Studying the Biosphere, part 2

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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, CO₂, 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.
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. 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
Units of Measure

- Mass, \( \text{kg} \)
- Length, \( \text{m} \)
  - Area, \( \text{m}^2 \)
  - Volume, \( \text{m}^3 \)
- Time, \( \text{s} \)
  - Rate, \( \text{m/s} \)
  - Acceleration \( \text{m s}^{-2} \)
- Current, Amp
- Temperature, Kelvin
- Mole

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 country to continue to use these units.
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.
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
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.
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.
Towards Estimating Fluxes Everywhere, All the Time

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.
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.
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.
Example of the large basis regions used by inversion modeling to estimate sources and sinks of trace gases
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
<table>
<thead>
<tr>
<th></th>
<th>GOSAT</th>
<th>OCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gases Measured</td>
<td>CO₂, CH₄, N₂, O₂, H₂O</td>
<td>CO₂, O₂</td>
</tr>
<tr>
<td>Instruments</td>
<td>SWIR/TIR FTS, CAI</td>
<td>Grating Spectrometer</td>
</tr>
<tr>
<td>IFOV / Swath (km)</td>
<td>10.5 / 60-700 (160)</td>
<td>1.29 x 2.29 / 5.2-10.4</td>
</tr>
<tr>
<td>Spectral Ranges (μm)</td>
<td>0.75-0.776, 1.58-1.72, 1.92-2.08, 3.56-14.3</td>
<td>0.75-0.772, 1.59-1.62, 2.04-2.08</td>
</tr>
<tr>
<td>Sounding/Day</td>
<td>10,000</td>
<td>500,000 to 1,000,000</td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>0.25 Hz</td>
<td>12 to 29 Hz</td>
</tr>
<tr>
<td>Orbit Altitude</td>
<td>866 km</td>
<td>705 km</td>
</tr>
<tr>
<td>Local Time</td>
<td>12:48</td>
<td>13:30</td>
</tr>
<tr>
<td>Revisit Time/Orbits</td>
<td>3 Days/72 Orbits</td>
<td>16 Days/233 Orbits</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>H-IA</td>
<td>Taurus 3110 (TBD)</td>
</tr>
<tr>
<td>Launch Date</td>
<td>January 2009</td>
<td>February 2013</td>
</tr>
<tr>
<td>Nominal Life</td>
<td>5 Years</td>
<td>2 Years</td>
</tr>
</tbody>
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GOSAT was optimized for spectral & spatial coverage.
OCO-2 was optimized for sensitivity and resolution.
Orbiting Carbon Observatory

https://www.nasa.gov/sites/default/files/mainco2mappia18934.jpg
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=j1ehcjDPy8
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
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 wavelengths 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
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.


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
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 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.
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 \( e \).

\[ \frac{dC}{dt} = \frac{a\, C}{(b + C)} \]

Models can simulate behavior of complex systems by having feedbacks and multiple processes interacting as a system.
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))
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/
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?
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.
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/
The isotopic value of $^{18}O$ in rainwater has been found to correlate well with temperature. So temperatures can be reconstructed from ice cores.
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
See the layering of the sediments with time. They will collect organic matter and sediments with distinct isotopic records.
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/