate over the area of the State or Nation?
- How does this number compare with the Energy we use to travel, heat our homes, produce our food and fiber and support our recreation?
- Change Land Use Change, with a change in Albedo, function as a way to offset Global Warming?

US uses 105 EJ per year; EJ is 10^18 J

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 using Annual Average Sunlight
  - 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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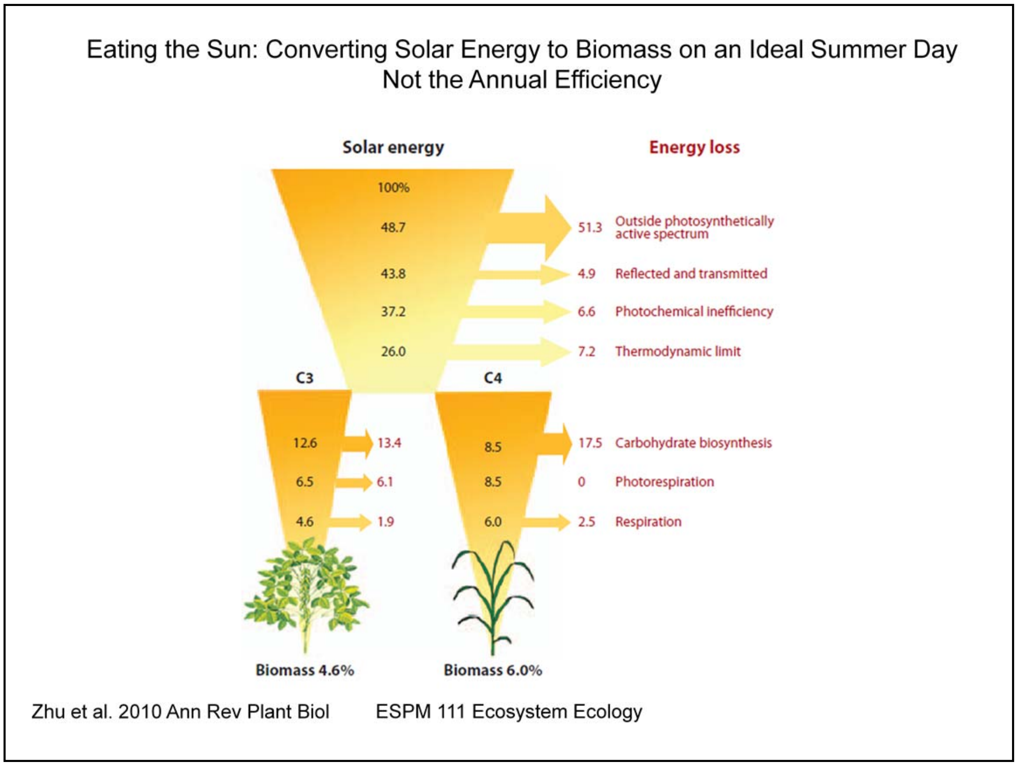
PS Efficiency, adapted from Bolton and Hall 1991



Not all incident energy is used. There are losses and inefficiencies through the energy cascade between intercepted energy and the biomass produced, and how that biomass is consumed by other trophic levels

How Does Energy Availability Compare with Energy Use?

- US Energy Use: 105 EJ/year
  - 10^{18}J per EJ
  - 3.5 10^{11} J/capita/year
- US Land Area: 9.8 10^{6} km^2=9.8 10^{12} m^2
- Energy Use per unit area: 1.07 10^{7} J m^{-2}
- Potential, Incident Solar Energy: 6.47 10^{9} J m^{-2}
  - Ione, CA
- A solar system (solar panels, biomass) must be 0.1% efficient, working year round, over the entire surface area of the US is needed to capture the energy we use to offset fossil fuel consumption
  - Alternatively, a 1% efficient system, on 10% of the surface area, will provide US Energy, assuming available water and not considering energy inputs to drive the system

Oxidized ⟶ Reduced

Oxidized ↑ Reduced	H_2O/O_2	C	N	S
H_2O/O_2	X	Photosynthesis $CO_2 \longrightarrow C$ $H_2O \longrightarrow O_2$		
C	Respiration $C \longrightarrow CO_2$ $O_2 \longrightarrow H_2O$	X	Denitrification $C \longrightarrow CO_2$ $NO_3 \longrightarrow N_2$	Sulfate reduction $C \longrightarrow CO_2$ $SO_4 \longrightarrow H_2S$
N	Heterotrophic nitrification $NH_4 \longrightarrow NO_3$ $O_2 \longrightarrow H_2O$	Chemoautotrophy (nitrification) $NH_4 \longrightarrow NO_3$ $CO_2 \longrightarrow C$	Anammox $NH_4 + NO_2 \rightarrow N_2 + 2H_2O$	?
S	Sulfur oxidation $S \longrightarrow SO_4$ $O_2 \longrightarrow H_2O$	Chemoautotrophy (sulfur-based photosynthesis) $S \longrightarrow SO_4$ $CO_2 \longrightarrow C$	Autotrophic denitrification $S \longrightarrow SO_4$ $NO_3 \longrightarrow N_2/NH_4$	X

Figure 2. *Coupled biochemical metabolisms. Each cell in the matrix is defined by one chemical element in the row that is oxidized, coupled to an element from the column that is reduced. From an original concept by Morowitz (1968), updated from Schlesinger (1997).*

Schlesinger et al 2011 Frontiers Ecology

Volts <<=>> Energy

Ohm's Law

Current = Volts/Resistance, I = V/R

Power = Current * Current * Resistance, I^2 R

Power=dW/dt = Volts * Current, V * I

Gibbs Free Energy: ΔG =- E' n F (kJ mole-1);

E, voltage from Nerst Equ; n: charge; F: Faraday Const. 96 kJ per volt gram eq