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Modeling the Critical Zone: Challenges and opportunities for network science

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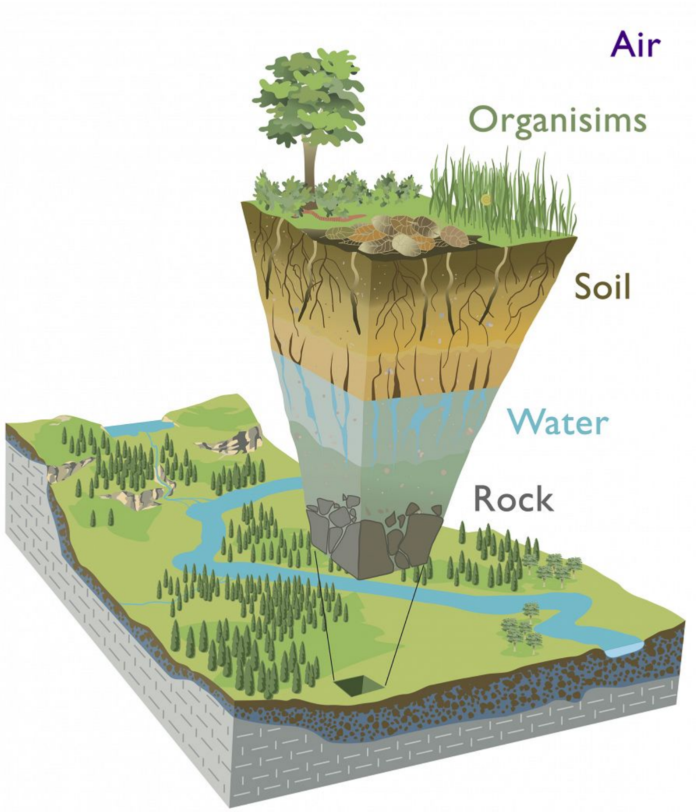
CSDMS Annual Meeting

Reynolds Creek
Critical Zone Observatory

Takeaways…

- Critical Zone Observatories (CZOs): a network of sites to advance fundamental critical zone understanding
- Models are critical tools for gaining insight into CZ processes
- CZO modeling efforts at present are robust, but fragmented
- Opportunities abound… (but maybe not money, yet)

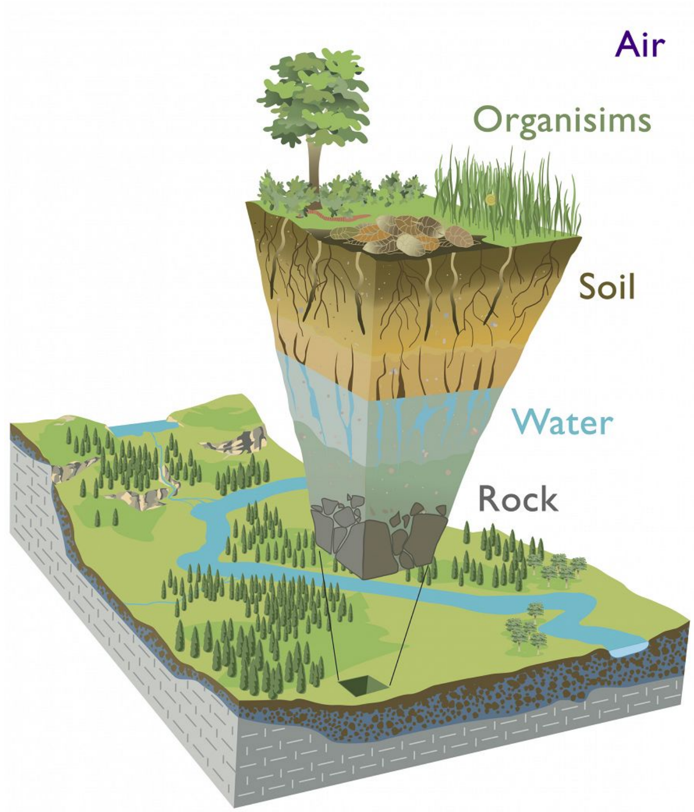
What is the critical zone?



- From the bedrock to the top of the canopy
- Where rock meets life

Illustration modified from Chorover, J., R. Kretzschmar, F. Garcia-Pichel, and D. L. Sparks. 2007. Soil biogeochemical processes in the critical zone. Elements 3, 321-326. (artwork by R. Kindlimann).

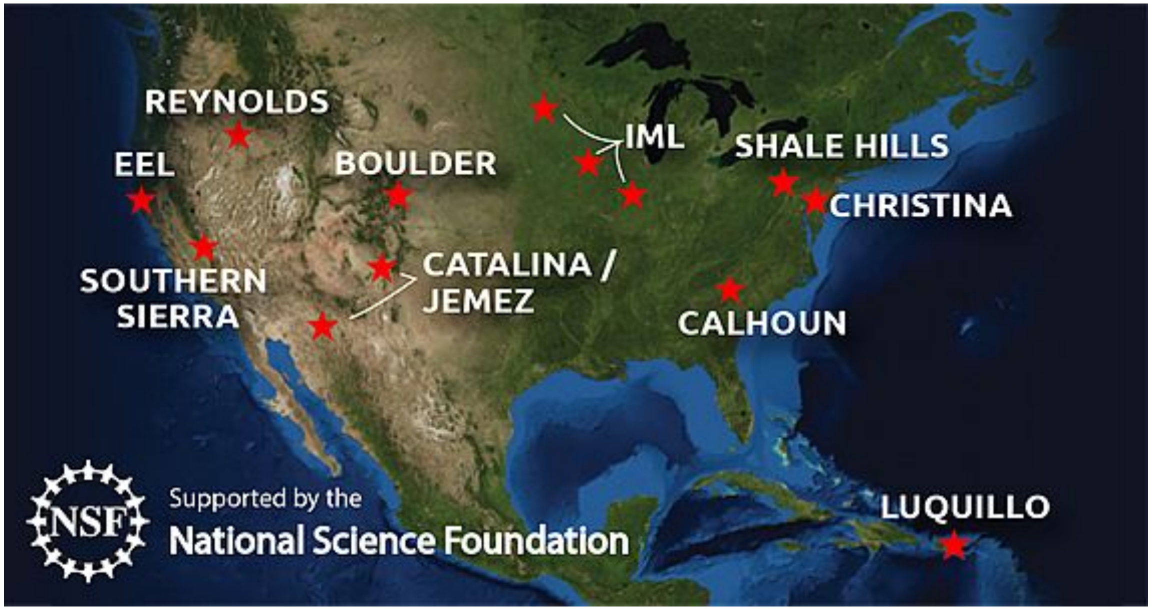
What is the critical zone?



- From the bedrock to the top of the canopy
- Where rock meets life
- Where rock ***becomes*** life

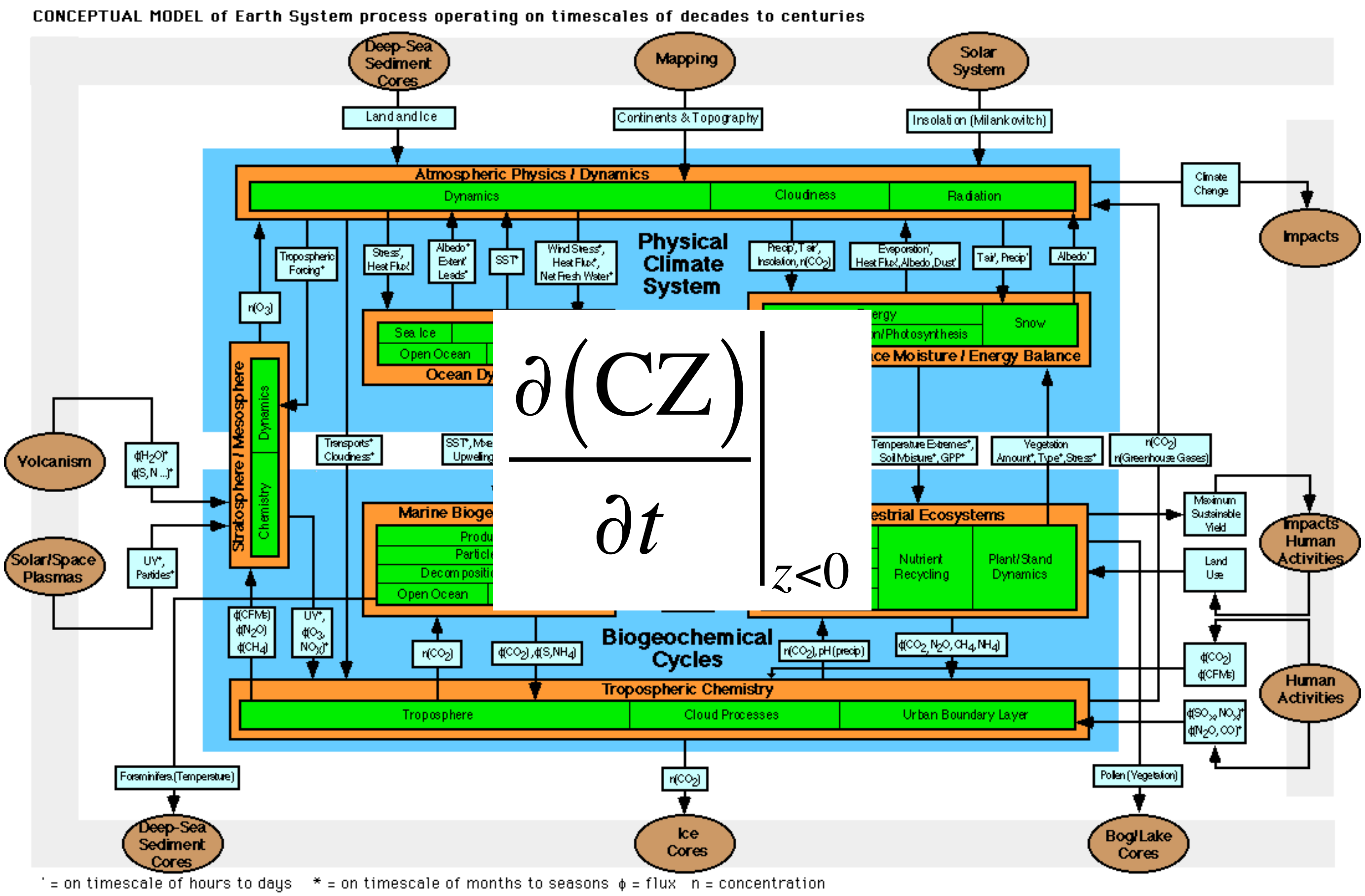
Illustration modified from Chorover, J.,
D. L. Sparks. 2007. Soil biogeochemica
Elements 3, 321-326. (artwork by R. Kindlmann).

A Network of Sites for CZ Science



- 10 CZOs established in 2 competitions
- Network office (Lou Derry, Tim White), data team (Anthony Aufdenkampe)
- International CZOs in Europe, Australia, China

The CZ as a central component to ESMs



$$\left.\frac{\partial(\mathrm{CZ})}{\partial t}\right|_{z<0}$$

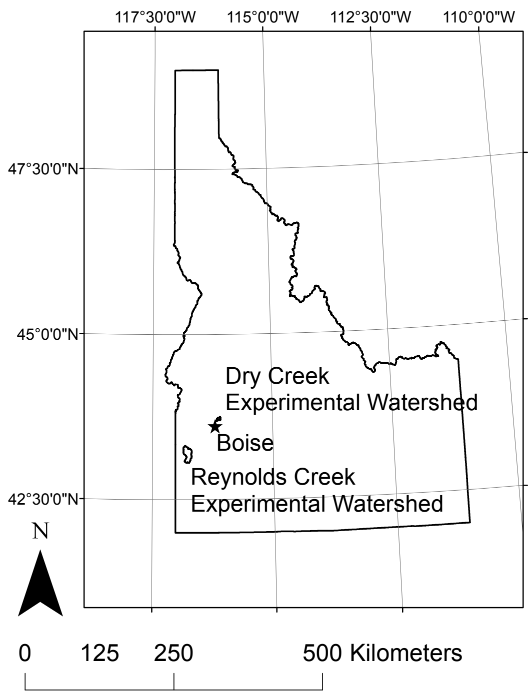
Bretherton, 1985

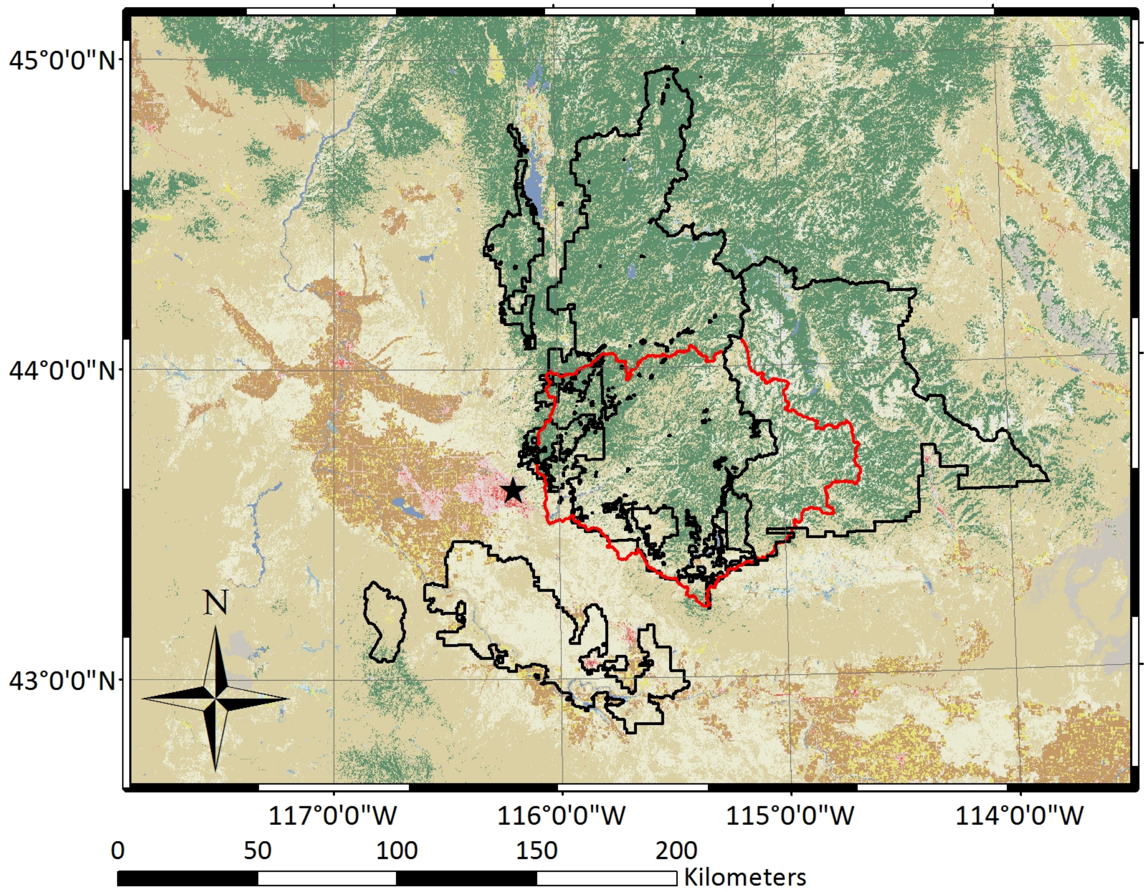
Some specific examples from Reynolds

- Background:
  - USDA ARS experimental watershed since the 1960s
  - Rich historical and contemporary datasets
- Key issues:
  - Large gradients in elevation, slope, aspect, vegetation cover
  - Land management activities (fire, grazing)
  - Significant warming in the last 50 years

Charge: Gain insight on how distribution of soil carbon changes under future scenarios of climate change, land management…

Geographic setting and context





Reynolds is part of a larger platform of cold desert sites for surface dynamics research in the Great Basin

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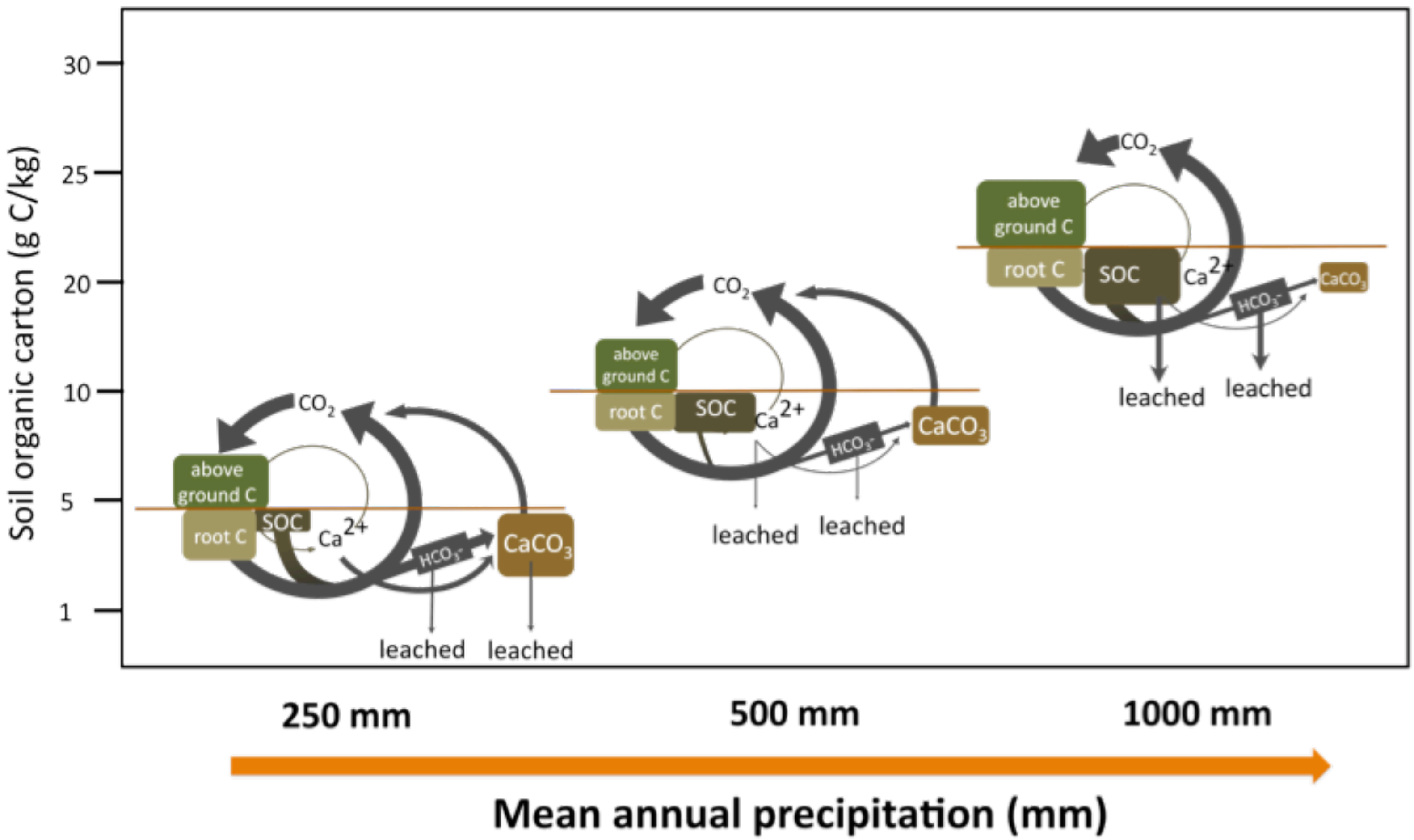
Reynolds Creek: A CZO for soil carbon



Modeling framework

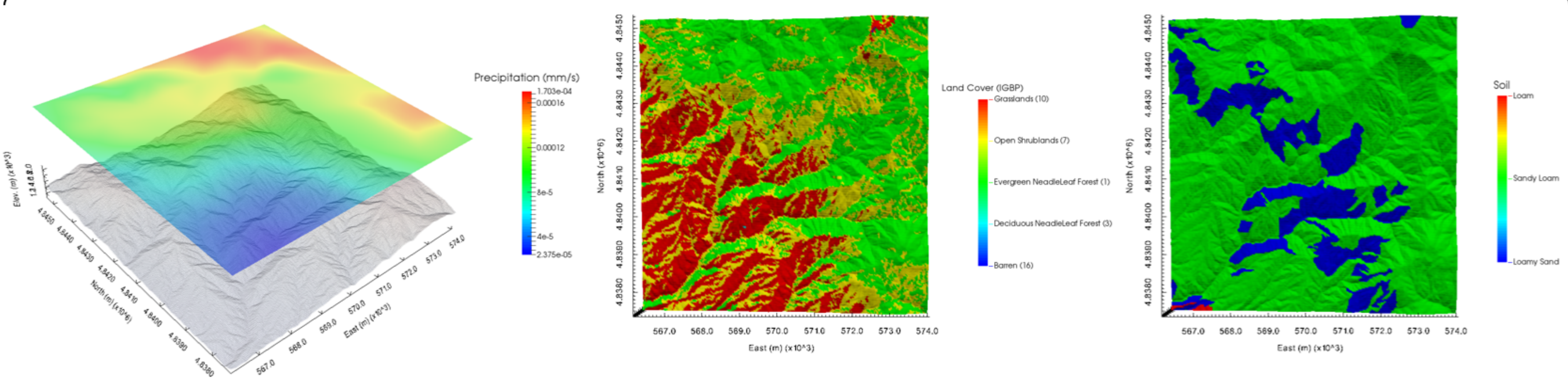
Atmosphere — WRF

\+

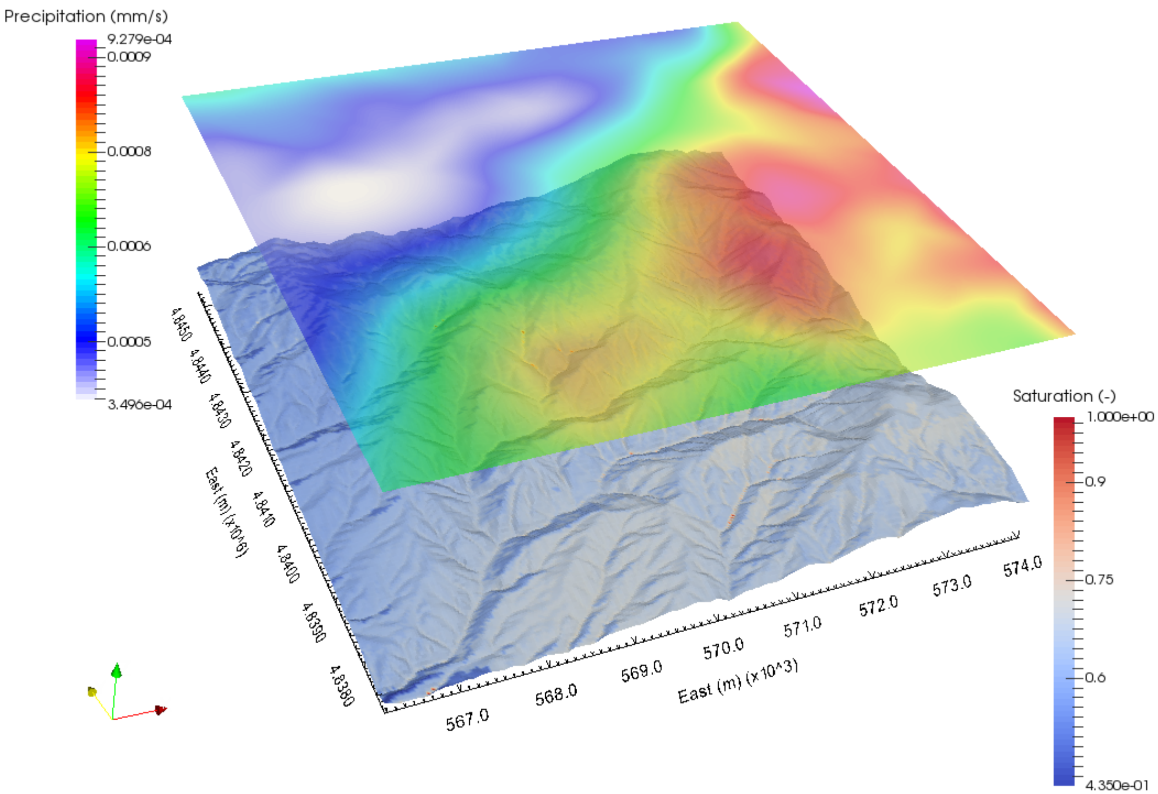
Land (surface) — CLM COMMUNITY LAND MODEL

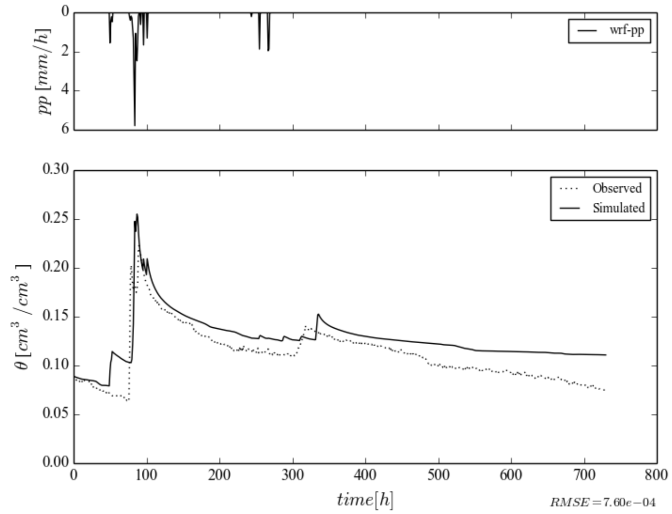
\+

Subsurface flow — The ParFlow Project: *modeling surface and subsurface flow on high performance computers*

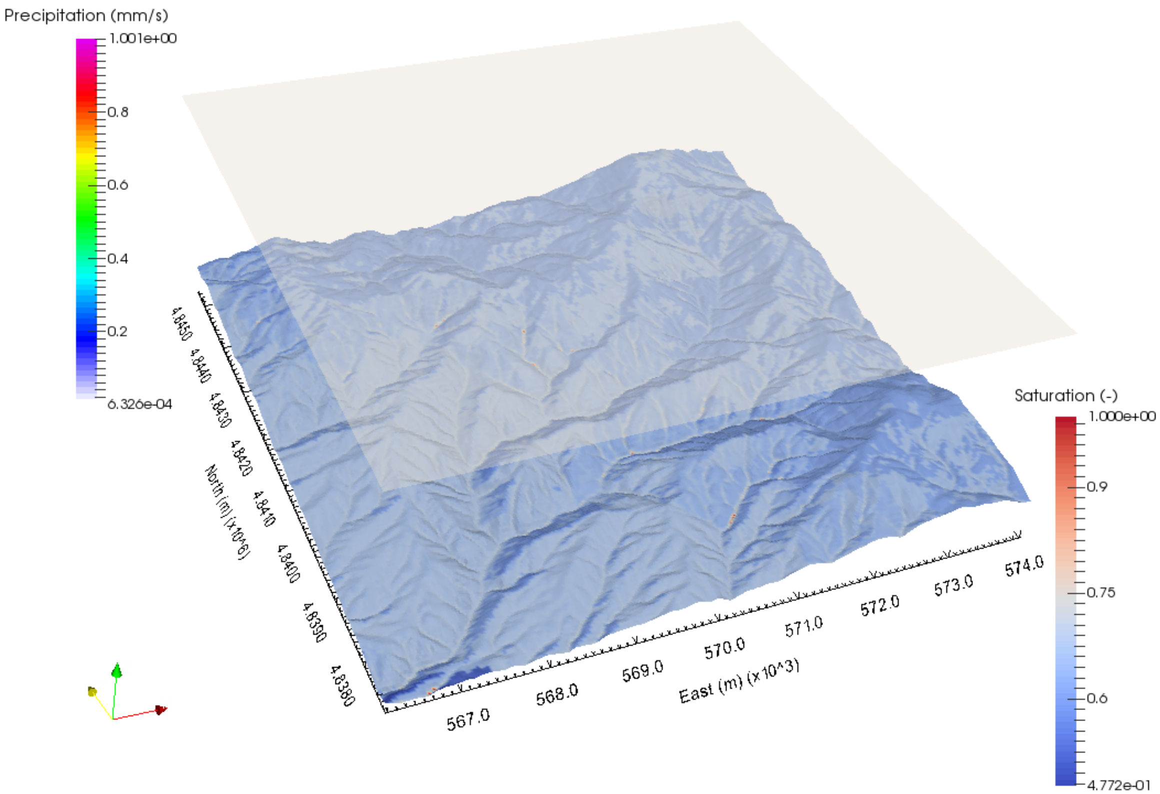


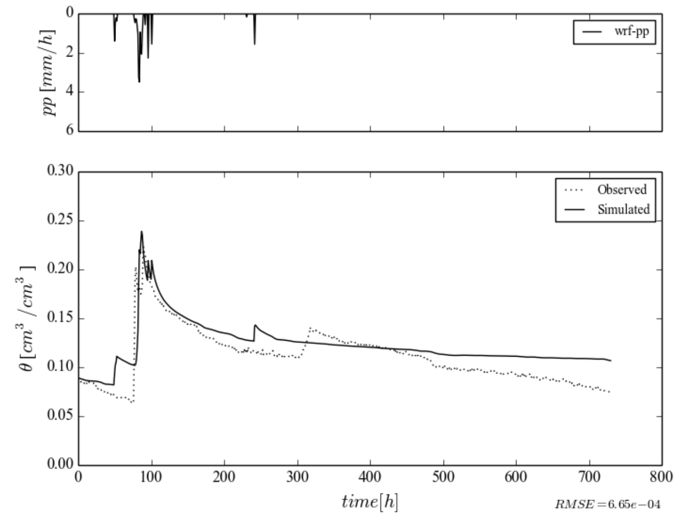
WRF: 1 km; ParFlow 30 m





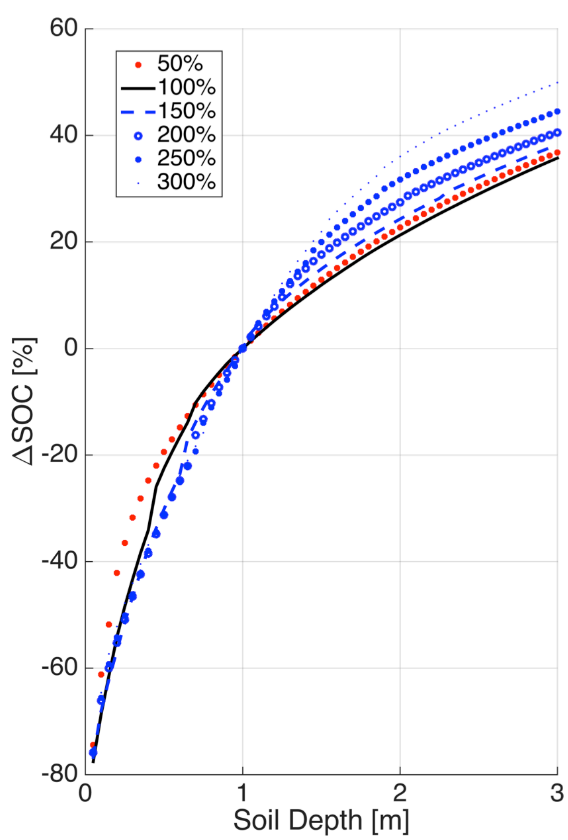
WRF: 9 km; ParFlow 30 m

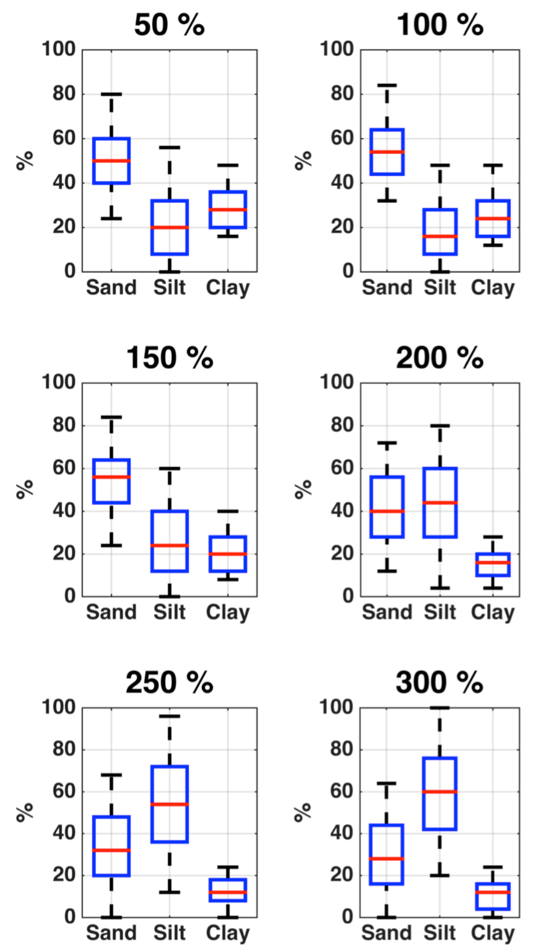




Resolution of forcings important for BOTH precipitation amount AND phase

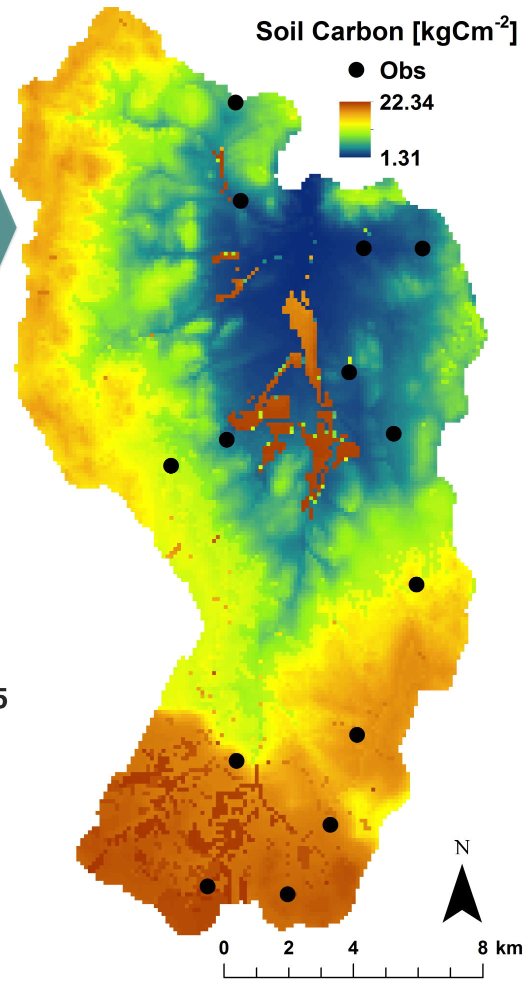
Ramifications for predicting SOC





But it's not the only story…

Figure 10. AT RIGHT: Distributed spin-up simulation soil C estimates. Black dots indicate locations of field observations (*n*=14).



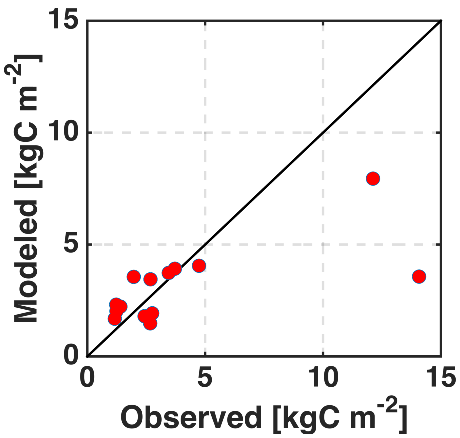


Figure 9. ABOVE: Modeled vs. observed SOC (top 30 cm).

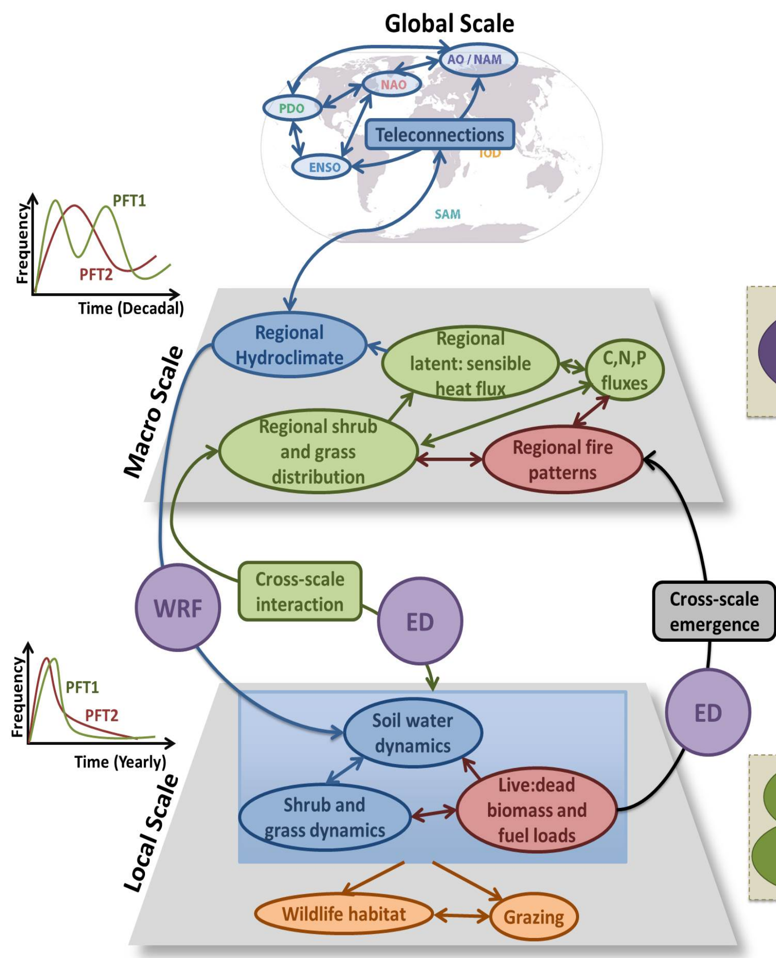
RMSE (low C) = 0.864 kgCm^{-2}

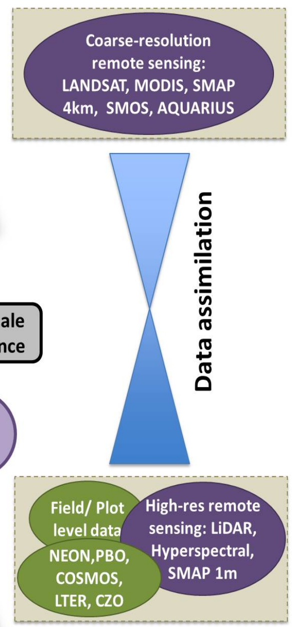
RMSE (all) = 3.125 kgCm^{-2}

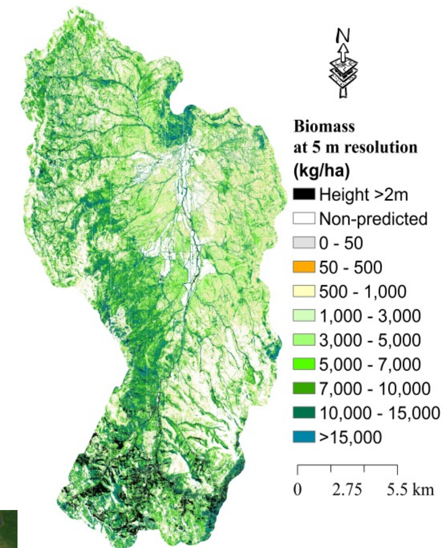
Opportunities on the horizon

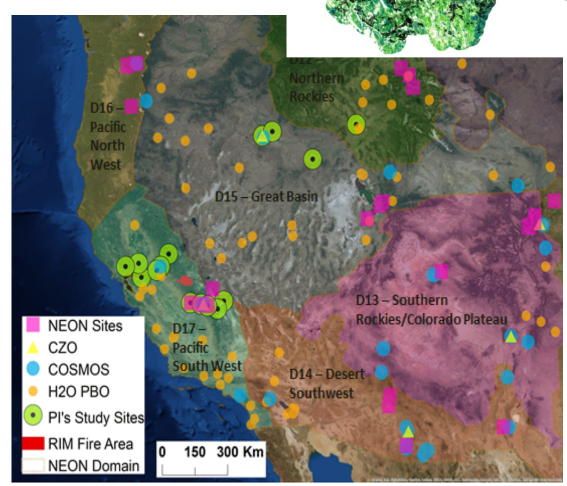
- Integration of models and data to advance understanding of cross-scale interactions
- Understanding of hillslope-scale controls on global water, energy, biogeochemical cycling
- Explicit representation of human dimensions of disturbance on the critical zone
- Modeling ***frameworks*** to facilitate network modeling efforts

Synthesis between models AND data





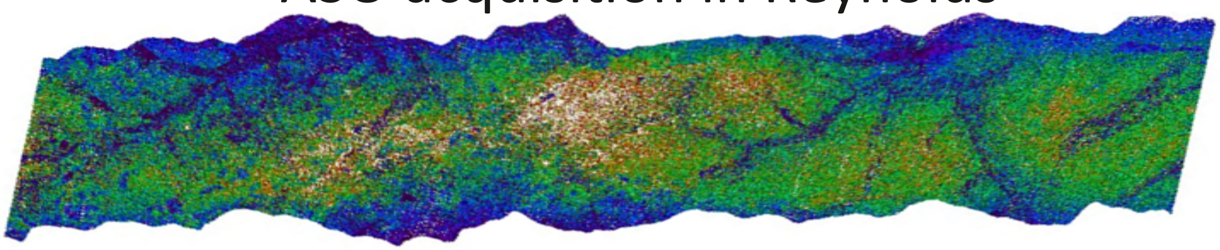


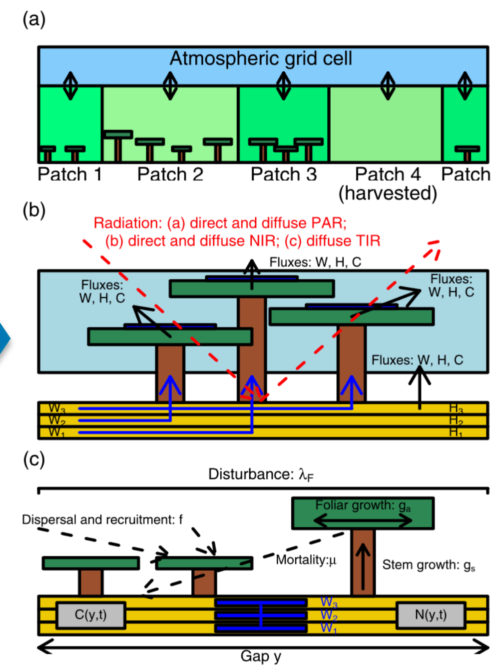


Synthesis between models AND data

AVIRIS-NG acquisition in Reynolds

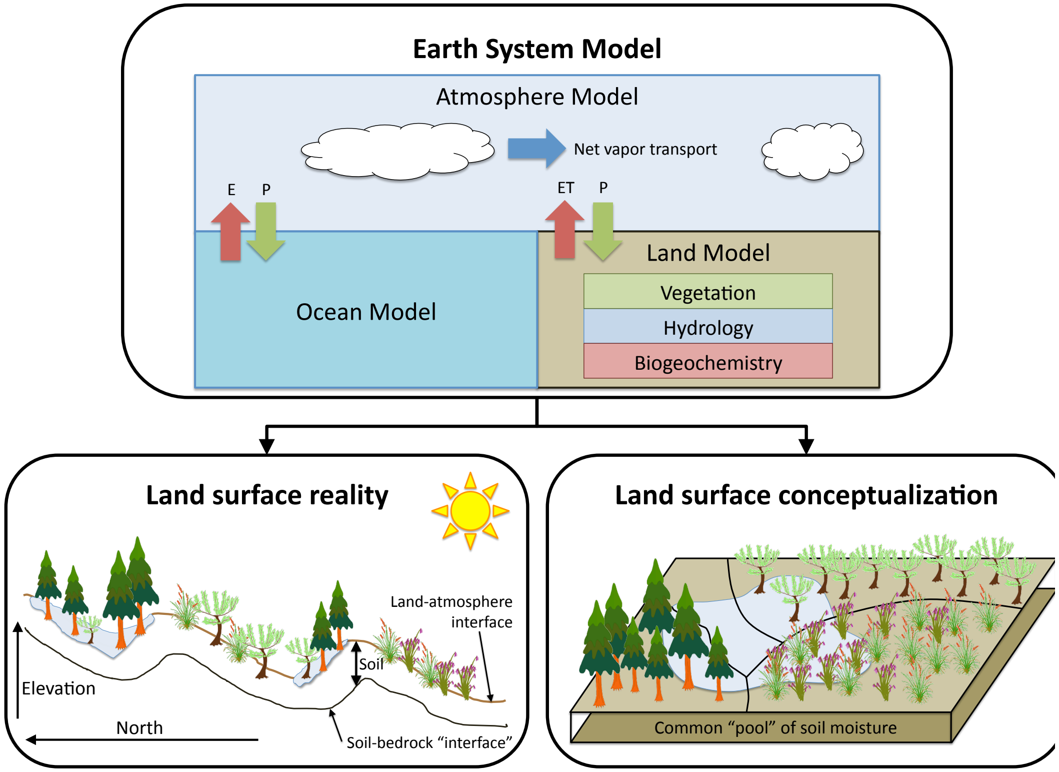
ASO acquisition in Reynolds

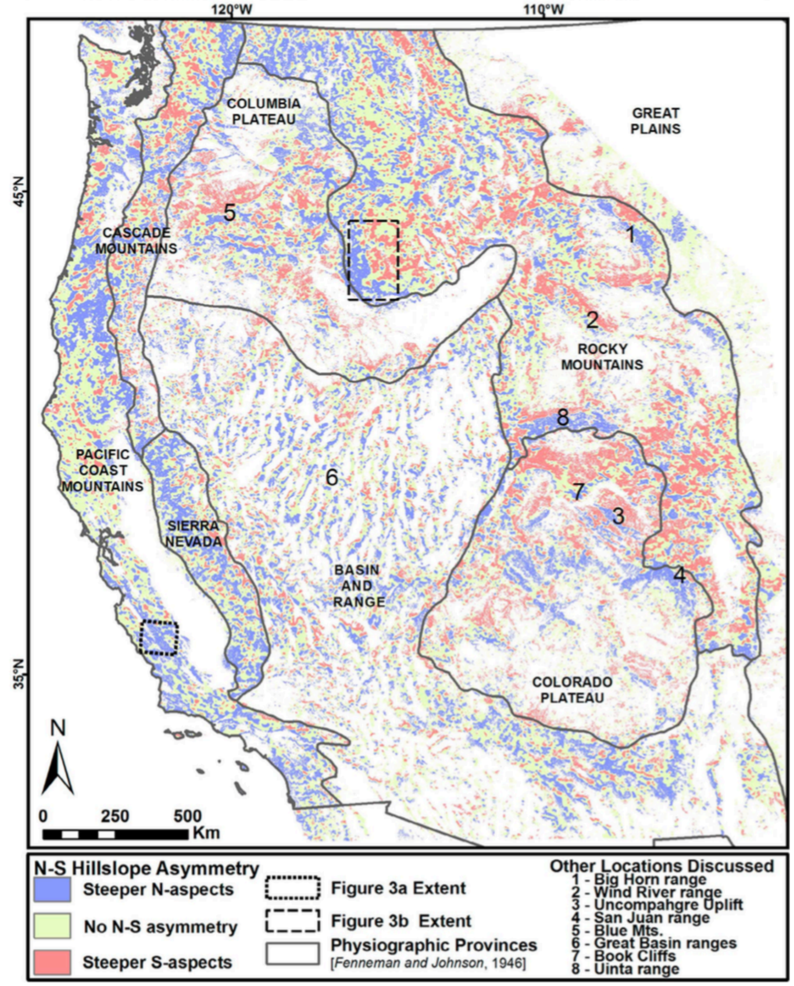




Medvigy, D. et al. 2009

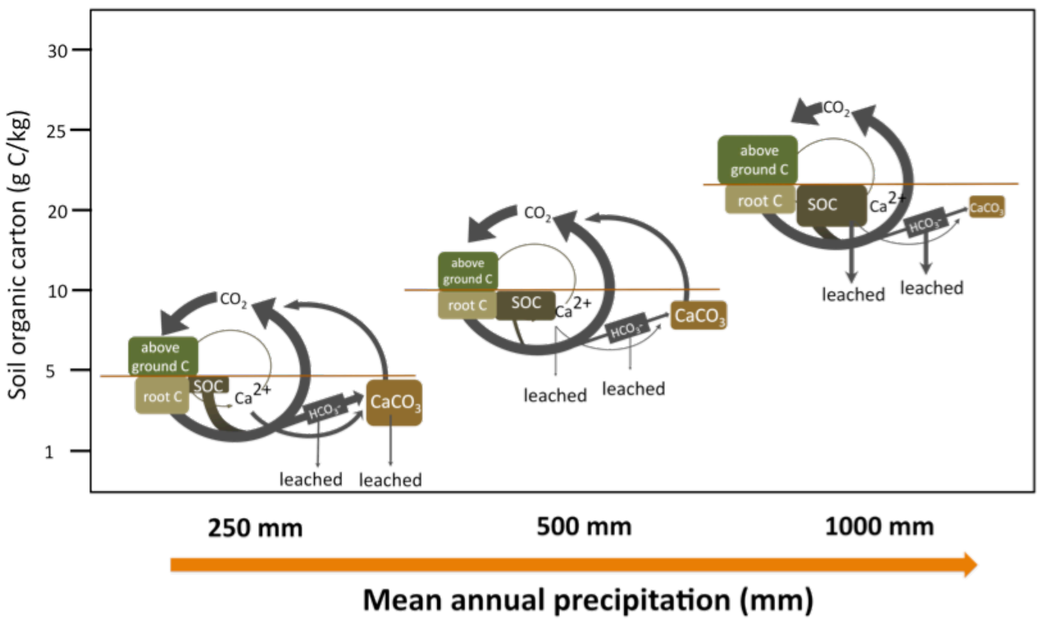
Hillslope-scale controls

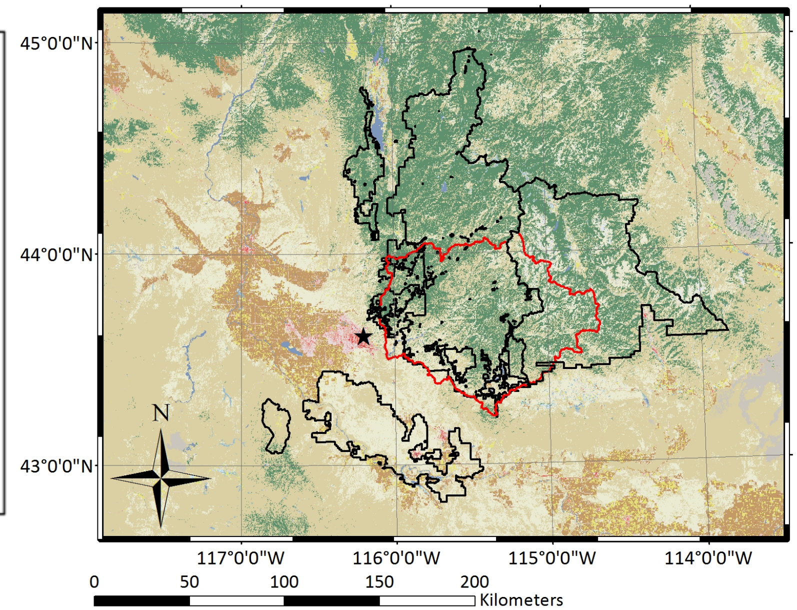




M. J. Poulos, J. L. Pierce, A. N. Flores, and S. G. Benner, "Hillslope asymmetry maps reveal widespread, multi-scale organization," Geophys. Res. Lett., vol. 39, no. 6, p. L06406, Mar. 2012.

Human dimensions of CZ dynamics

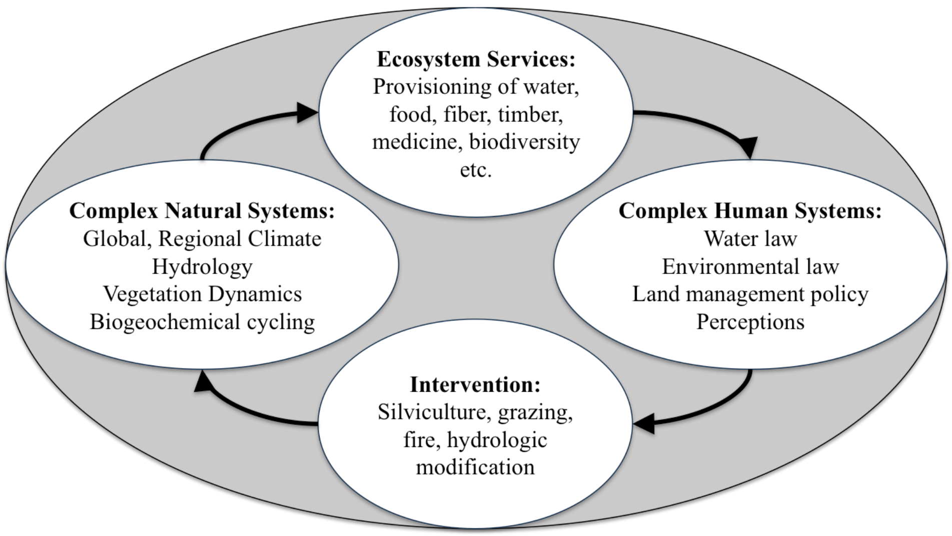


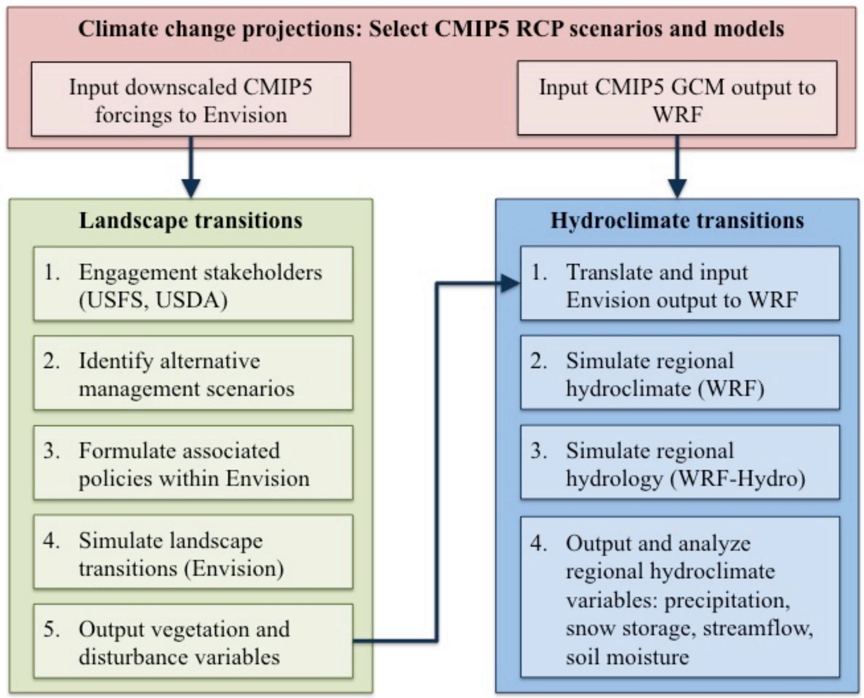


- Land modification occurs against a climatic, lithologic, and geomorphic template
- At Reynolds Creek CZO: Grazing, fire, juniper removal

Human dimensions of CZ dynamics

To what degree are social and biophysical systems coupled? And does this coupling need to be explicitly included in models?





Human dimensions pervade CZOs

- IML CZO: Completely re-plumbed physical system, nutrient input
- Christina River CZO: Nonpoint source nutrient loading, urbanization
- Eel River CZO: Illegal marijuana farms and associated hydrologic modification
- Reynolds Creek CZO: Mixture of public/private land management activities (grazing, fire, etc.)

PIHM-X framework

Table 1. Models in use at the Susquehanna Shale Hills CZ Observatory.

Model name	Purpose	Responsible party	Timescale of simulations
PIHM[1]	Modelling hydrologic fluxes	C. Duffy	Minutes to decades
Flux-PIHM	Modelling water and energy fluxes	Y. Shi	Minutes to decades
Flux-PIHM-BGC	Modelling carbon and nitrogen fluxes	Y. Shi	Hours to decades
PIHM-SED	Modelling sediment transport	C. Duffy	Minutes to decades
RT-Flux-PIHM	Modelling reactive transport	L. Li	Minutes to decades
Regolith-RT-PIHM	Modelling reactive transport	L. Li	Minutes to millions of years
LE-PIHM	Modelling landscape evolution	R. Slingerland	Minutes to millions of years

[1]Penn State Integrated Hydrologic Model

C. Duffy, Y. Shi, K. Davis, R. Slingerland, L. Li, P. L. Sullivan, Y. Goddéris, and S. L. Brantley, "Designing a Suite of Models to Explore Critical Zone Function," Procedia Earth and Planetary Science, vol. 10, pp. 7–15, 2014.

Governing equations for rock and regolith

1. Evolution of ground surface

$$\frac{\partial z}{\partial t} = \left(\frac{\sigma_{ro}}{\sigma_{re}} - 1\right)\sec\theta P_0 e^{-\alpha H} - \frac{\partial q_x}{\partial x} + U - \frac{\partial E}{\partial x}$$

2. Evolution of bedrock

$$\frac{\partial e}{\partial t} = -\sec\theta P_0 e^{-\alpha H} + U$$

3. Evolution of regolith

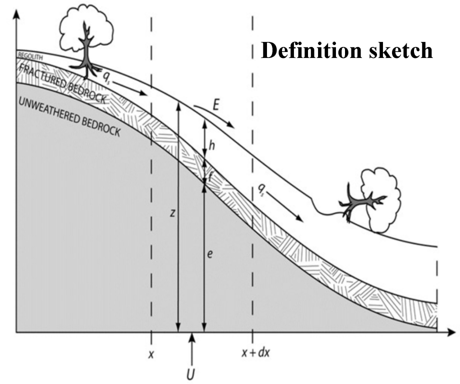
$$\frac{\partial h}{\partial t} = \frac{\partial z}{\partial t} - \frac{\partial e}{\partial t} = \frac{\sigma_{ro}}{\sigma_{re}}\sec\theta P_0 e^{-\alpha H} - \frac{\partial q_x}{\partial x} - \frac{\partial E}{\partial x}$$

4. General equation for downslope regolith flux

$$q_x = K_1\tan\theta + K_2\sin\theta\cos\theta + K_3\sin\theta$$

5. Downslope sediment transport

$$E = 4(\tau_0^* - \tau_c^*)^{\frac{3}{2}}\sqrt{RgDD}$$



Definition sketch

Parameters	Description	Unit
P_0	Bare bedrock weathering rate	m/yr
τ^*_c	Sediment critical Shields stress	dimension
τ^*_0	Overland flow Shields stress	dimension
D	Grain diameter	m
P	Channel wetted perimeter	m
S	Ground surface slope	dimensionless
ψ	Pressure head	m
σ_{ro}	Rock density	kg/m^3
σ_{re}	Regolith bulk density	kg/m^3
θ	Slope angle	Degree
R	Submerged specific gravity	dimensionless
C	Specific moisture capacity	1/m

Governing equations for hydrology

1. Overland flow

$$\frac{dQ_w}{dt} = A\frac{1}{n}\left(\frac{A}{P}\right)^{\frac{2}{3}} S^{\frac{1}{2}}$$

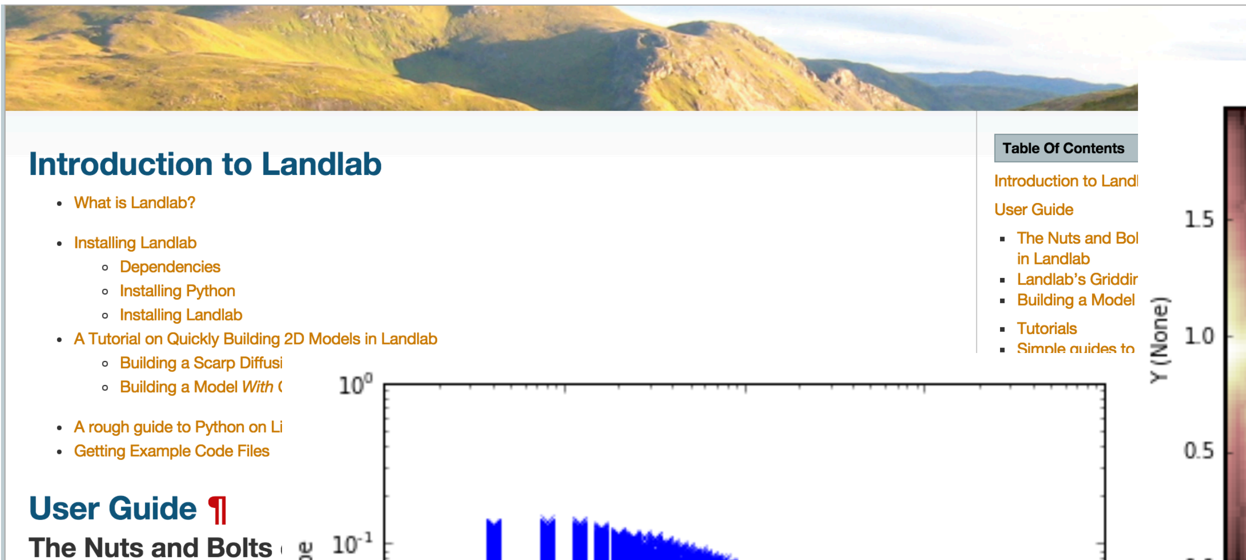
2. Unsaturated Flow

$$C(\Psi)\frac{\partial\psi}{\partial t} = \nabla\cdot(K_w(\Psi)\nabla(\Psi + z))$$

3. Groundwater Flow

$$C(\Psi)\frac{\partial\psi}{\partial t} = \nabla\cdot(K_w(\Psi)\nabla(\Psi + z))$$

LandLab framework


Introduction to Landlab

- What is Landlab?
- Installing Landlab
  - Dependencies
  - Installing Python
  - Installing Landlab
- A Tutorial on Quickly Building 2D Models in Landlab
  - Building a Scarp Diffusi
  - Building a Model *With* (
- A rough guide to Python on Li
- Getting Example Code Files

User Guide ¶

The Nuts and Bolts

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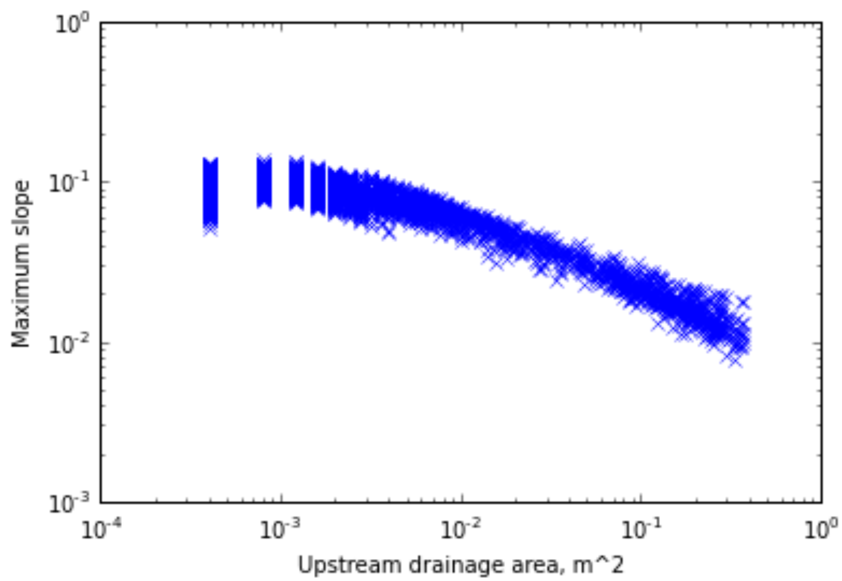

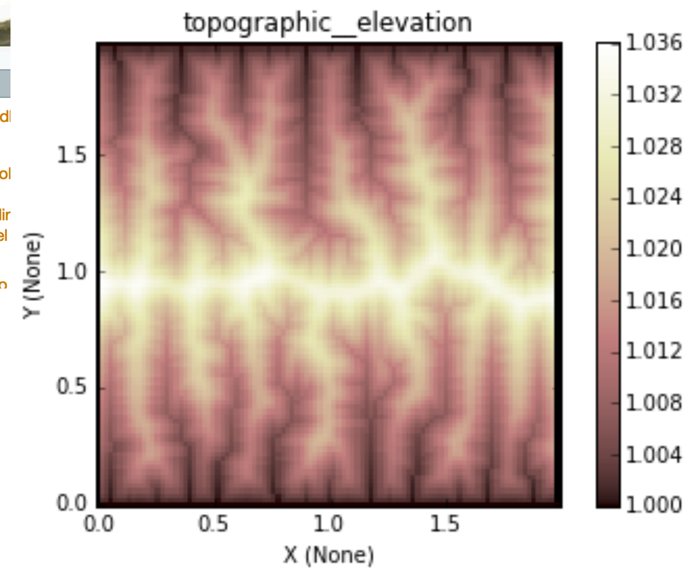

Some challenges

- There is no conceptual model of the CZ that community has developed and agrees upon
- Cross CZO communication among modelers limited (who needs another monthly telecon?)
- Network CZ modeling efforts were not something originally in scope
- A great opportunity for CSDMS and infrastructure to play a facilitative role

Thanks! Questions?

Post script:

- Chris Duffy, Scott Peckham, Adrian Harpold and I are working on a workshop proposal
- Outcomes:
  - A conceptual model of the CZ
  - Mapping of ongoing modeling activities to that conceptual model; identification of gaps, synergies, and opportunities
  - List of 5-7 science questions to enable network modeling
  - White paper, a move towards an RCN proposal