Studying the Biosphere, part 2

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ESPM 2

The Biosphere, Fall 2017

12/2/17

How to Measure the Biosphere?
Tool box of the Biosphere Scientist

- Principles/Methods
  - Hierarchal Scaling Studies
    - Cell, Organ, Organism, System
  - Scientific Method
  - Conservation Budget
  - Laws of Physics and Chemistry
  - Statistics to Interpret Data
- Multiple constraints
  - Laboratory v Field Studies
  - Surveys, Inventories
  - Manipulation
    - CO2, rain, N, temperature, etc
  - Ecological Transects, Gradients
    - Random vs stratified sampling, f($ & # instruments)
  - Comparisons
    - Species/functional types, soils, climate, topography
  - Monitoring
    - Climate, trace gases, pollution
- Integration in Time and Space
  - Models
  - Space-Based Remote sensing
- Systems and Sensors
  - Sample and Weigh
  - Micrometeorological
  - Cuvettes
  - Tracers
    - Stable and radioactive isotopes
    - SF6, CFCs
  - PCR, Electrophoresis

How you measure the biosphere depends upon time and space scale.

Our scientific tool box contains sensors and systems of sensors.
Many principles of physics and chemistry are foundation of our sensor and instrument systems, like conservation budget and spectroscopy.
As the scales get larger on starts relying on remote sensing from satellites and aircraft, models and networks of sensors. Experiments can be done by monitoring past, current and future, by using manipulation and controlled comparison studies, making measurements along ecological and climatic gradients.

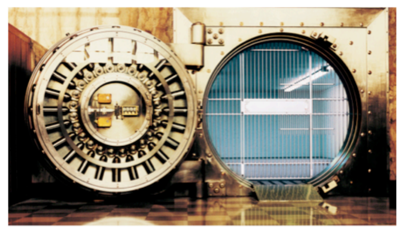
What to Measure?

- Variables of State
  - Temperature, Wind Speed, CO_2, Radiation, Humidity, Pressure, Chemical Composition of Rock, Soil, Plants, Air
- Pool Size
  - Mass of plants, Carbon or Nitrogen in soil, number of individuals…per unit area, unit volume or entity
- Change of State, or Fluxes
  - Mass or energy per unit area per unit time
- Residence or Turnover Time

The list above is a bit atmospheric and ecologically-centric. So, think about variables of state, pool size and fluxes associated with the sun, oceans, rivers, soils, geology… many of these will become more obvious in following lectures

Concepts/Vocabulary

- Pools
  - Volume, Content
- Turnover Time
  - Residence Time, Decay Rate, Growth Rate, Transit Time, Age
- Fluxes
  - $F \sim C/\tau$
  - Mole m-3 Time-1
- Flux Density
  - Moles m-2 time-1
- Steady-State
  - Homeostasis
  - Equilibrium
  - Dynamic



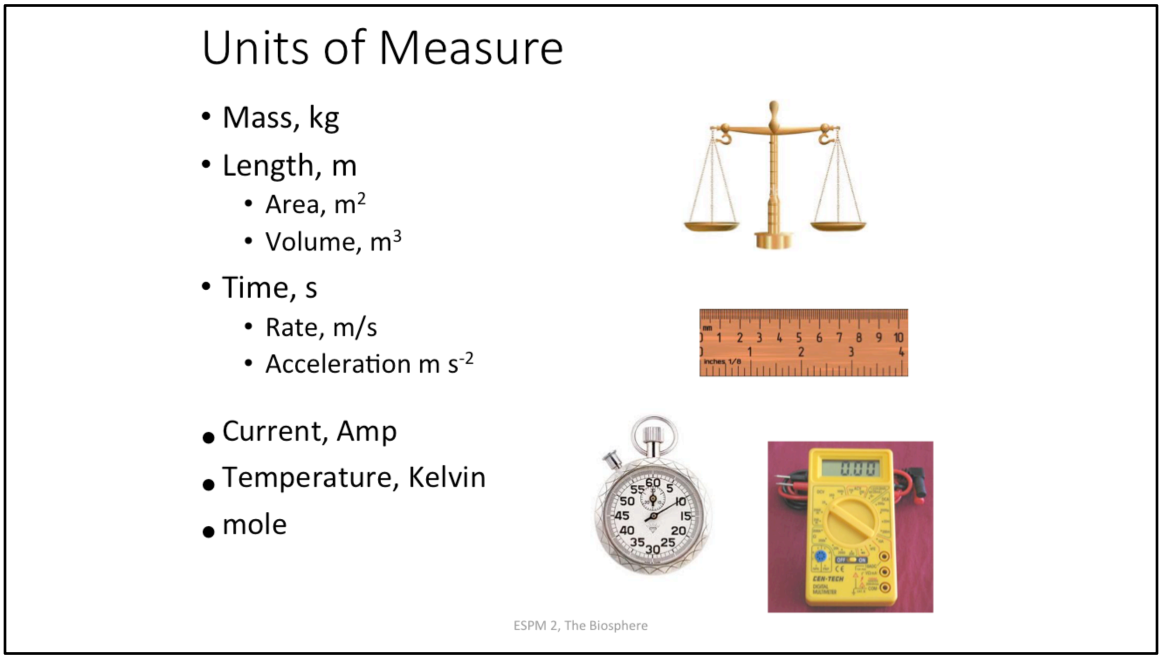
How big is the pool? How much material of quantity, X, is stored in that pool?; e.g. soil carbon pool, vegetation carbon pool, atmospheric pool?
What are the rates of exchange among pools? How fast is Pool A gaining or losing material?
How long does the material remain in that pool?

Analogous to $$$ in your bank account or Water in your Bath Tube

Homeostasis: the tendency toward a relatively stable equilibrium between interdependent elements, especially as maintained by physiological processes.

https://www.scientificamerican.com/article/what-is-homeostasis/

In a chemical reaction, **chemical equilibrium** is the state in which both reactants and products are present in concentrations which have no further tendency to change with time.[1] Usually, this state results when the forward reaction proceeds at the same rate as the reverse reaction. The reaction rates of the forward and backward reactions are generally not zero, but equal. Thus, there are no net changes in the concentrations of the reactant(s) and product(s). Such a state is known as



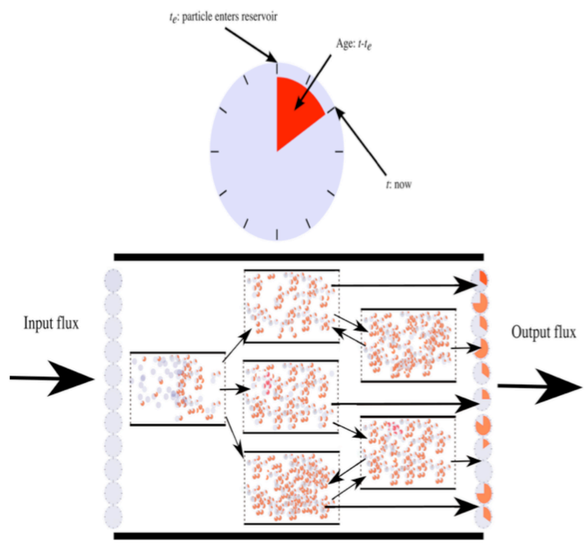
From this system units can be derived that describe energy, force, work, pressure, flux density, electrical resistance and capacitance

Read about units from the National Institute of Standards and Technology web site, NIST:

http://physics.nist.gov/cuu/Units/

It is embarrassing that the US continues on the feet-pound-Fahrenheit unit system. We are the only major county to continue to use these units.

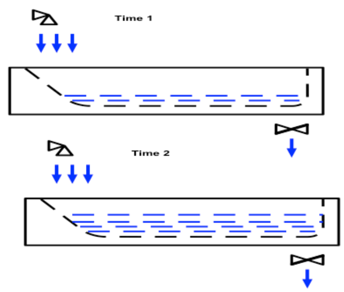
The muddle of ages, turnover, transit, and residence times in the carbon cycle



Global Change Biology
Volume 23, Issue 5, pages 1763-1773, 25 NOV 2016 DOI: 10.1111/gcb.13556
http://onlinelibrary.wiley.com/doi/10.1111/gcb.13556/full#gcb13556-fig-0001

Schematic representation of the concepts of pool age, system age, and transit time with respect to the ages of particles in the system. Each particle, which can be thought of as a C molecule, is represented here as a clock that measures their age in the system. A system (e.g. a given soil volume) can be represented as a set of pools (rectangles) with mass transfer among each other (arrows), with an input flux in which particles enter with age = 0. At any given time *t*, particles in each pool have different ages and therefore each pool has a *pool-age distribution* with a corresponding *mean pool age*. For all particles in the system at any given time *t*, it is also possible to define a *system-age distribution* with a corresponding *mean system age*. Particles in the output flux have also different ages, and the age at which they leave the system is their transit time. The output flux can be characterized by a *transit-time distribution*, with a corresponding *mean transit time*. Notice that the concepts of system age and transit time do not rely on assumptions about model structure, steady state, or whether the system is autonomous.

Conservation Budget:
The Bathtub Problem



Change in C (mass, population, moles) per unit volume with TIME (t) equals the Difference between the Fluxes (F, C per unit area per unit time) In and Out of the pool of a given volume

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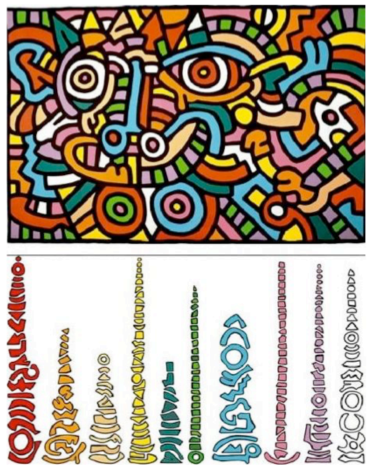
New idea or concept, Fluxes and Flux density. It takes systems of instruments to measure fluxes. Flux densities are the amount of material or energy that is crossing a unit area per unit time, moles per meter squared per second. Fluxes are the amount of material entering or leaving a pool per unit time, like Petagrams-Carbon per year.

The Conservation Budget is Ubiquitous

- Plant, insect, microbe, wildlife and human population dynamics
- Growth of individuals
- Weather and Climate
- Air and Water Pollution
- Biogeochemical Cycles, C, N, P
- Principles of many Environmental Instruments
- Hydrology
    - Management of water resources, Dams, irrigation
- Migration and Demographics of Forests, People, Emissions
- Movement of Magma in Volcanos
- Economics and Policy
    - Flows of money



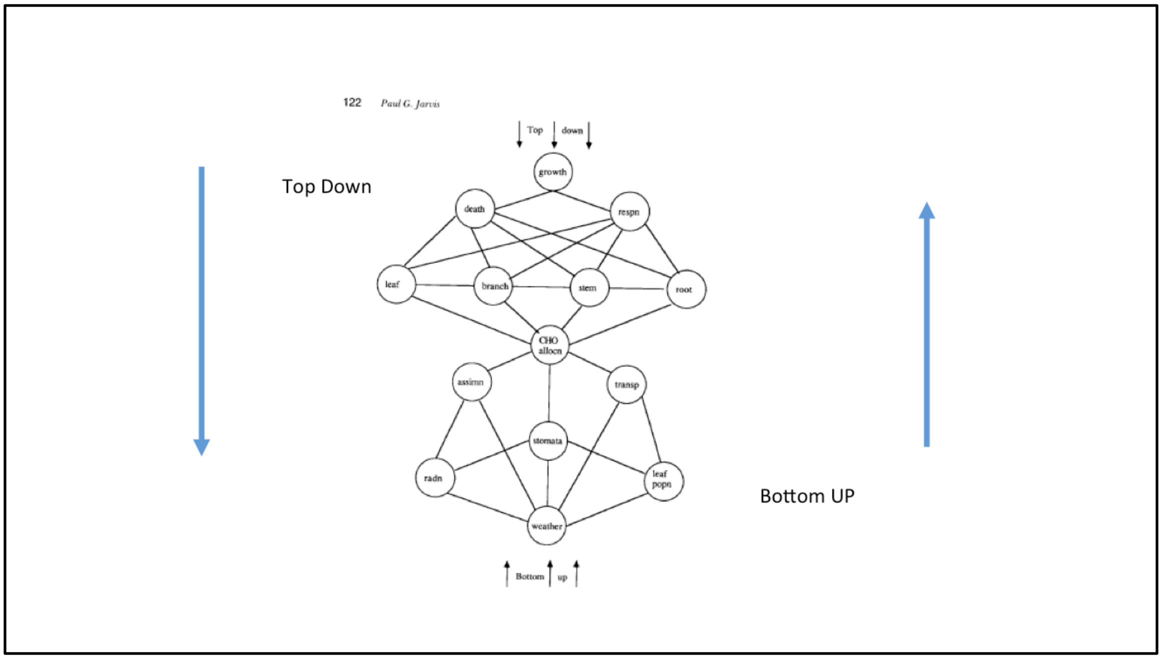
Wholistic, Top Down

Reductionist,
Bottom Up

https://s-media-cache-ak0.pinimg.com/736x/e2/7d/82/e27d825101a6b6b4a03d033e7194e2e6.jpg

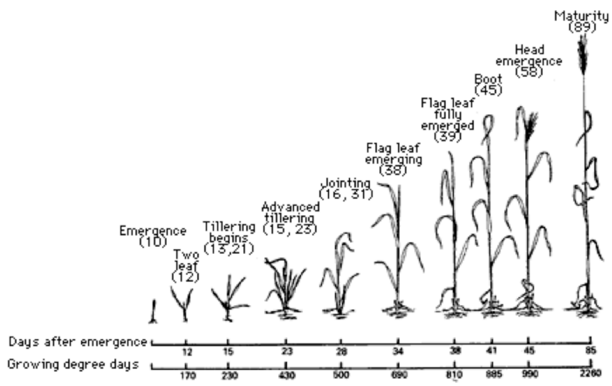
Thanks to Bruce Hungate for pointing out this example.

Keith Haring artist, ideas of Tidying up Art by Ursus Wehrli.



There are two complementary ways to study the biosphere. One is Top down and the other is bottom up. We hope that the methods can agree giving us a better understanding of what, how and why. For large complex systems it is useful to use a top down approach, such as measuring the absorption of sunlight and relating that to growth, or relating sums of heat units to seed production of crops. While we may miss all the details, this large scale integrated approach gives useful information. The bottom up method breaks the system into its constituent parts, tries to measure or model each component and add them up. Often this does not work because we don't know enough about the details, the model parameters and there can be surprises like scale emergent properties.

Crop Growth and Growing Degree Day



https://www.extension.umn.edu/agriculture/small-grains/growth-and-development/spring-barley/img/2548-1.gif

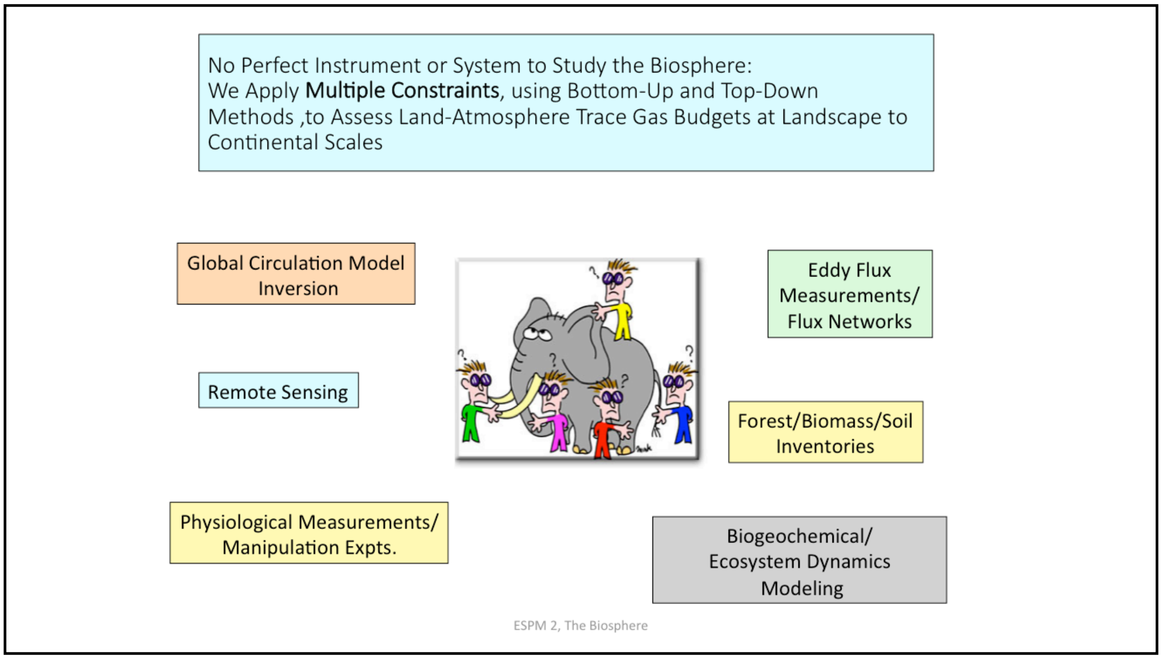
Wang, J. Y. 1960. A Critique of the Heat Unit Approach to Plant Response Studies. Ecology **41**:785-790.

Reductionist Science is Important to Deconstruct and Understand how Whole May Function

But

Adding up the Pieces does not always Reassemble the Whole due to Scale Emergent Properties, Errors in Measuring/Modeling the Pieces or Lack of Representative Sampling

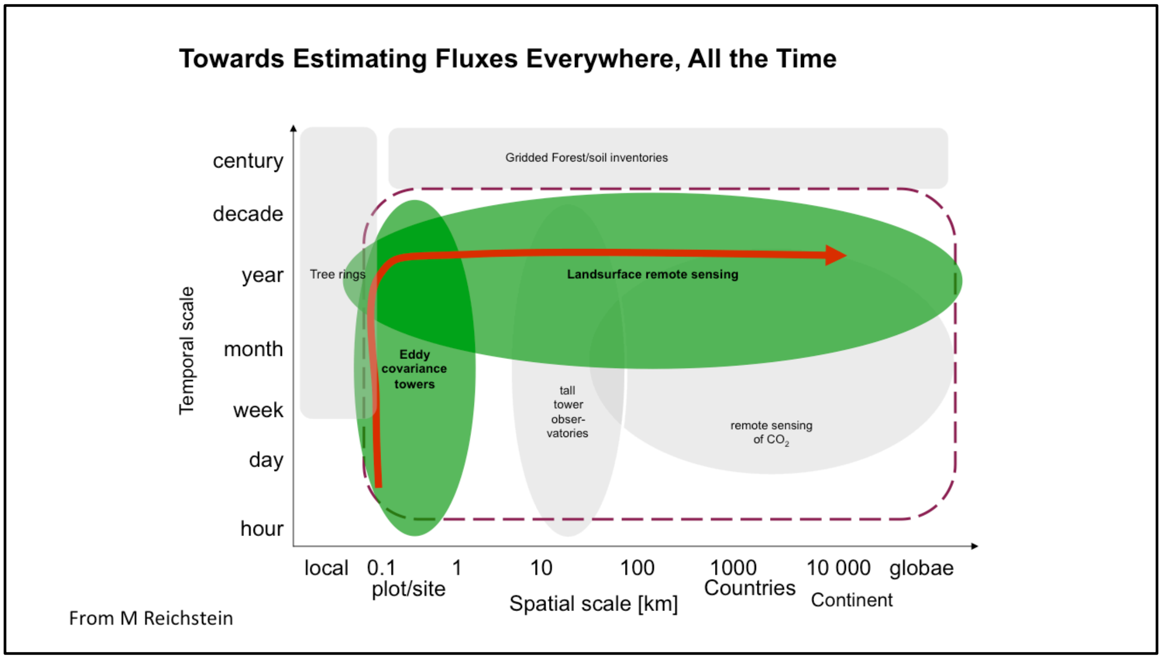
One reason we cannot explore the Biosphere in a bit by bit Reductionist manner, as is done by some of science. We need to apply a Systems Approach. With the Earth System the Whole may not Function as the sum of the parts!



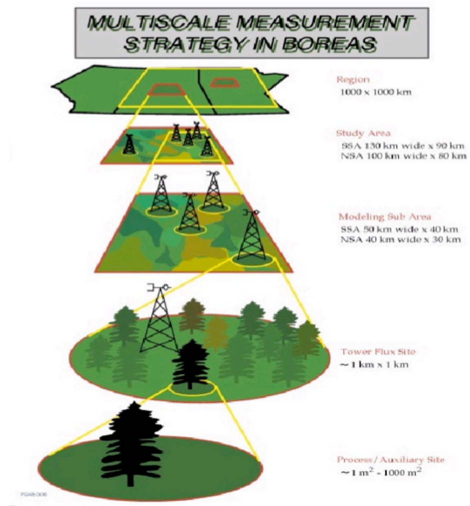
There is no single or perfect way to study the biosphere, as all the methods have limits in their relevant time and space scales. Consequently, biosphere scientists tend to study the Earth System with multiple methods.

In the following slides we discuss these methods in more detail.

The paper by Running et al gives an overview of these topics. It is a good example of reading a general scientific paper.



This is a good example showing the time and space spectra associated with each of the methods discussed above. Note, none cover the full spectra of the biosphere. Those associated with small scales cover vast time scales and those covering vast spatial scales tend to be associated with infrequent sampling.



Experimental Design, Across Multiple Space and Time Scales

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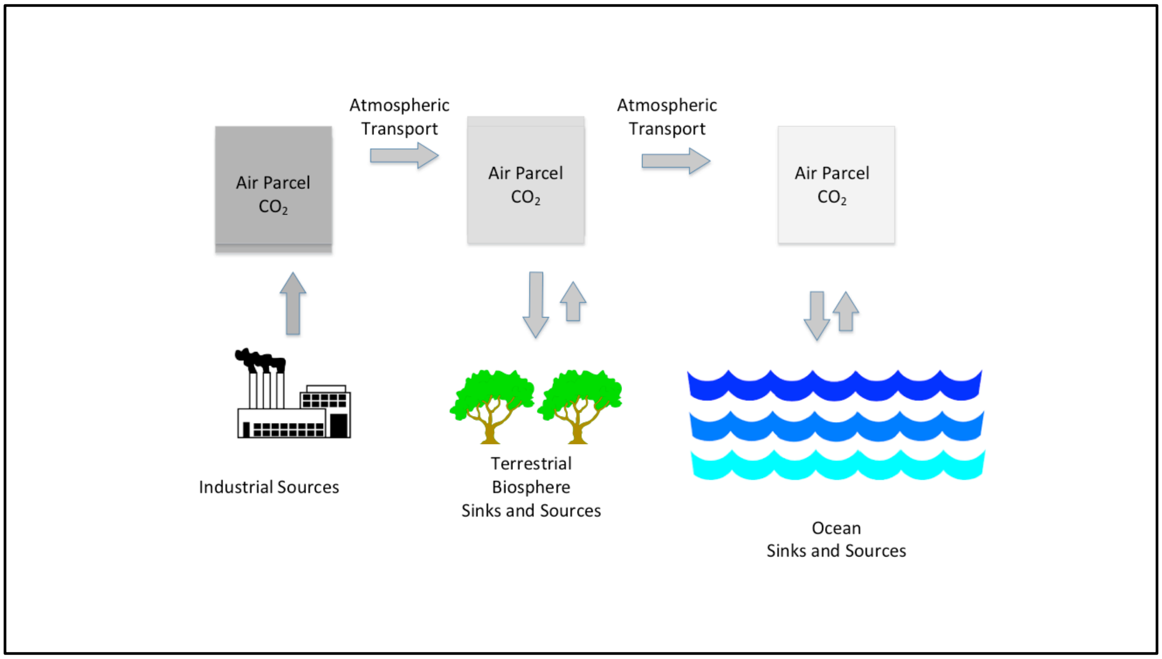
Example of the hierarchal approach biosphere scientists are inclined to use to study the biosphere across a spectrum of scales. This approach was used in the BOREAS project, in which I participated circa 1993-94.


Atmospheric Transport
Atmospheric Transport
Air Parcel CO2
Air Parcel CO2
Air Parcel CO2
Industrial Sources
Terrestrial Biosphere Sinks and Sources
Ocean Sinks and Sources

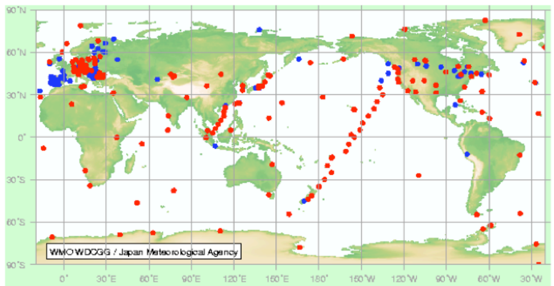
Inversion Modeling

Rate of Change with Time in C + Horizontal Transport in C = Sources-Sinks

Measured, dC/dt

Measured: dC/dx
Model: U

Inferred=S(t,x,y)



Global CO2 Sampling Network

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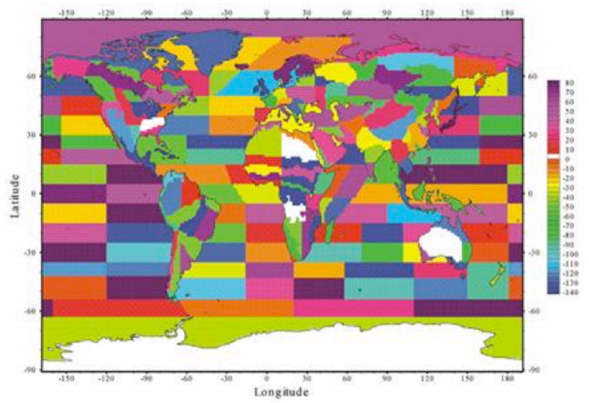
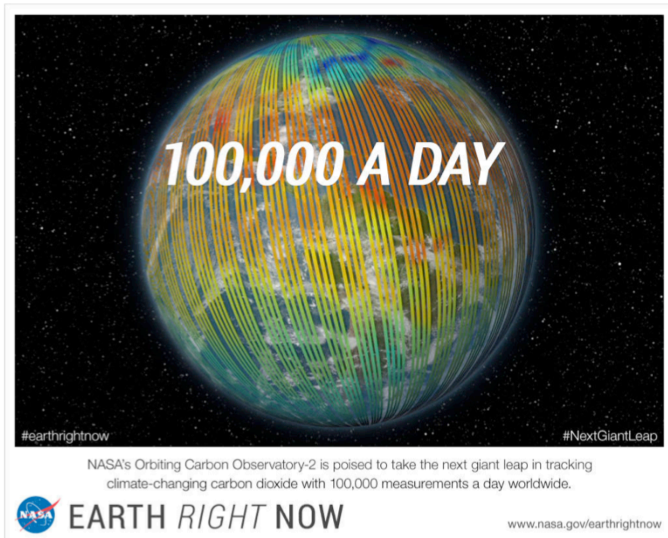
Global circulation inversion models deduce sources and sinks of trace gas by monitoring trace gas concentrations across the globe and the wind fields. It divides the Earth into grids and on this basis dynamic mass transport models are inverted to produce sources and sinks that match the given concentration and transport fields.

‘Top-Down’,Global Inversion Models Divide the Globe into Coarse Basis Regions

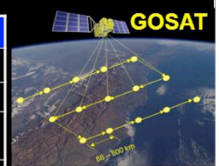


Example of the large basis regions used by inversion modeling to estimate sources and sinks of trace gases

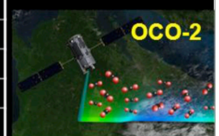

100,000 A DAY
#earthrightnow
#NextGiantLeap
NASA's Orbiting Carbon Observatory-2 is poised to take the next giant leap in tracking climate-changing carbon dioxide with 100,000 measurements a day worldwide.
EARTH RIGHT NOW
www.nasa.gov/earthrightnow

OCO-2 and GOSAT

	GOSAT	OCO
Gases Measured	CO_2, CH_4, O_2, O_3, H_2O	CO_2, O_2
Instruments	SWIR/TIR FTS, CAI	Grating Spectrometer
IFOV / Swath (km)	FTS: 10.5 / 80-790 (160) CAI: 0.5 / 1000	1.29 x 2.25 / 5.2-10.4
Spectral Ranges (μm)	0.758-0.775, 1.56-1.72, 1.92-2.08, 5.56-14.3	0.757-0.772, 1.59-1.62, 2.04-2.08
Soundings/Day	10,000	500,000 to 1,000,000
Sampling Rate	0.25 Hz	12 to 25 Hz
Orbit Altitude	666 km	705 km
Local Time	12:48	13:30
Revisit Time/Orbits	3 Days/72 Orbits	16 Days/233 Orbits
Launch Vehicle	H-IIA	Taurus 3110 (TBD)
Launch Date	January 2009	February 2013
Nominal Life	5 Years	2 Years



GOSAT was optimized for spectral & spatial coverage

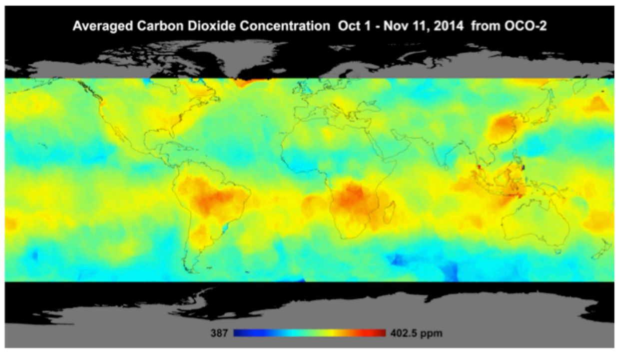


OCO-2 was optimized for sensitivity and resolution

7

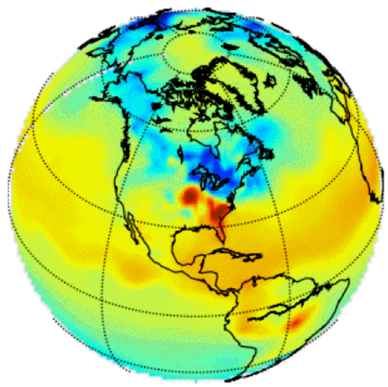
http://slideplayer.com/6387811/22/images/7/
OCO-2+and+GOSAT+GOSAT+OCO-2+GOSAT+OCO.jpg

Orbiting Carbon Observatory



https://www.nasa.gov/sites/default/files/mainco2mappia18934.jpg

Carbon Tracker, CO2 Source/Sink Distributions



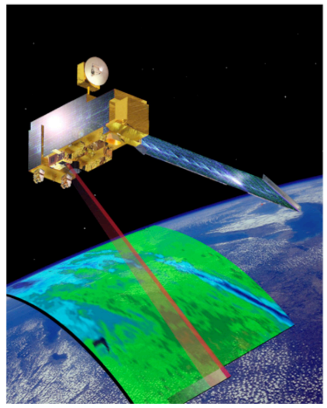
http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/

Carbon Tracker is an example of a program that is using inversion modeling to deduce sources and sinks of carbon dioxide across the globe

http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/

YouTube Video of the breathing of the biosphere
http://www.youtube.com/watch?v=j1ehcjjDPy8

Space or Aircraft-Based Remote Sensing



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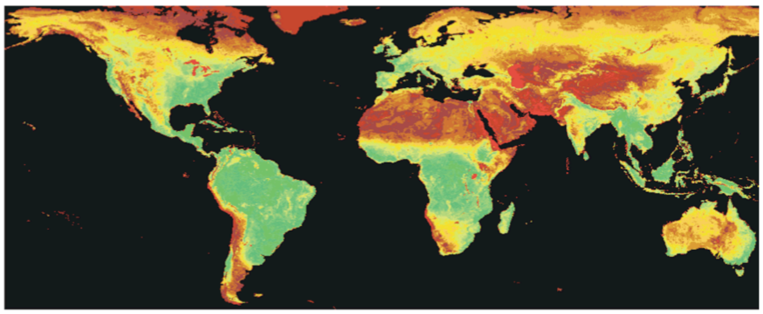
Space based remote sensing gives us the opportunity to view the Earth as a whole.

If you are truly interested in the Biosphere, I strongly recommend taking classes on remote sensing and geographical information systems. We have a constellation of satellites circling the Earth and there is much activity interpreting these measurements. Many job and career opportunities

Global Normalized Difference Vegetation Index, NDVI



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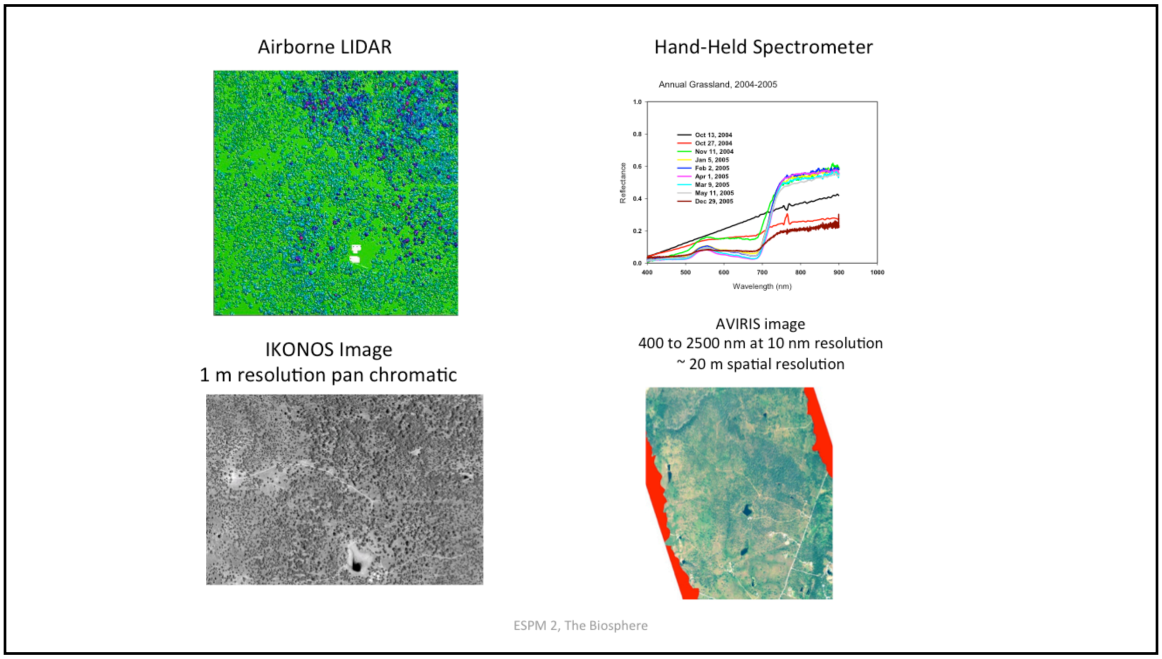
Example of the information about vegetation on the Earth that can be deduce by remote sensing. It tells us how much vegetation there is, where it is most and least plentiful and how this may vary over the course of a season or decade.



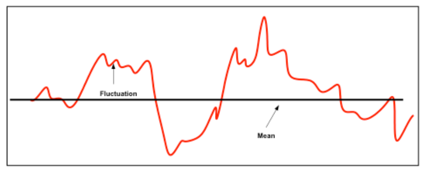
LIDAR looks at the timing of reflected light to tell us how high the vegetation or underlying soils may be. High resolution sensors like IKONOS and QuickBird can detect objects on the surface of Earth 1 meter ins size. Spectrometers on satellites can detect reflected light of different colors, or wavelengths, and detect the health, amount and metabolic activity of the underlying vegetation.

Remote Sensing

- **Pros**
  - Provides Wall-to-Wall Information at a variety of scales and spatial resolution
  - Provides information at hard to reach locations
  - Looking at reflectance of light from Different wave lengths gives novel information
- **Cons**
  - It is Inferential and measures Reflected Light
  - Suffers from Presence of Clouds, Smoke and Aerosols
  - Produces Inferential information on Fluxes and Vegetation Status
  - May view Surface once a day or week

Eddy Covariance Technique

$$F = \overline{\rho w s} \sim \overline{\rho_a} \cdot \overline{w' s'} \qquad s = (\frac{\rho_c}{\rho_a})$$



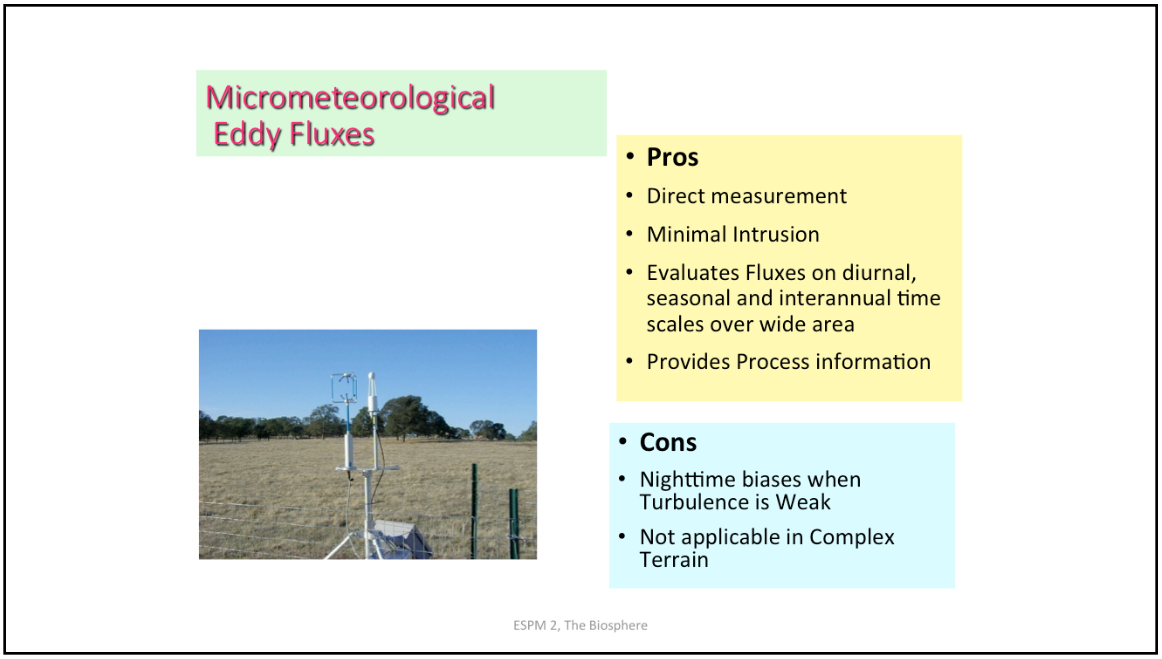
- Direct
- *In situ*
- Quasi-Continuous

The eddy covariance method measures the net Flux is the sum of the mass flux moving across a plane (w s) in the up and down-drafts of air. It does so by sampling up to 10 times per second, constructing means and fluctuations of means over a half-hour and computing the covariance between fluctuations in vertical velocity and the scalar concentration.

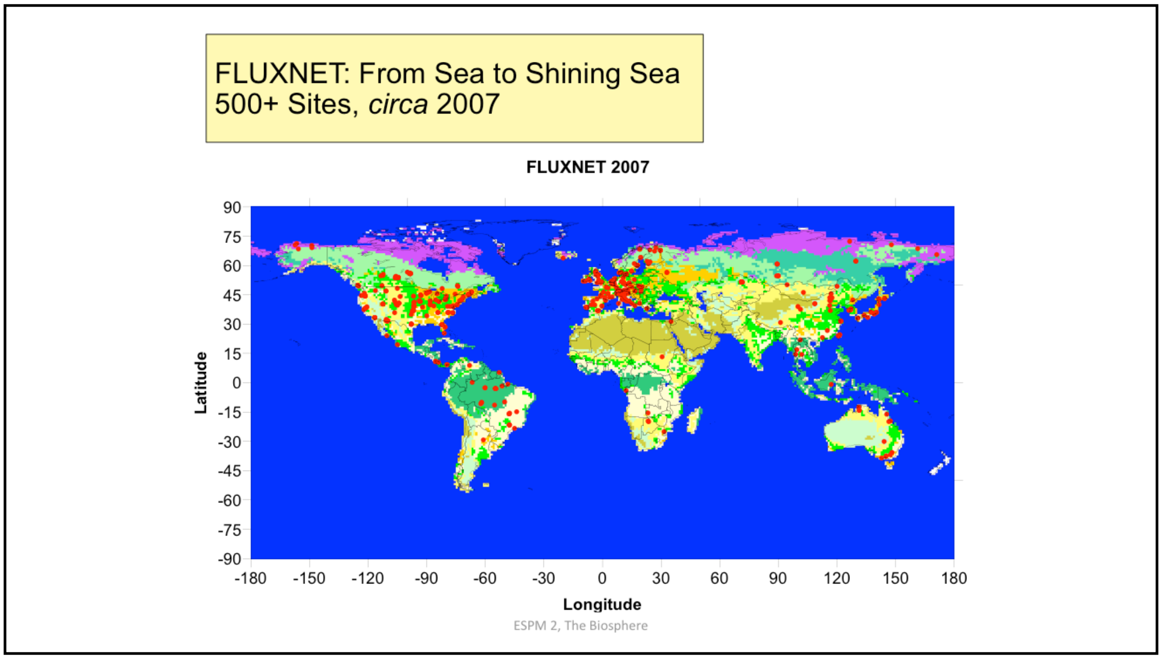
It is one of the few methods in the atmosphere that measure fluxes directly, not inferentially.

If you are interested in this topic you can read pages 7 through 13 in
http://www.instrumentalia.com.ar/pdf/Invernadero.pdf

This is the topic I use in my research, I also teach more about it in Biometeorology, ESPM 129, and the graduate course, ESPM 228



To be applicable the method should be applied on level terrain, with homogeneous vegetation several hundred meters to a kilometer upwind. The measurements are best under temporally steady conditions.

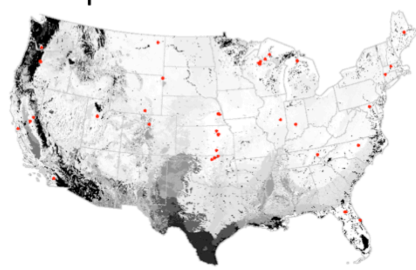


Fluxnet is a global network of eddy covariance sites, of which I have been PI. We have over 500 sites measuring carbon dioxide, water and heat fluxes hour by hour, day by day, year by year. These data are shared and used to synthesize how the biosphere breathes. Because they are direct flux measurements they are used to validate remote sensing algorithms and models.

You can learn more about it on the web site

http://www.fluxdata.org/default.aspx

Networks and Representativeness



Pros:
Don't need to be Everywhere, All the Time
Cons:
Need Dense Enough Network to Cover Each Class
??? Definition of Relevant Classes???
??? Networks are Expensive $$$

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Monitoring networks provide spatial-temporal information on the biosphere.

This can also involve geological monitoring of earthquakes and tsunamis,

http://earthquake.usgs.gov/earthquakes/map/

Acid rain

http://nadp.sws.uiuc.edu/

Aircraft as probes of the Atmosphere and Underlying Land

NOAA Long EZ

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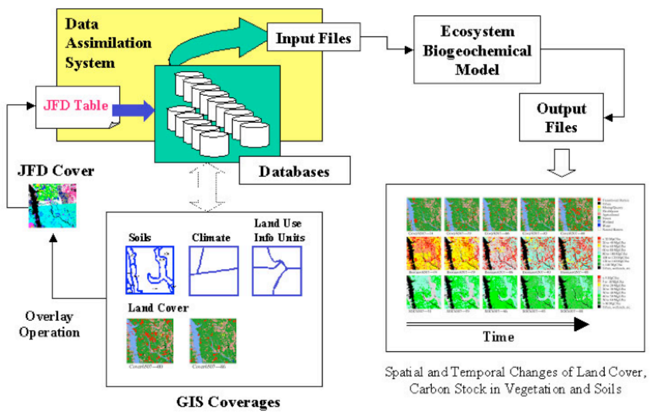
Aircraft can measure wind in 3D by knowing motions of airplane and pressure fields on a hemispherical head. It can sense reflected light from the surface to understand land cover and sample air for measurements of temperature and trace gases

Mathematical Models of the Biosphere



Models, represent processes in nature as mathematical functions. They may be linear, non-linear, single factor or multi-factor, or sets of differential equations

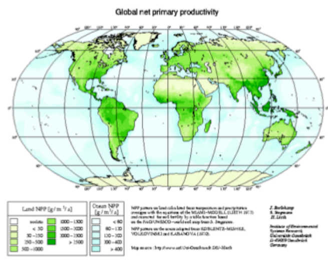
For example

Y = a + b X + c X^2 + d Z + e Z^2, rely on independent variables, e.g. X and Z, and values of the model parameters, e.g. a, b, c, d and e.

dC/dt = a C /(b +C)

Models can simulate behavior of complex systems by having feedbacks and multiple processes interacting as a system

Ecosystem and Biogeochemical Models



- **Pros**
  - Discrete/Continuous Fluxes in Time and Space
  - Mechanistic Models can Forecast
  - Empirical Models can Fill Knowledge and Information Gaps

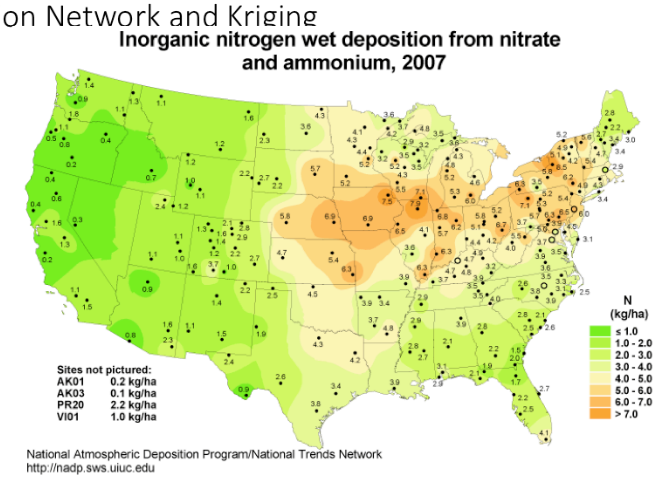
- **Cons**
  - Errors in inputs
  - Scarcity and Uncertainty of Parameters
  - Variation in Parameters in Time and Space
  - Errors Attributed to Model Simplicity
  - Uncertainty in Structure and Components of the Model

Models represent a synthesis of our knowledge, and have acknowledged pros and cons.

The answers can be sensitive to the spatial and temporal resolution of the model. For example is the time step hours, days or years. Or is the spatial step meters, kilometers or degrees of longitude and latitude.

Empirical models can fill gaps in knowledge and information. Mechanistic prognostic models can simulate future conditions (dC/dt= f(C))

Acid Deposition Network and Kriging

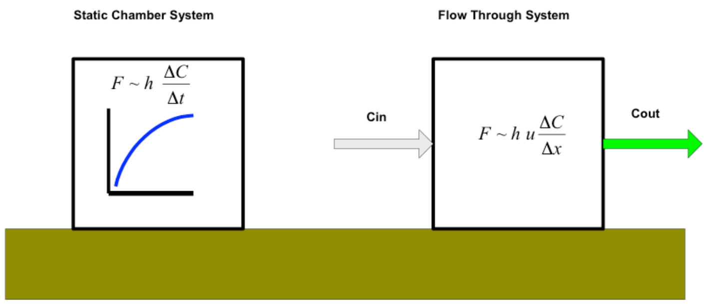


Long term networks like the NADP acid rain network can produce spatially interpolated maps where acid rain is greatest. It can tell us if reductions in pollutant emissions are cleaning the rain.

The Web site for this program is

http://nadp.sws.uiuc.edu/

Chambers/Cuvettes measure Fluxes



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Static Chambers can deduce Fluxes (moles per meter squared per second) by knowing how the concentration of a gas that is either accumulating (or being depleted) in the chamber varies in time. If there is a feedback between the source and sink and the concentration in the chamber it may bias the flux being measured.

If the concentration is increasing in the chamber is the underlying soil a sink or source for that gas?

A dynamic or flow through chamber tries to keep a null balance, to minimize biases and artifacts. It deduces a flux by knowing the difference in the concentration of the air entering the chamber vs that leaving. It is also dependent upon the volumetric flow rate.

If the concentration entering the chamber is greater than that leaving is the soil or leaf underlying the chamber a sink or source?

Leaf and Soil Cuvettes/Chambers

Pros
- Direct measurement

- New Systems can Control Leaf Environment to Assess Response Functions

Cons
- Modifies the local environment, which disturbs the flux.

- Difficult to sample Natural Variation

- Small sample area

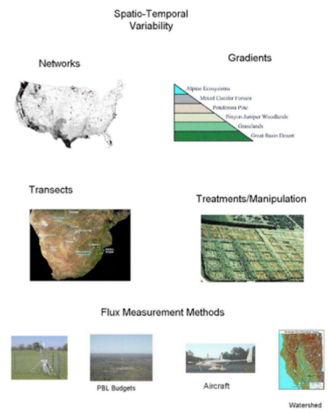
- Cannot work well over whole ecosystems

8100-104 Long-Term Chamber open at 90° (top) with soil collar; fully closed (below right).

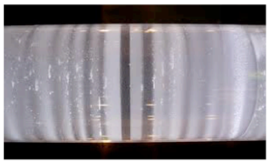
Examples of the type of cuvette or chamber systems used in my lab or by my colleagues

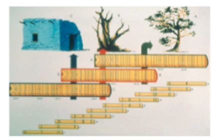
Experimental Manipulation Methods

- Transects/Gradients
- Open-Top Chambers
- Free-Air Exposure (FACE)
- Heating
- Exclusion/Addition
  - Rain, fertilizer
- Issues
  - Artificial alteration of system, limited sampling, expensive



Sampling Back in Time:
Ice Cores, Ocean/Lake Sediments/Tree Rings





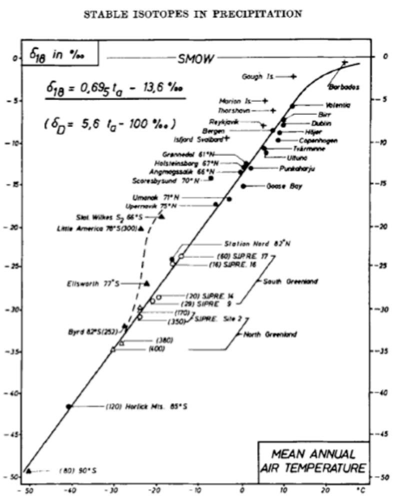
http://www.ncdc.noaa.gov/data-access/paleoclimatology-data

Sampling the isotopic records in ice and sediment cores and tree rings helps us look backward in time and infer relations between climate and isotopes.

Ice Cores Tell Us about Climate and Atmospheric Composition, back 800,000 years

We can study the past biosphere by looking at the composition of air and dust on accumulated layers of ice or lake sediments. Isotopes are important as they serve as proxies for temperature and rain. Direct sampling of air bubbles tell us what was in the air. Counting layers, like growth rings on a tree help us age the cores.

http://earthobservatory.nasa.gov/Features/Paleoclimatology_IceCores/



Dansgaard, 1964 Tellus

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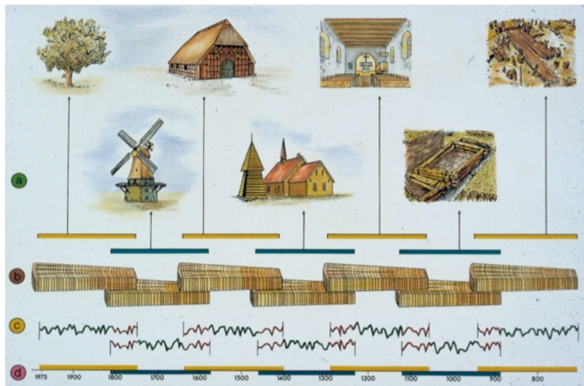
The isotopic value of ^{18}O in rainwater has been found to correlate well with temperature. So temperatures can be reconstructed from ice cores.

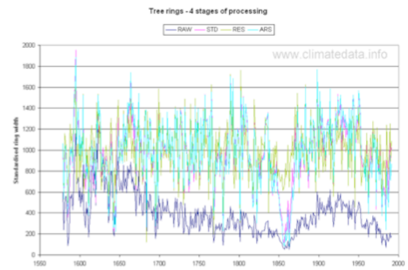
Paleo-Climate Reconstruction with Tree Rings, back to year ~ 1000 AD



Corals can also provide information on paleo-climate

Tree Ring Temperature Reconstruction

- Raw data are normalized in regards to average growth of the whole time series
- Normalized time series is corrected for age with a fitted line
- Correction for Serial Correlation is made
- Time series is analyzed with T, ppt, etc



http://www.climatedata.info/proxies/tree-rings/

http://www.climatedata.info/proxies/tree-rings/files/stacks_image_9687.png

Ocean/Lake Sediments Cores

See the layering of the sediments with time. They will collect organic matter and sediments with distinct isotopic records.

Stable and Radioactive Isotopes Serve as Biosphere Tracers and Clocks

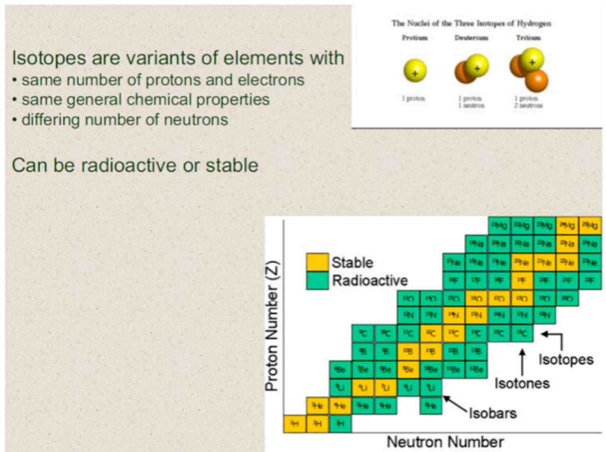


Figure from Dave Bowling, Univ Utah

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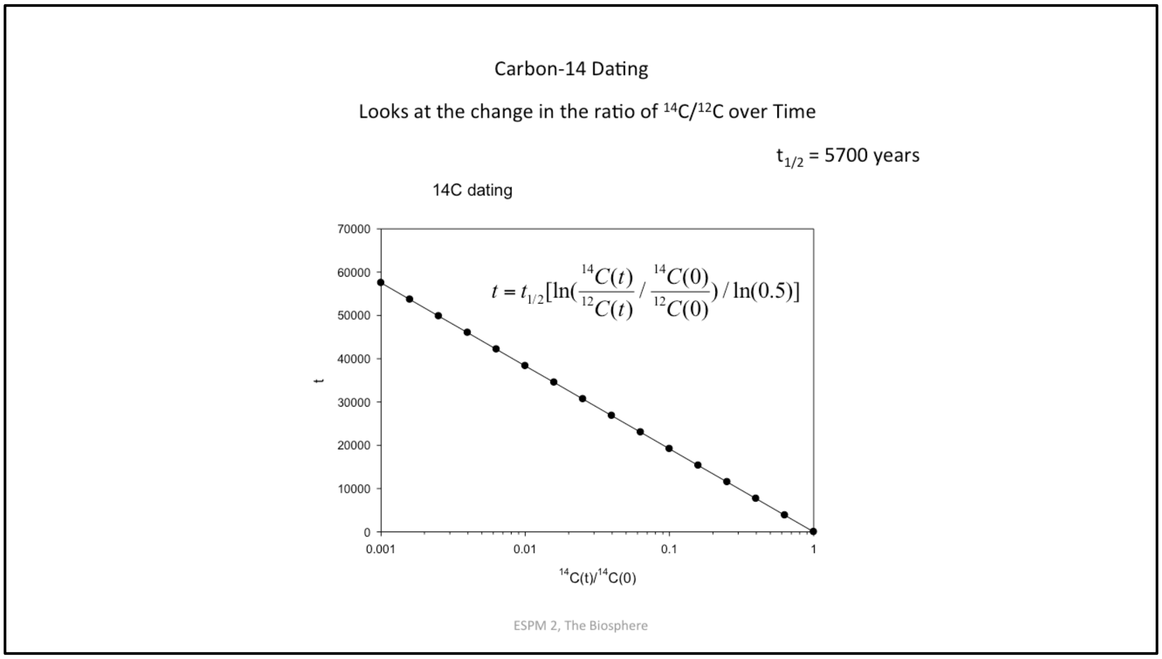
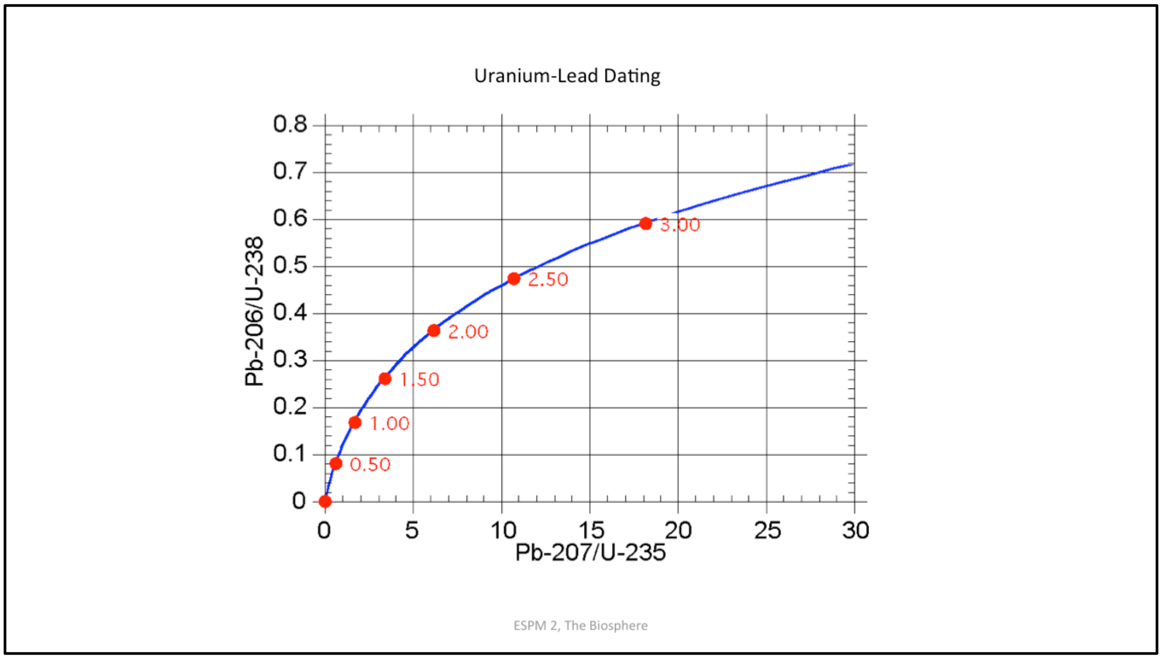
Examples of stable isotopes used as tracers in the biosphere



Radioactive carbon 14 dating is used to find how old organic material may be



Ancient rocks can be dated looking at the ratios of Lead (Pb) and Uranium (Ur) isotopes, Pb 207 is the standard lead on the Periodic table.

U238 has a half life of 4.468 billion years U 235 has a half life of 703.8 million years

http://www.uwgb.edu/dutchs/Graphics-Geol/GEOCHEM/U-PbConcordia.gif

Key Take Home Points, pt 2

- Need Multiple methods to study the biosphere, as each has distinct space and time scales
- Know key groups of methods
  - Top-down inversion Models, Bottom-up Biogeochemical Models, Remote Sensing, Eddy Covariance
  - Know some Pros and Cons
- Understand the Principle of the Conservation of Mass and the role of Fluxes and the dynamics of Pools
- Know how the concentration in a chamber is varying with time, depending if it is measuring a source or sink

Discussion

- Focus on several instruments used to study the biosphere, eg CO2 sensor, water vapor sensor, thermometer.
- Discuss issues with representative sampling, biases, physical principles, accuracy, range, detection limits
- Consider the Patterns of CO2 across the globe inferred from Carbon Tracker by latitude and time
- http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/