Scale, Complexity and the Biosphere

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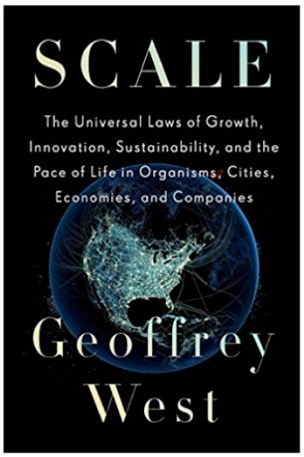
ESPM 2 Biosphere

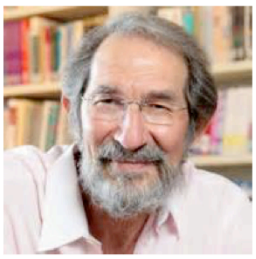
12/2/17

Outline/Topics

- Spectrum of Time and Space Scales of the Biosphere
- Biosphere as a Complex System
- Complexity vs Complicated, a Paradigm Shift
- Feedbacks
- Reductionist vs Wholistic; Bottom-Up vs Top Down
- Scale Emergence!
- Power Laws
- Reading
  - West, G. B. and J. H. Brown. 2004. Life's universal scaling laws. Physics Today **57**:36-42.

Suggested Reading, Biosphere Library





‘Everything is Connected, from Small to Large’:
Scaling Information on ‘Biosphere Breathing’ from Chloroplast to the Globe

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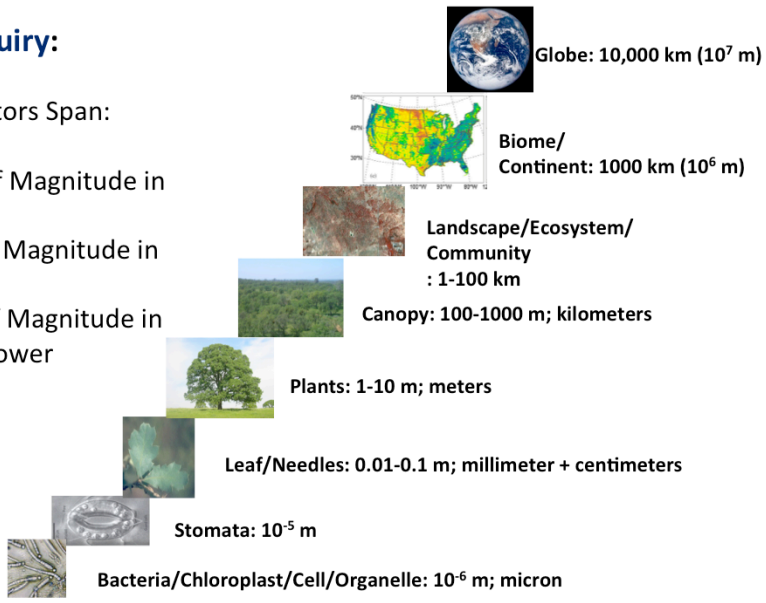
In studying the biosphere we start with the smallest microbes (bacteria, archaea) and work up to stomata on leaves, leaves, plants, landscapes, continents and the globe

Scales of Inquiry:

Biosphere's Actors Span:

- 15 orders of Magnitude in Length
- 27 orders of Magnitude in Mass
- 21 Orders of Magnitude in Metabolic Power



Why is measuring the biosphere so hard? Actors span a huge spectrum in space scales, from the tiniest bacteria, that may be on the order of a micron; to the organelles and cells of a leaf, and how they are assembled together to form a leaf; how leaves are assembled to form a plant; how plants are assembled to form a canopy; how patches of vegetation and soil interact to form a landscape; how landscape interact to form an ecosystem; how climate and ecosystems interact to form a biome; how biomes are collected on a continent and finally, how these continents act together on the globe

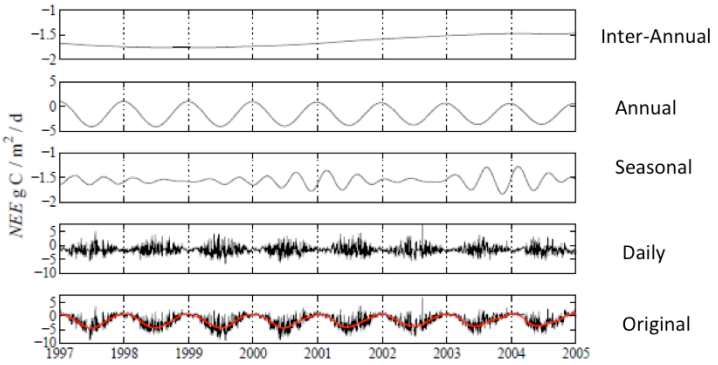
The life process covers more than 27 orders of magnitude in mass—from molecules of the genetic code and metabolic machinery to whales and sequoias—and the metabolic power required to support life across that range spans over 21 orders of magnitude (West and Brown, 2004 Physics Today)

Critical Time Scales of the Biosphere

- Seconds/Hours/Day, 10^{-6} to 10^{-3} yr
  - Physiology
    - Photosynthesis, Respiration, Transpiration, Stomatal Conductance
- Seasonal & Annual, 10^{0} yr
  - Net and Gross Primary Productivity
  - Autotrophic and Heterotrophic Respiration and Decomposition
  - Plant Acclimation
  - Mineralization and Immobilization
- Decadal, 10^{1} yr
  - Competition, Gap-Replacement, Stand Dynamics, Fire, Disturbance
  - Changes in Soil Organic Matter
- Century, 10^{2} yr
  - Succession, Mortality
- Millennia, 10^{3} yr
  - Species migration
  - Soil Formation
- Geological Periods, 10^{6} yr
  - Evolution, Speciation, Extinction, Climate Regimes
- Eons, 10^{9} yr
  - Evolution of Life and the Formation of our Atmosphere

Different biophysical processes operate on different time scales. Some processes are fast, < milliseconds, like how chloroplasts respond to sunflecks that drive photosynthesis. Other processes operate with daily cycle of the rise and fall of the sun in the sky; it is daily variation in sunlight that provides the energy that draws water out of the plant, warms the soil and draws CO2 out of the atmosphere. Slower oscillations are associated with how organisms grow and compete with one another on monthly, seasonal and annual times scales. The birth, life and death individuals leads to slower transitions on years, to decades and century time scales. The decomposition of dead material slowly works into the soil and rock substrate, forming soils on century and millenia. At geological scales—many millenia, periods and eons--there are the movements of continents, major changes in climate and the evolution and extinction of species.

Environmental Signals are the Super position of Fast, slow, Slower and long Term oscillations



Mahecha et al 2007, Biogeosciences

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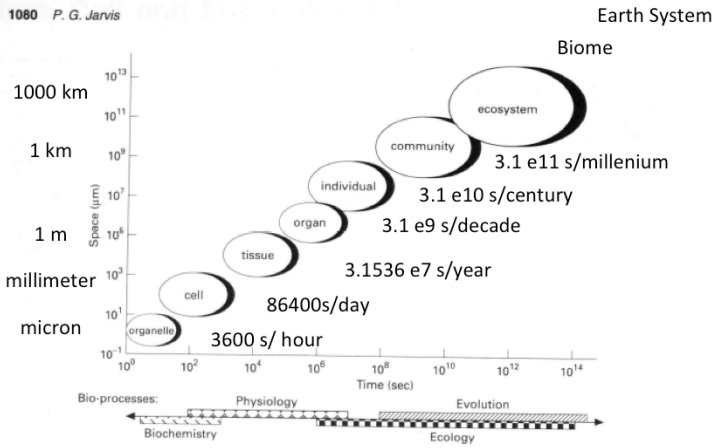
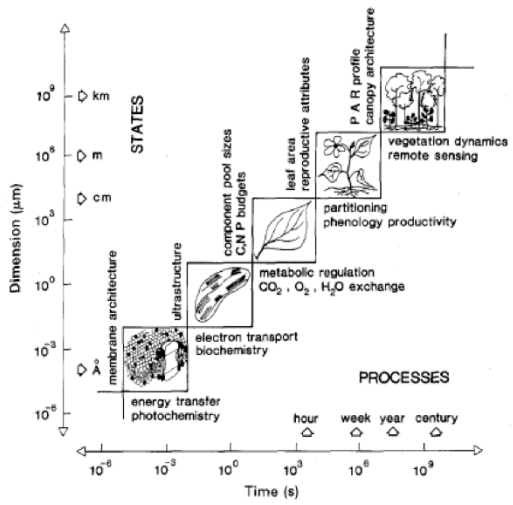
This example shows a time series of carbon dioxide exchange of an ecosystem. Starting at the bottom we see the original signal with cyclic patterns, superimposed with lots of fluctuations. This total signal can be deconvoluted into the sum of daily oscillations, plus slower seasonal and annual cycles. Superimposed on all of these 'higher' frequencies signals is a long term trend as the ecosystem grows or responds negatively or positively to trends in pollution, CO2, climate, etc.



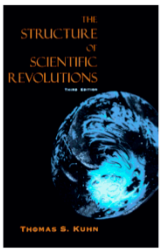
Jarvis, P. G. 1995. Scaling Processes and Problems. Plant Cell and Environment **18**:1079-1089.

Coupling Time and Space Scales of Biosphere Processes



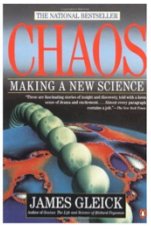
Osmond and Chow 1988 Aust J Plant Physiology

The Biosphere as a Complex System



We are Experiencing a Paradigm Shift from a Clock-like Mechanical, Newtonian View of how the World Works to one based on an acceptance and understanding of Complexity

Studying the Biosphere as a Complex systems forces us to think and act differently in how we study, quantify, predict, manage and manipulate complex systems



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We have to think differently when studying ecosystems and the biosphere around us. This takes us from a conventional Newtonian approach, where the world seems clocklike, to one that embraces chaos and complexity. Lessons derived here also can play roles in understanding advances in economics, climate, political science and health. We all are complex systems. Treating these systems in this manner help us understand better how to manage these systems and understand the limits of our ability to predict future states.

Attributes of the Complex Biosphere

- Hierarchal System
  - Microbe to Biome
- Multiple-scales
  - Power Law Behavior
- Many Coupled Processes
  - With Non-Linear Response to Forcing
  - Subject to Positive and Negative Feedbacks
- Deterministic/Predictable
- Sensitive to Initial Conditions
  - Path dependency
- Self-Organization
- Scale-Emergent Properties
- Resiliency and Robustness, but Vulnerable to Extremes
- Homeostasis and Self-Regulation

$$y = a + bx + cx^2$$

$$y = a \cdot x^n$$

$$\frac{dc}{dt} = \pm kc$$

Sum of parts does not = whole

This is the list of many attributes of complex systems. I will explore these more in the following slides

Scaling

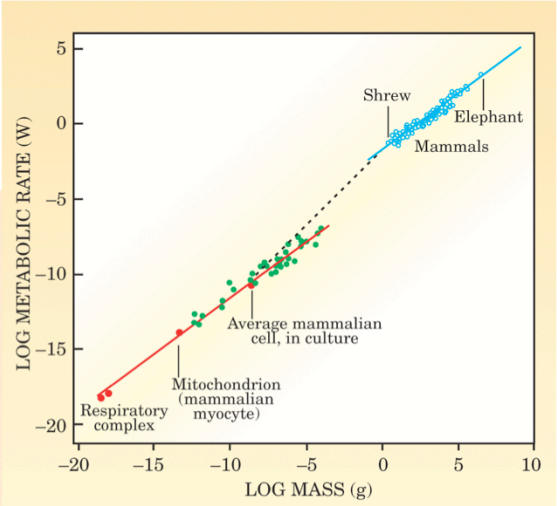
a transformation that enlarges or diminishes objects

http://www.finescale.com/~/media/images/how-to/build-great-scale-models/fsm-na1314_03.jpg?mw=1000&mh=800

Why Consider Scaling Theory?

- Puts us in the Ball Park on Information on How Big or Small an Organism may Be?
- Tells you Combinations which Don't Exist
- How Much Food must it consume?
- What is its Mass to Volume Ratio?
- How many Individuals Can the Land Sustain
- Projection and Inference of Things Easy to Measure that Represent something Hard to Measure, Tree diameter vs Mass, at Larger or Smaller Sizes

Scaling of Mass and Metabolic Energy



West and Brown, 2004

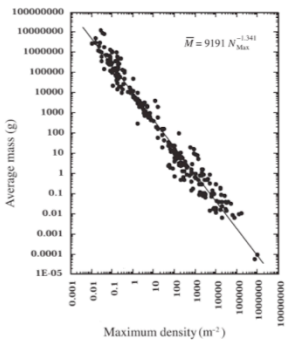
W ~ a M ^b; log W = log a + b log M

Size vs Number Density transcends 9-12 orders of magnitude in an Orderly Manner

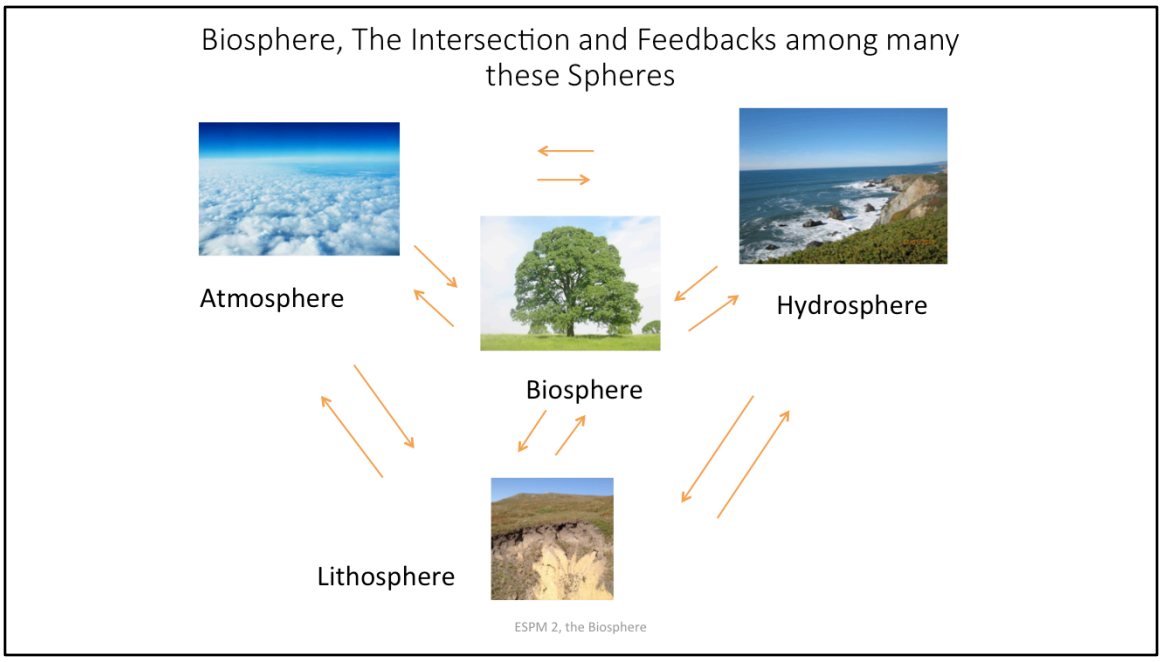
Physics Wins:
You can only be so big and sustain
so many individuals
for the resources available

Corollary 1: You can only grow so
Big and So Fast; an Ecological lesson
for the Stock Market and the
Federal Reserve.

Corollary 2: Don't Eat anything
Bigger than your Head (Mom)



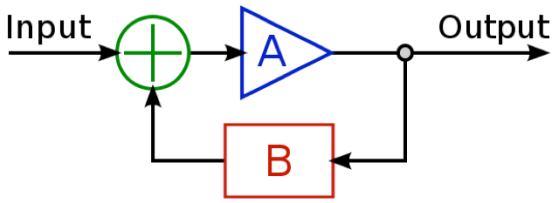
Enquist et al. 1998. Nature, 395



The biosphere is not an isolated concept, it is connected to the atmosphere, hydrosphere and lithosphere. It affects their state and fate, and vice versa. Let's discuss some of these feedbacks. How do plants affect the Atmosphere?; Vice Versa, etc, etc. Also note that life is effectively everywhere and inhabits these other spheres. Microbes, plankton, algae, fish, invertebrates live in the hydrosphere. Roots and microbes penetrate deep into the soil and lithosphere. The atmopshere is full of insects, birds, microbes, viruses, pollen and spores

What are Feedbacks?' and Why are they Important?

- Feedback
  - the return to the input of a part of the output of a machine, system, or process
- Positive Feedback
  - Amplifies the Input
- Negative Feedback
  - Mutes the Input



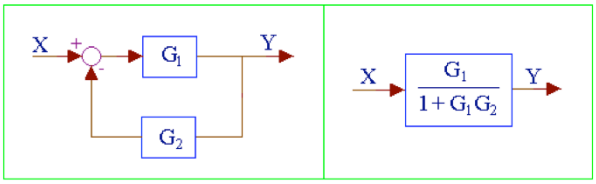
Give me some examples of feedbacks you may experience. Think about running and sprinting, what happens?
What about the thermostat in your house or this room?
What about the water level in your toilet?

Think of some natural feedbacks you can envision. Melting glaciers and icecaps?; drought and more drought, wet and more wet?

Feedback Loops

Output (Y) = Input (X) x Gain (G1) +/- Output (Y) x Gain (G1) x Feedback (G2)

$$Y = G_1X - G_2G_1Y = \frac{G_1}{1+G_1G_2}X$$



Output = (Input x Gain)/(1 – Gain x Feedback)

Output = (Input x Gain)/(1 + Gain x Feedback)

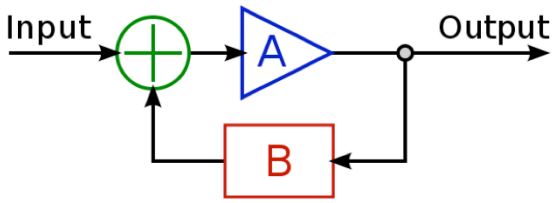
http://www.msubbu.in/sp/ctrl/Rule-6.gif

Examples of Feedbacks in Every Day Life

- Feedback Loops
  - Stock Market moves up, people are encouraged and buy more stock, Stock Market Moves up further….
  - People are miserable, people take drugs and drink to excess, their life is more miserable…
  - Richer families invest in their children and send them to better schools..they get good education, better jobs….
- Feedback Instruments
  - Water Level in your Toilet
  - Thermostat in your house

. Think about running and sprinting, what happens?
What about the thermostat in your house or this room?
What about the water level in your toilet?

Feedback on the Biosphere



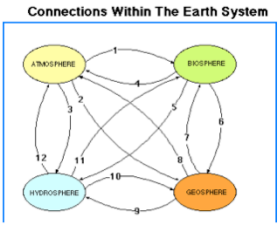
Negative feedback, Cyanobacteria produce O2 via photosynthesis; iron
Exposed to oxygen forms rust; positive O2 perturbations are dampened

Positive feedback, photosynthesis produces O2; Ozone (O3) layer is able to form;
Uv light is filtered protecting cyanobacteria; O2 levels increase;
eukaryotes are able to evolve; life explodes; plants evolve, more O2 produced

Examples of Feedbacks in the Natural World

- Evaporation humidifies the air; more moisture in the air reduces pertubations in evaporation
- Isolated plants increase the fertility of the soil by providing organic inputs and nutrients
- Snow on the ground, reflects light, keeping the air cold and more snow on the ground
- Dust on snow melts the snow, making the surface darker, melting more snow

Examples of some Specific Connections we Will Cover



Explanation of Connections

1. Atmospheric chemistry and temperature affect organisms
2. Atmospheric chemistry and temperature affect weathering of rocks
3. Atmospheric temperature affects evaporation
4. Photosynthesis affects atmospheric CO_2 concentration
5. Plants aid weathering (physical and chemical) of rocks
6. Plants control water transfer from soil to atmosphere
7. Weathering and erosion controls nutrient supply to life in the oceans
8. Volcanic eruptions add CO_2 and aerosols to atmosphere
9. Locations of continents controls circulation pattern of oceans
10. Rainfall and runoff erode the land surface
11. Soil water limits plant growth
12. Ocean circulation controls how much CO_2 is removed from atmosphere

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Examples of some of the Connections we will cover over the course

http://www3.geosc.psu.edu/~dmb53/DaveSTELLA/intro%20ESS/3.gif; good set of notes http://www3.geosc.psu.edu/~dmb53/DaveSTELLA/entrance.htm

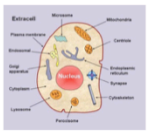
Scale Emergent Properties

..' a cell is more than its molecules, as an organ is more than its cells, and as an organism is more than its organs, in a food web, new structure emerges at every organizational level up to and including the whole web'

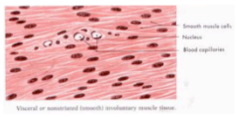
Cohen et al 2009, PNAS

One of the reasons I am fascinated with complexity is the idea of scale emergent properties. The whole acts differently than the sum of the parts

Example of Scale Emergent Property, v1

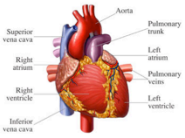


Cells

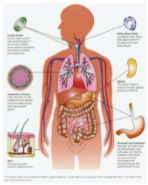


Tissue

Thought, Language, Creativity



Organs



Body

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The idea, ‘scale emergent property’ may sound odd or foreign. But it is all around us. Humans are good examples of the idea of scale emergent properties

Example of Scale Emergent Property, v2

Melting Ice Cube vs Melting Glacier

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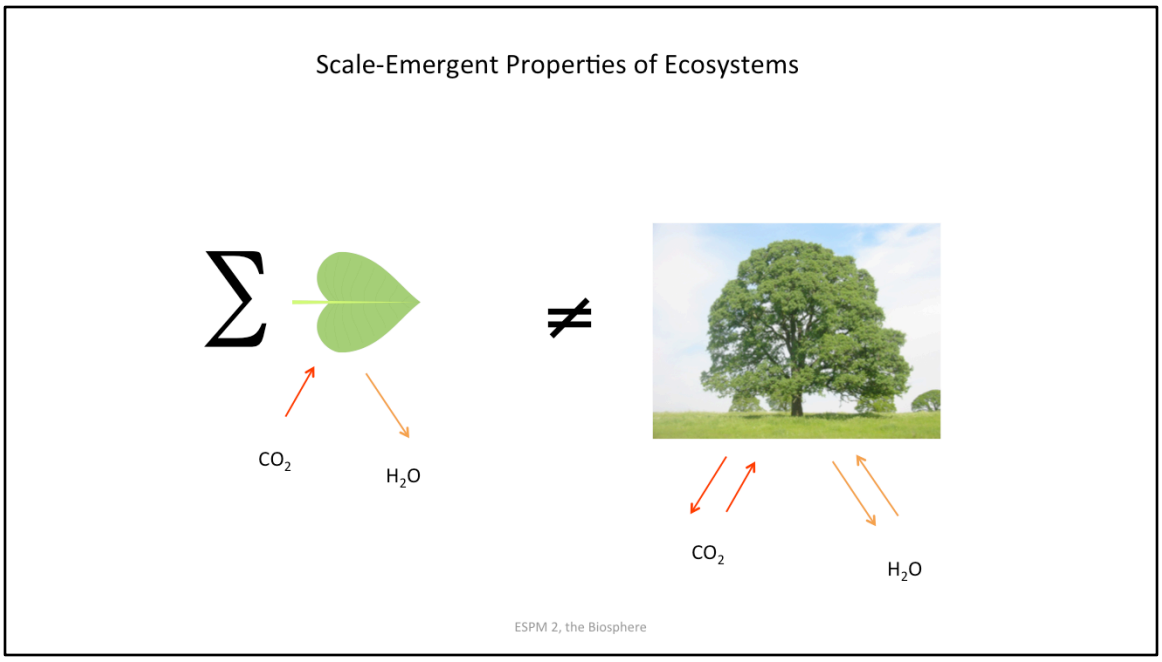
The melting of ice is complex and is something that needs to be factored better into global climate change models if we are to correctly predict the melting of the ice caps with warming, and understand their albedo feedbacks



In my realm, the sum of leaves acts differently than how the whole ecosystem functions, with regards to CO2 and water vapor exchange

Adding the leaves leads to the need to have a root system that taps water from the soil and a xylem that is a conduit for that water to the leaves and nutrients from leaves to roots. So the plumbing system of the plant will have impacts on the capacity of leaves. Conifers will grow on poorer soils, have leaves with less capacity for photosynthesis and a less conductive xylem than near by deciduous broadleaves tress, for example

Sum of the Pieces Don't Equal that of the Whole,
And Cause Scale Emergent Properties

Spruce shoot is
Much Darker in
In Natural Array
Than the display of
All the individual Needles

http://www.rawfunction.com/wp-content/uploads/2012/11/The-Art-of-Clean-Up2.jpg

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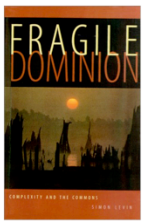
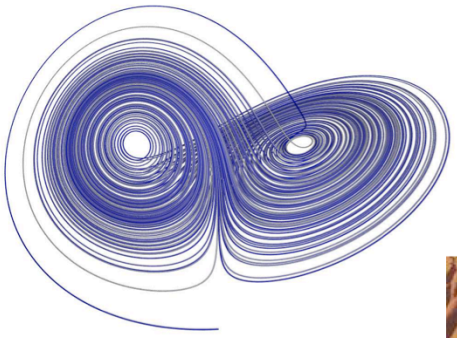
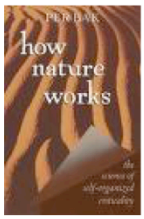
Complexity:
Creating Order out of Chaos and Establishing the Limits on Predictability





Lorenz Attractor



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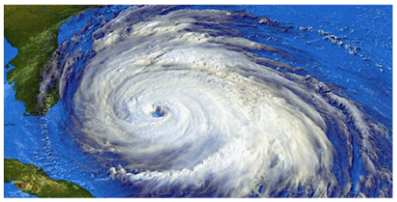
Butterfly Effect: If a butterfly flaps its wings can a Hurricane form? Idea is that complex systems are sensitive to initial conditions. The butterfly effect is often invoked. Though it may be a red herring or a fallacy as the flap of a wing is dissipated by the viscosity of the air. It does not have enough energy to perpetuate a large enough uncertainty in the variance of the wind velocity.

Self Organization in Nature

Bee hive

Flock of Bird

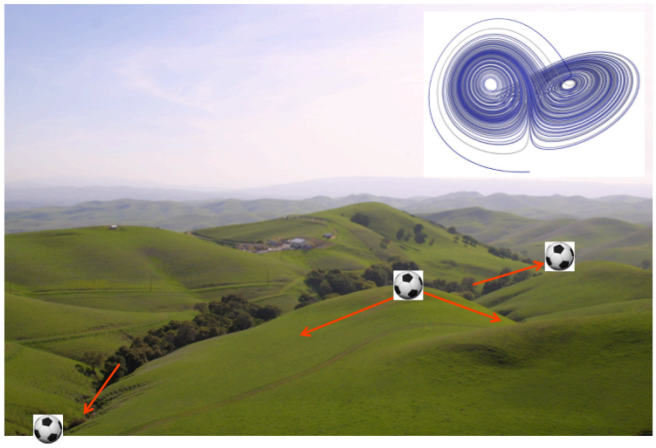


Hurricane

Tundra Polygons

Self organized structures are everywhere in nature. So the idea of complexity is important when thinking about, interpreting and managing/perturbing the biosphere

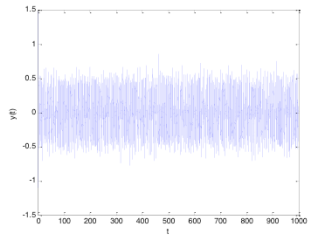
Sensitivity to Initial Conditions and Path Dependence

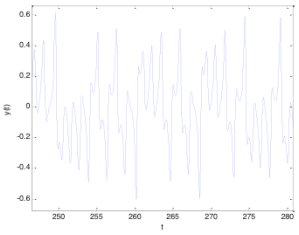


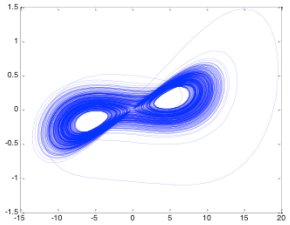
ESPM 111 Ecosystem Ecology

Lorenz found that chaos emerged due to sensitivity to initial conditions.

Lorenz Equations for Atmospheric Circulation:
The Butterfly Effect







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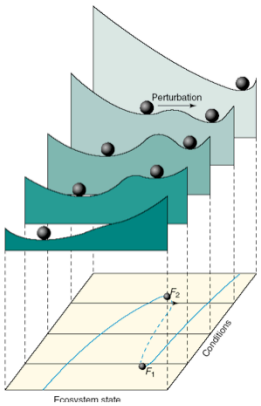
Lorenz discovered complex behavior and sensitivity of non linear equations almost by accident. He was programming the equations of motion into an early computer. He decided to truncate the initial input for simplification and got different answers. In the early days of computer science, one was likely to blame the computer. But the computer was correct and a new science was discovered. Serendipity and brilliant insights to see something when no one else has.

Non-Linearity and Complex Systems are Robust to Perturbations, they but are subject to Regime Shifts, too



Scheffer and Carpenter, 2003 TREE

A Lesson and Warning for Unintended Consequences, when Perturbing Complex Systems

Hysteresis

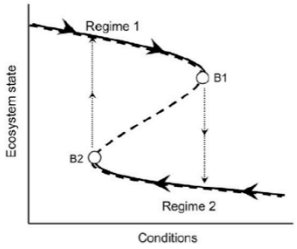
An Example of the Delicate balance between Stability and Collapse

ESPM 2 Biosphere

The many feedbacks of complex systems produce robust systems, until there is a regime shift. It is my opinion that this robustness is causing society to be cavalier about global warming. The climate system has been fairly robust to our initial insults by changing greenhouse gas forcing. But ultimately, glaciers will melt, permafrost will release vast stores of methane and CO2, and we will entire a new climate state.

Hysteresis

1.Hysteresis is the time-based dependence of a system's output on current and past inputs. The dependence arises because the history affects the value of an internal state. To predict its future outputs, either its internal state or its history must be known.



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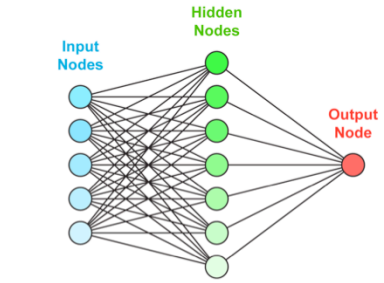
http://oceantippingpoints.org/sites/default/files/uploads/Hysteresis.png

Hysteresis is an important concept with regards to management of the biosphere, as you change a system from State 1 to State 2 based on an environmental perturbation, there is no guarantee it will recover along the same trajectory if original conditions returned.

Networks are Ubiquitous in Nature,
As they Transfer Material, Resources and Information
Most Efficiently

Process Networks, Neural Networks



http://www-d0.fnal.gov/Run2Physics/top/singletop_observation/Neural_network_image.png

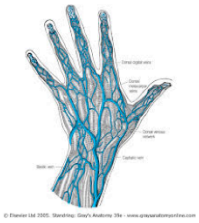
http://www.extremetech.com/wp-content/uploads/2013/09/340.jpg

ESPM 2, the Biosphere

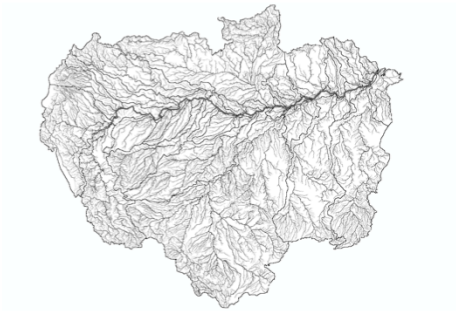
Networks and network theory are all around us. Mathematicians have borrowed the idea of neural networks, from how our brains work, to describe coupled systems that high high levels of predictability. My lab uses neural networks to predict carbon and water fluxes to and from ecosystems when direct measurements are missing and we train our neural networks with simple input information like sunlight, temperature, humidity and amount of vegetation.

Network Examples in the Biosphere

Leaves



Us



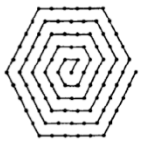
Rivers, the Amazon

ESPM 2, the Biosphere

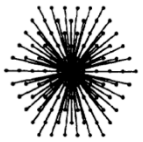
Networks are ubiquitous throughout the biosphere. Life needs to move material and energy to and from sources and sinks. Theory has shown that networks are the most efficient way to do this.

Fractal nature of Nature, causes a Fourth Dimension, a volume filling dimension, to play a role and affect the Scaling Power Laws of Nature

Connectivity of River Drainage Networks:
Minimize average path and length of the network



'Spiral'; long average path to the outlet (<L>= 45); short integrated path for whole (L= 90)



'Explosive'; every parcel is directly connected to output (3.37); total path of the system is large (233)

'Branching', best of 2 extremes, quasi-direct path to output (3.73) and quasi-short integrated path (90)

Rodriguez-Iturbe et al 1992 WRR

What type of river networks are possible and why do branched networks tend to form?

Fractal Geometry, Space-Filling Perspective,
adds 4th spatial dimension

Area (a), Volume (v), Length (l), Density (ρ) Scaling:
1/4 Power Law Dependency

West et al 1999 Science

End member size is finite, leading to 4th power scaling.

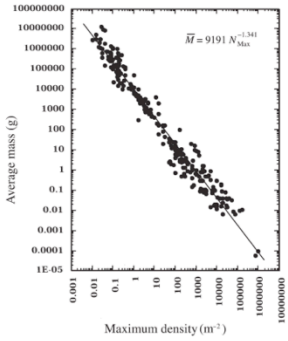
Examples of Fractal (1/4th Dimension) Power Law Behavior in Nature

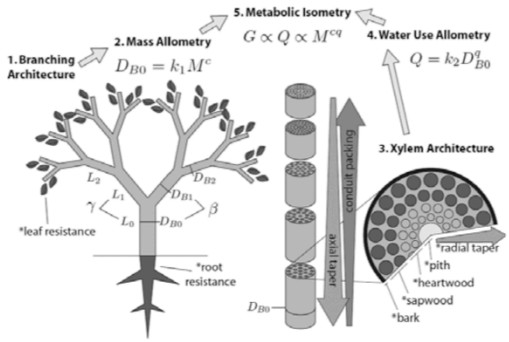
Rate of Metabolism with Body Mass

Density of Trees with Mass

Species diversity with Area

Tree Height or Leaf Area with Trunk Diameter



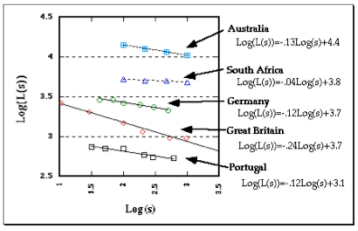


Sperry et al 2012 Functional Ecology

Examples of power law scaling and branching in plants

Power Law Behavior:
The World is Fractal

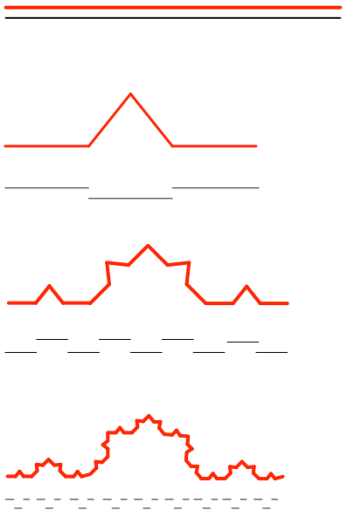
http://upload.wikimedia.org/wikipedia/commons/2/20/
Britain-fractal-coastline-combined.jpg



http://www.vanderbilt.edu/AnS/psychology/cogsci/
chaos/workshop/Fig4.2.GIF

Fractals exhibit similar patterns at increasingly small scales.

Fractals and Self Similarity

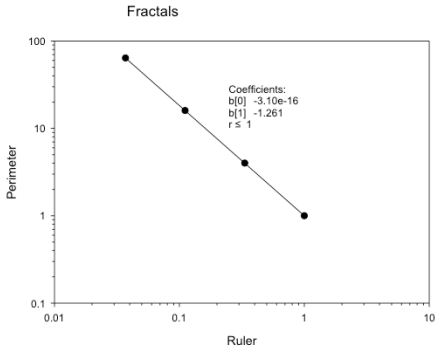


1/1

4/3

16/9

64/27



Take Home Points

- The Biosphere is Connected to Air, Water, Land
- The Biosphere Operates across +Decades of Time and Space Scales
- The Biosphere is a Complex System, with Feedbacks, Hierarchy of Scales, has Branched Networks to Facilitate Transfer of Mass and Energy, exhibits Scale Emergent Properties and Self Organization
- We have to Be Careful about How we Perturb the Biosphere, as we Depend upon it for the Sustenance of Life
- Scaling Laws show what is possible and impossible as you get bigger or smaller

ESPM 2, the Biosphere

This background is important as our management and modification of the biosphere is not simple. By ignoring the complexity of the system we are vulnerable to many unintended consequences. An example of unintended consequences? Just think about the impact of the societal choice to forsake nuclear power and instead depend upon fossil fuels to energize our societies. While the events at Chernobyl, Three Mile Island and Fukashima have indeed been terrible, many more people have died directly and indirectly due to the impacts of global warming from greenhouse gases and in the retrieving of fossil fuels from the ground. And as we study environmental change the pace of species extinction and habitat loss continues to accelerate.

Discussion Challenges and Homework

- Discuss examples of:
  - Chaos, look at the Pendulum video
  - Positive and Negative Feedbacks in your Life and the world about you
  - Examples of Scale emergent Properties
  - Examples of Unintended Consequences
  - Relate how your personal examples may help you better understand and study the biosphere
- Reading
  - Chapter 1, pg 1-18
  - The Pendulum effect http://youtu.be/RrX2yTGJ6N0

The Study of the Biosphere is:

- Multi-, Inter- and Intra- Disciplinary
  - Biology, Physics, Chemistry, Math, Computer Science, Engineering, Remote Sensing
- Consists of Small to Large Components that Operate on fast to slow time scales
- Need to think of it as a Complex System
  - How the parts interact to affect the performance of the whole
  - The sum of the parts don't necessarily equal that of the Whole…Scale Emergent Properties
- Reductionist vs Wholistic
- Bottom-Up vs Top Down