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Climate Change Impacts on Soils

Reactions, Processes, Interactions and Feedback Controlling Elemental Cycling in Soil Systems and Interfaces

Nik Qafoku, Chris Murray and Chris Brown

Geosciences Group, Pacific Northwest National Laboratory
Richland, WA

Contributors and Collaborators: Jay Grate, Yilin Fang, Janelle Downs, Sherry Cady, Nigel Browning, Jim De Yoreo, Amity Anderson, Niri Govind, Nancy Washton, Karl Mueller, Tim Scheibe, Vanessa Bailey, Nancy Hess

ACS Spring Annual Meeting 2014
Dallas, TX
March 18, 2014

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The Argument: Climate change

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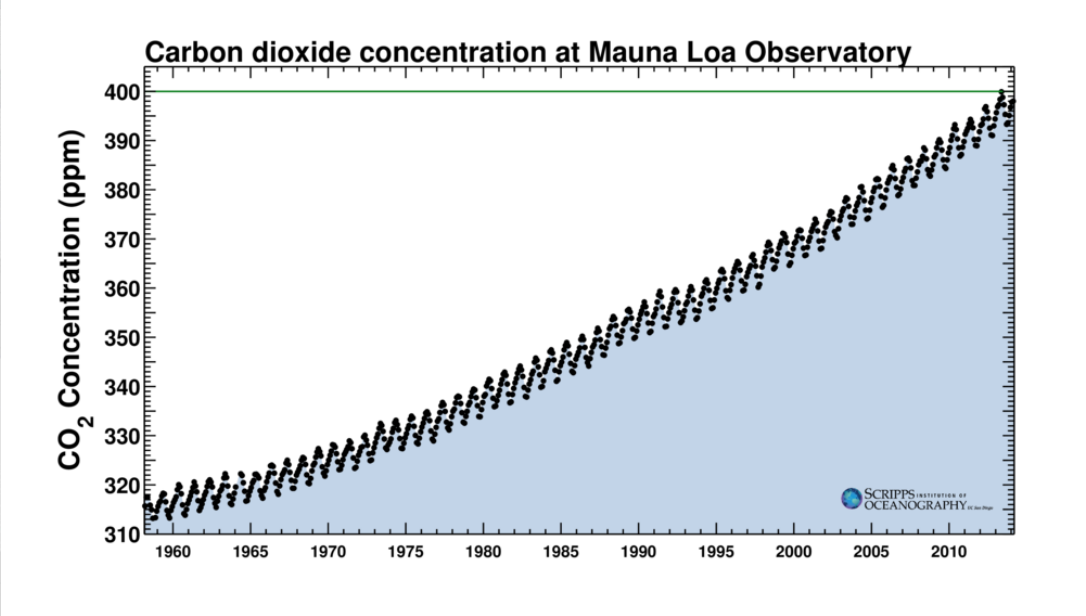
The Keeling Curve



http://keelingcurve.ucsd.edu/

www.sciencemag.com

"I'm not here to debate what's not debatable. The threat from climate change is real and urgent. The science fully demands a prudent response."
Dr. Ernest Moniz

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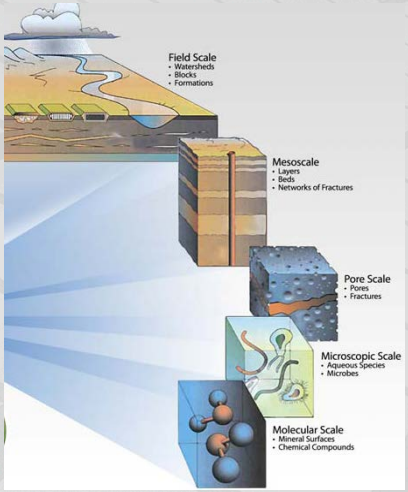
New Directions in DOE-SC Subsurface Science and Terrestrial Ecosystem Programs

Climate Science Program



Subsurface Science Program

Terrestrial Ecosystem Program

- State-of-the-art climate-land models utilize km-scale grid sizes
- Molecular-scale processes are studied within nano/micrometer-scales
  - 9 orders-of-magnitude scaling gap!
- Source/sink soil behavior depends on molecular-scale reactions
- Incorporation of molecular-scale process knowledge is limited by:
  - the complexity of the soil system (reaction network)
  - limitations in model up-scaling schemes
  - limitations in computational power

The Challenge: Complexity of the soil system

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- **The soil responses to climate change variables are multifaceted and rather complicated because of:**
  - **The presence of an intricate network of sequential, simultaneous and/or coupled (often time-dependent) chemical, biological and hydrological reactions and processes**
  - **Climate extremes (heat wave and dry spells) induce poorly understood and interconnected, long-lasting effects in soils**
  - **Chemical elements, nutrients and contaminants involved in these reactions and processes are distributed in the soil solid, liquid and gas phases**
  - **Scale-dependent effects related to the solid phase mineralogical, chemical and physical spatial heterogeneities**

http://esask.uregina.ca

http://www.123rf.com

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Climate change impacts on soils
A scale-dependent perspective

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- **Climate change variables:**
  - Higher atmospheric CO_2 concentrations (400 ppm or greater)
  - Higher temperatures (2-4 ^{0}C)
  - Changes in daily, seasonal and inter-annual temperature
  - Changes in the wet/dry cycles
  - Intensive rainfall and/or heavy storms
  - Extended periods of drought
  - Extreme frost
  - Heatwaves and increased fire frequency

- **Soil related consequences:**
  - Significant/dramatic changes in soil properties
  - Surface water and groundwater quality
  - Food (national) security
  - Water supplies
  - Human health
  - Energy
  - Agriculture, forests, ecosystems

- **Scales**
  - Temporal scale: months to year, years to decade, decades to century, centuries to millennium, and millennia to epoch/era
  - Spatial scale: molecular, nano, soil particle, aggregate, horizon, type, order, regional and global scale

Research Area 1
C pools and budgets

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- **There is a need to understand how climate change variables would:**
  - **disrupt the balance between C utilization by plants and microbes and C emissions:**
    - **soils are the largest repository of organic and inorngaic C in the terrestrial systems**
  - **affect the primary controls on soil CO_2 flux and soil C sequestration and storage capacity (including highly stable pyrolytic C) under chronic soil warming conditions**
  - **affect the efficiency of soil amendments (e.g., biochar additions)**
  - **disturb the macronutrient (e.g., N and P), micronutrients (e.g., Fe and Mn) and metal cycles in soils, and their gradients and interfacial fluxes**

Research Area 2

Impacts on Species, Community, and Ecosystem Structure

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- **Interactions between plant and soil communities play a major role in determining the impact of climate change on ecosystem functioning and the carbon cycle**:
  - the mechanisms involved operate over a wide range of spatial and temporal scales
- **Significant potential exists for climate change to decouple plant-soil interactions at multiple scales:**
  - ranging from individual and physiological responses at local scales to community structure and species immigration at regional and global scales
- **Understanding how and where climate change destabilizes ecosystem carbon fluxes requires an integrated research approach to:**
  - Determine indirect impacts of plant species redistribution, community reordering and potential biome shifts on soil carbon, and improve our understanding of how climate change impacts on plant-soil interactions and carbon cycling vary across communities ecosystems, and biomes
  - Predict how climate-induced changes in soil structure and mineral nutrient availability affect the growth and structure of plant communities and subsequently alter the amount and quality of plant-derived carbon entering soil via root exudates and plant litter (shoot and root), and identify cascading effects on soil organisms and the processes of carbon cycling

Janelle Downs, PNNL

Research Area 3
Abrupt microbiological and vegetation shifts

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- **The effect of climate change on forcing abrupt microbiological and vegetation shifts**
  - **At what scales would this occur (locally, regionally and/or globally)?**
    - **What would be the dependence of those shifts on soil properties?**
  - **Greater biomass (the "CO_2 fertilization" effect) but the response to increasing CO_2 concentrations could be complex**
    - **To what extent would this response be affected by yield-limiting soil properties and the availability of other yield-limiting factors, such as soil N and P and other essential nutrients?**
  - **How would climate change affect plant growth and evapotranspiration and their interactions and combined effects in different soil types at field and temporal scales that are relevant to policy- and decision-makers?**

Research Area 4
Soil loss and health

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- **Effects on soil loss (via erosion) and soil health degradation**
  - **Several climate change induced processes act to degrade soils including, erosion, compaction, acidification, salinization, toxification, and net loss of organic matter**
  - **Climate change coupled with population growth would further increase the pressure on soils currently under production and result in further degradation of soil resources**
  - **Scientific questions to be addressed are:**
    - **Spatial distribution and termporal dynamics of soil properties most likely to be affected by climate change**
      - **soill depth, soil structure, soil bulk density, soil permeability and available soil water holding capacity**
    - **What would be the spatial-temporal interactions of soil properties to identify the most vulnerable areas or the so called “hot spots” for a targeted strategy in addressing the impacts on soil-ecosystem functions and human lives?**

Research Area 5
Accelerated weathering

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- Controls on biotically- and abiotically-promoted accelerated weathering of soil minerals and organic matter
- Impacts on the stability of soil inorganic, organic and mixed aggregates
- Important scientific issues:
  - Dissolution followed by C sequestration in neo-phases (i.e., carbonate mineral)
  - Release of nutrients (or contaminants) that promote (or inhibit) microbial activity, plant productivity and biotic C sequestration
  - Mineral dissolution/OM mineralization and C release back to atmosphere
  - Release of elements and potential contaminants in surface waters
    - rivers, lakes and oceans (e.g., changes in freshwater and marine environments may contribute to reduced Chinook salmon survival and lower population productivity)
    - Ocean acidification
  - Are these reactions and processes spatial- and/or time-scale dependent?

PUF System

Scale-dependent investigation of weathering

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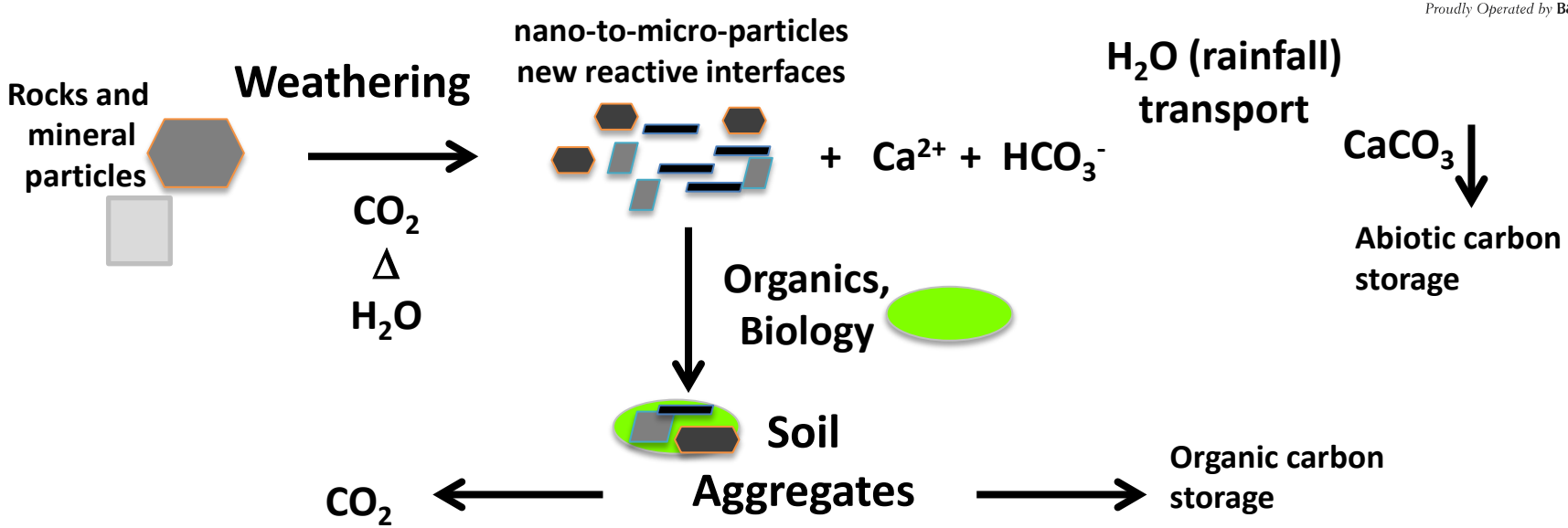

- Weathering and aggregate creation is initiated and observed using high resolution in situ TEM tools imposing a variety of environmental conditions under static and dynamic conditions, including conditions to artificially accelerate the weathering process
- We will also use in situ AFM to understand how the change in soil chemistry brought about by accelerated weathering alter the rates of mineral dissolution and the precipitation of secondary phases on both inorganic and organic surfaces in real soils.
- Define the parameters for microscopic rate equations that are needed to develop up-scaled models of weathering founded on a predictive understanding of the underlying mechanisms in much the same way as atmospheric chemical reactions are included in climate models.

Natural Scales	Tool Scales	BioParameters
Molecular	DTEM	Enzymes
Particle	AFM	Microbes
Aggregate	DFS	Plant roots
	Microfluidic	
	PUF-Column	

Jim De Yoreo, Nik Qafoku, Jay Grate

Modeling -- Effect of CO_2 and temperature on soil mineral weathering

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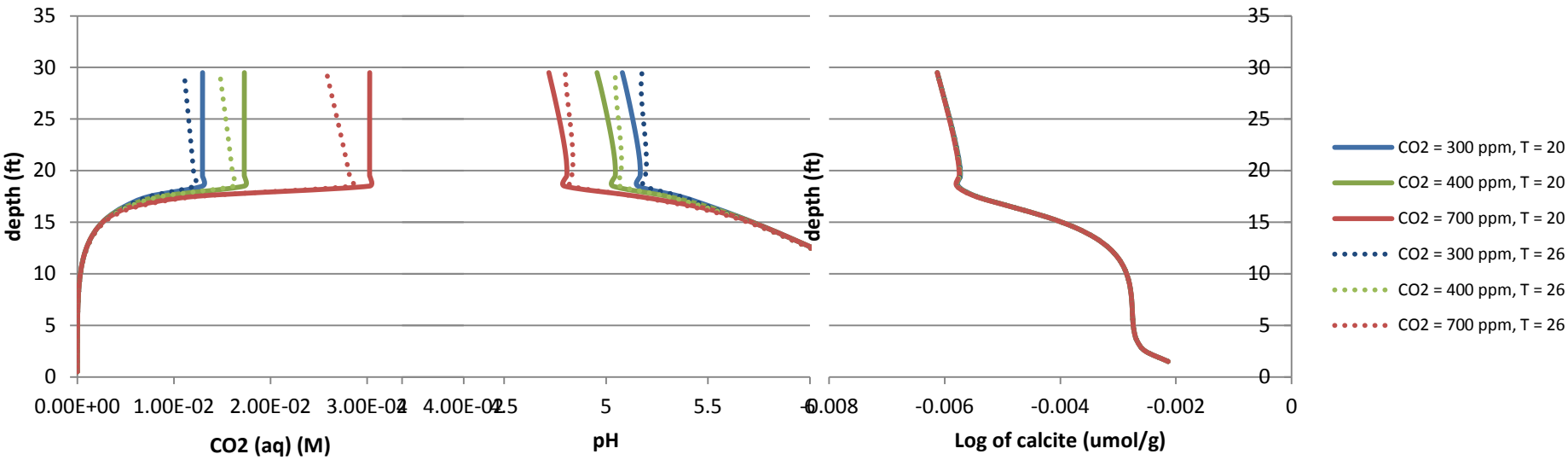
Conditions

- One dimension, vertical column, 30 ft long, nonisothermal two phase model
- IC: pH = 7.3, calcite = 1 µmol/g
- BC: Bottom: no flux, outflow for solute,
- Top, Neumann flux 3 cm/yr, Temperature 20 C and 26 C, CO2 300 ppm, 400 ppm and 700 ppm
- Assumption: TST rate law for calcite precipitation, rate = $f(T/T_{ref})$. T_{ref} is reference temperature = 20 C.
- Model: 10000 days at pCO2 = 300 ppm to obtain initial condition. For each case, one year was run for the final results.

Findings

- Increase of pCO_2 causes pH decrease in the soil, soil mineral dissolution followed by carbonate mineral precipitation
- Temperature increase has the opposite effect (non-isothermal simulation is important)



Yilin Fang and Nik Qafoku

Chemical Imaging Initiative (PNNL)
Molecular-scale control on SOM and soil minerals interactions and aggregate stability

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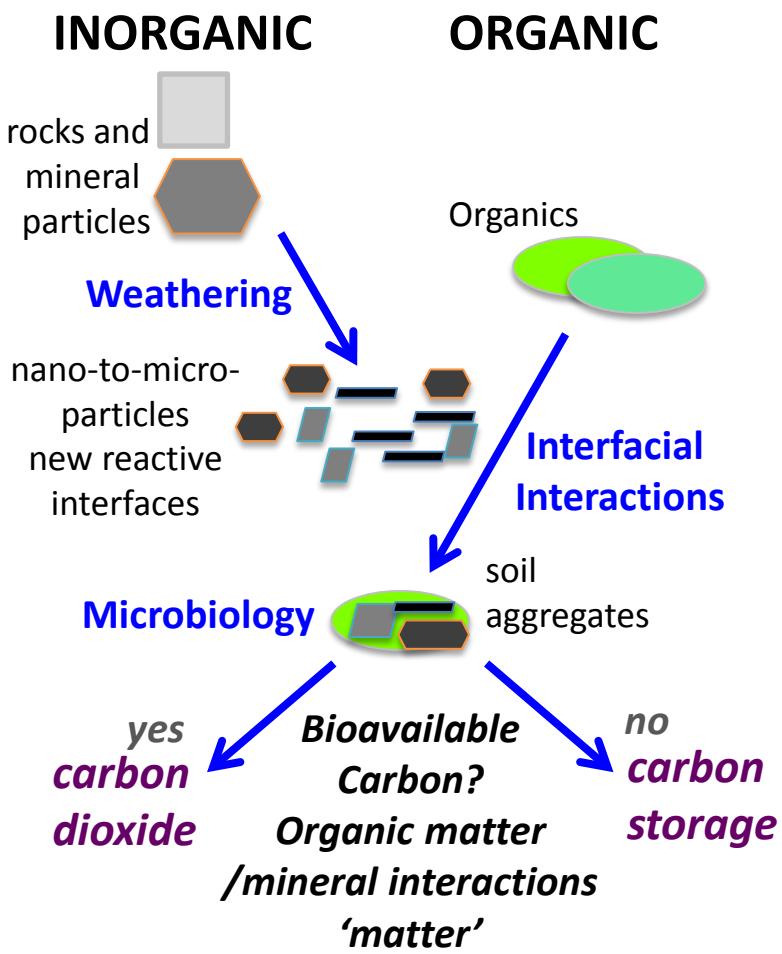
- New perspectives on the structure and mineralization of soil organic matter:
  - Soil aggregates are complex structures containing OC and mineral particles, with features at the nanoscale
  - Role of the chemical structure of SOM, and the associations of SOM with inorganic mineral surfaces
  - The association of OC with mineral particles creates abiotic controls on SOC mineralization, and hence on carbon storage/sequestration
  - These processes will be influenced by climate change variables carbon dioxide, heat, and water

Hypothesis: Organic mineral associations will develop concurrrent with mineral weathering processes, ultimately affecting SOM decomposition

Approach: Investigate, with a bottom up approach, from mineral weathering as it is affected by climate change variables, to weathering in the presence of OC



Process level understanding and representation is lacking from carbon cycling models at larger scales

Jay Grate, Nik Qafoku, Sherry Cady, Nigel Browning

EMSL Project

Understanding molecular-scale complexity and interactions of soil organic matter

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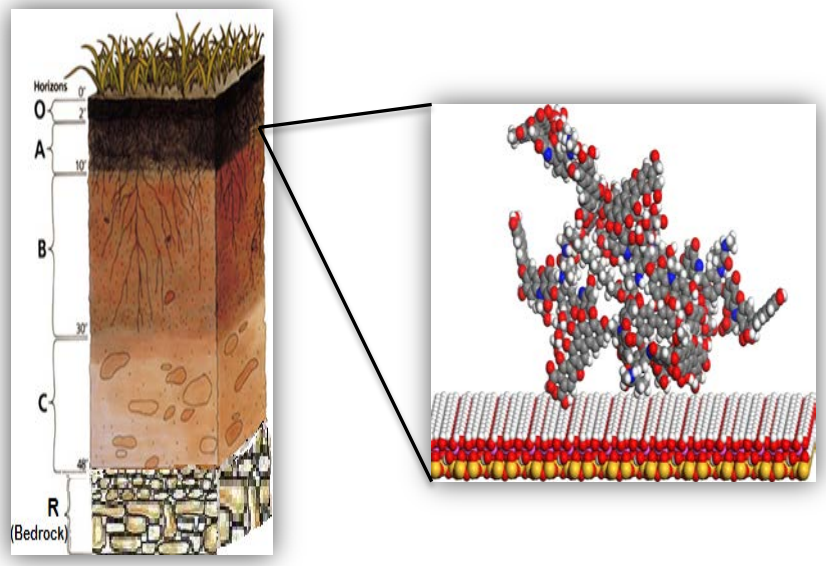
"We know more about the movement of celestial bodies than about the soil underfoot" – Leonardo da Vinci, circa 1500

EMSL

- **Summary/Essence:**
  - Combined computation and experiments for molecular-level elucidation of soil organic matter (SOM) structures and interactions with minerals and ions
- **Importance of studying soil/SOM:**
  - Soil is largest terrestrial source/sink of global carbon
    - Accurate depiction needed for earth carbon cycle models
  - Soil fertility for food, fiber, fuel, ecosystem
    - SOM moisture and nutrient retention/release
  - SOM contaminant sorption/remediation
  - Molecular-level understanding of SOM structure and interactions is largely unexplored



Amity Anderson, Niri Govind, Nik Qafoku, Nancy Washton