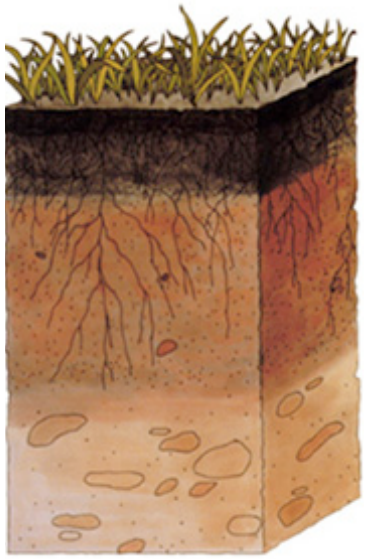


A New Conceptual Model of Soil Carbon Cycling

Suggestions for New Numerical Modeling of Carbon Cycling

Margaret S. Torn, Lawrence Berkeley Lab

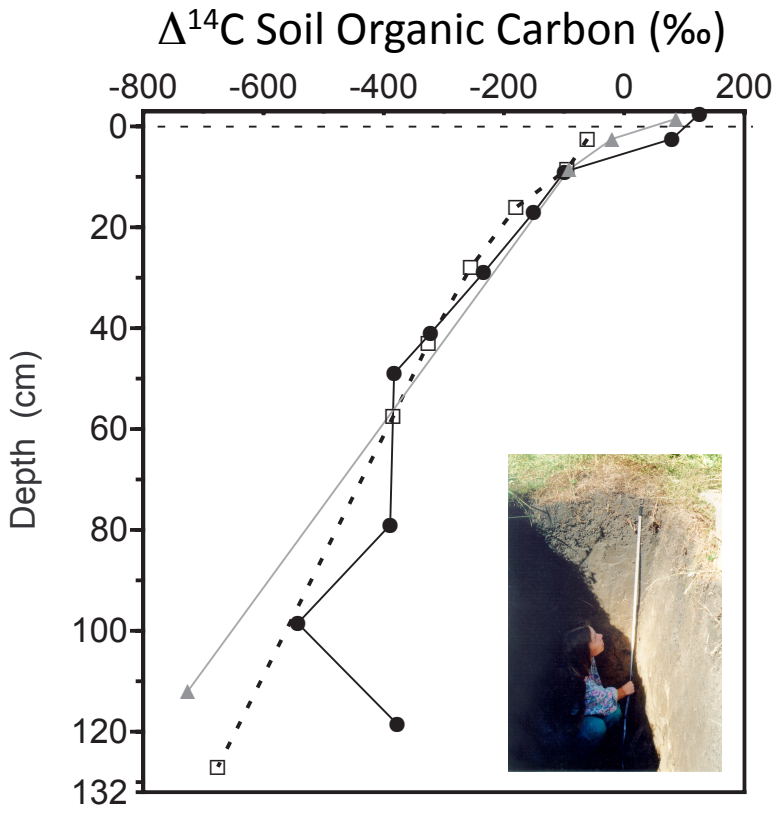
Lake Constance ESF workshop on SOM, 2009

M.W.I. Schmidt (CH); Samuel Abiven (CH); Thorsten Dittmar (GER); Georg Guggenberger (GER); Ivan Janssen (BEL); Markus Kleber (USA); Ingrid Kögel-Knabner (GER); Johannes Lehmann (USA); David Manning (GB); Paolo Nannipieri (ITA); Daniel Rasse (NOR); Susan E. Trumbore (GER); Steve Weiner (ISR)

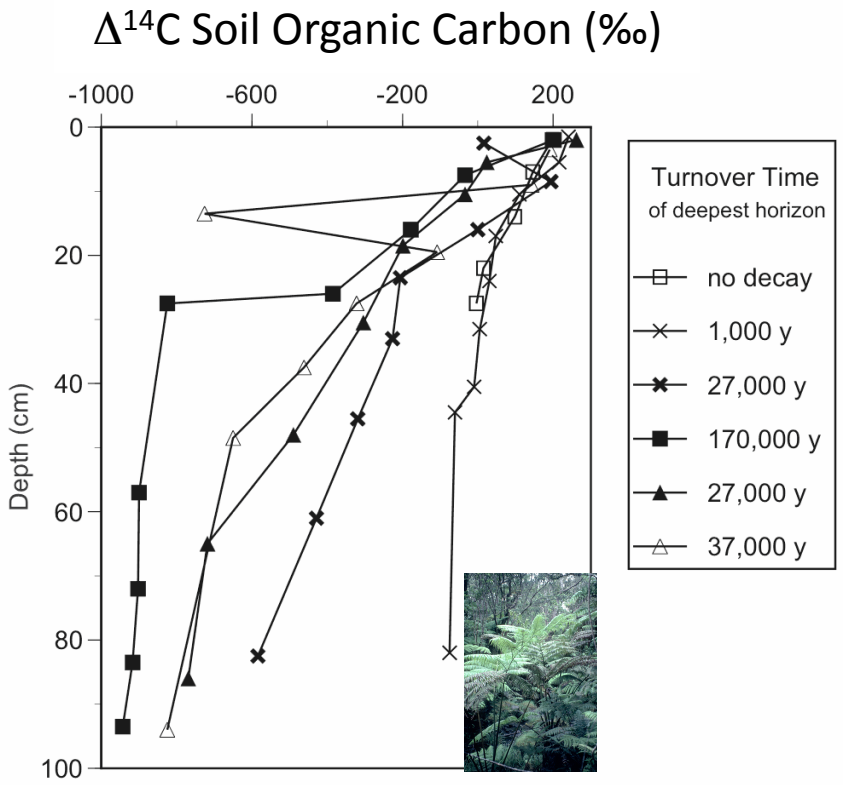
Bill Riley, Zack Subin and Andy Jones, LBL

Turnover time increases with depth

Russian Grassland



Hawaiian Rainforest



Hammes et al. 2008, Torn et al. 2002, Torn et al. 1997

- **Most SOM turns over very slowly**
- **Russia: BC turns over faster than bulk SOC**
- **Hawaii: Minerals explain turnover time**

Models focus on surface, but most SOC is below 20 cm depth

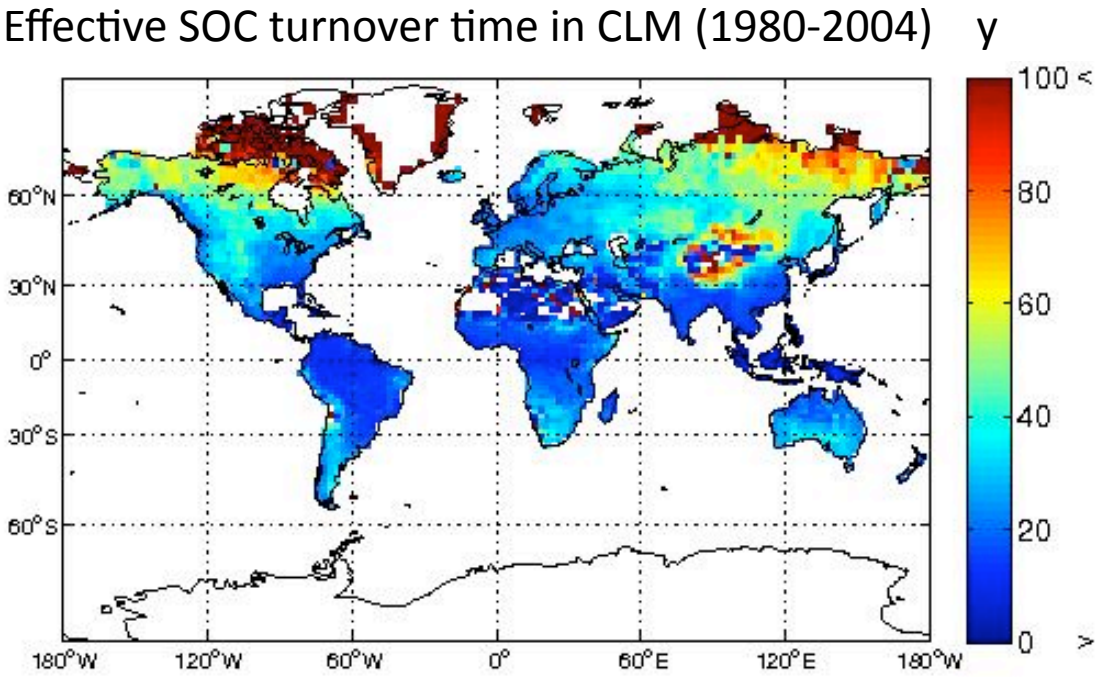
Depth	Global SOC stock (Pg)
0-1 m	1,300-1,600
1-2 m	500
2-3 m	350
Below 40 cm	~ 50%
Below 20 cm	~ 80%
Permafrost+Peat	>1,000

- Most deep soil organic carbon is very stable (τ > 1,000 y)
- Mechanisms influencing long turnover times are not included in ecosystem models such as CLM
- Since we don't know why it is stable, we don't know about vulnerability to change

Jobbagy and Jackson 2000, Torn et al. 2009

CLM turnover times are faster than observed turnover times

- Land models are missing mechanisms of stabilization.
- Rely on surface litter chemistry, moisture and temperature
- No physical controls, explicit depth functions, or O_2 limitation.
- Microbes not represented



Observed turnover times to 1 m > 500-1000 y

New understandings from new tools and techniques:

I. Recalcitrance

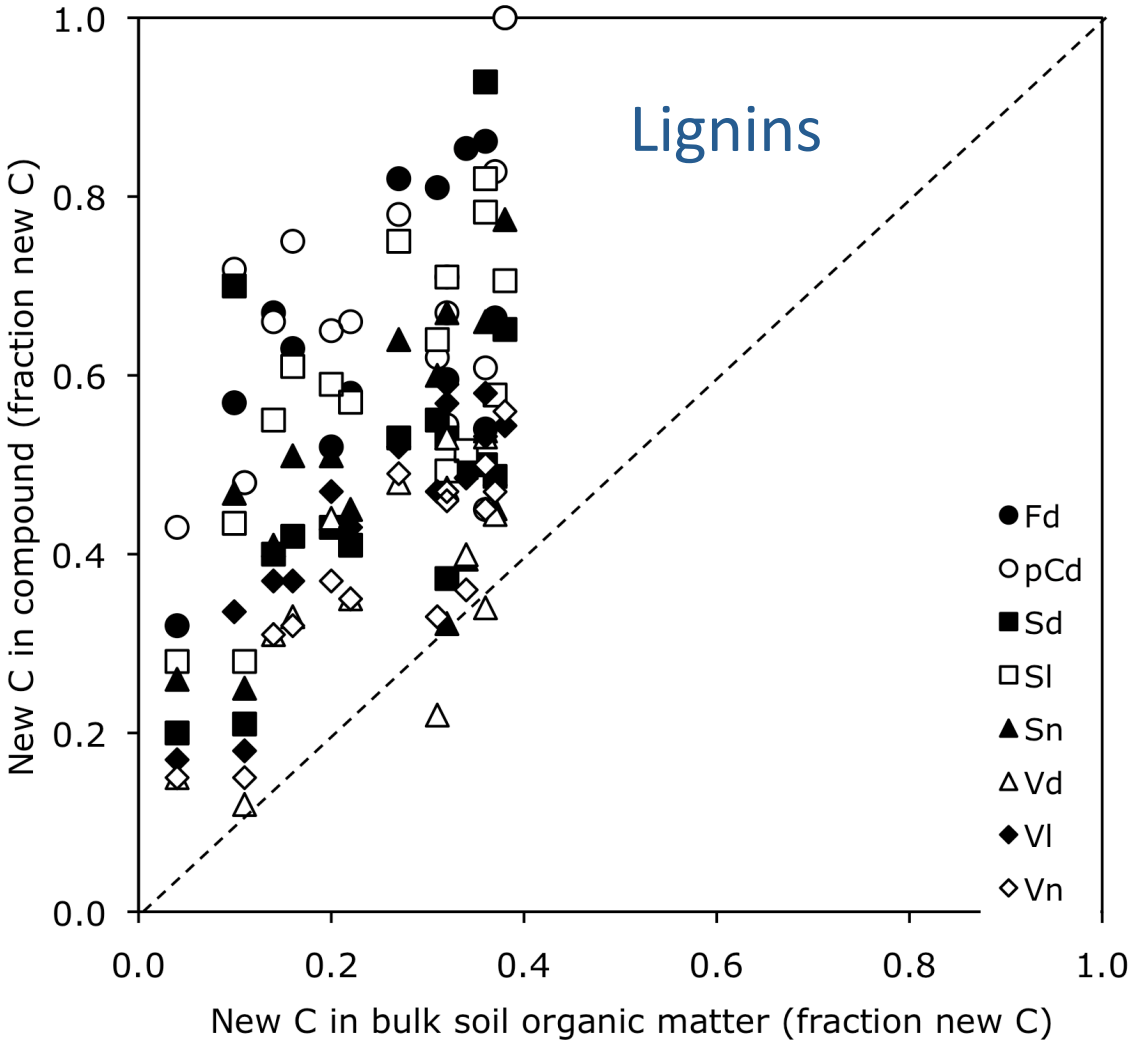
- Recalcitrance is not a dominant control of SOC turnover time
  - Not selective preservation (*v. Lützow et al. 2006; Amelung et al. 2008; and others.)*
  - Not humic acids. Humic polymers are not observed in soil by in situ methods (Kleber and Johnson 2010)
- Fire-derived organic matter (BC, char) is 10-40% of total SOC
  - It has been considered inert but decays fast in some soils
  - Need better understanding to model BC decomposition in soils

Summary of 6-year German research program:

"The view that OM stabilization is dominated by the selective preservation of recalcitrant organic components that accumulate in proportion to their chemical properties can no longer be accepted."

v. Lützow, Kögel-Knabner, Ekschmitt, Matzner, Guggenberger, Marschner, Flessa. 2006

Lignin compounds are replaced more rapidly than is bulk soil organic matter

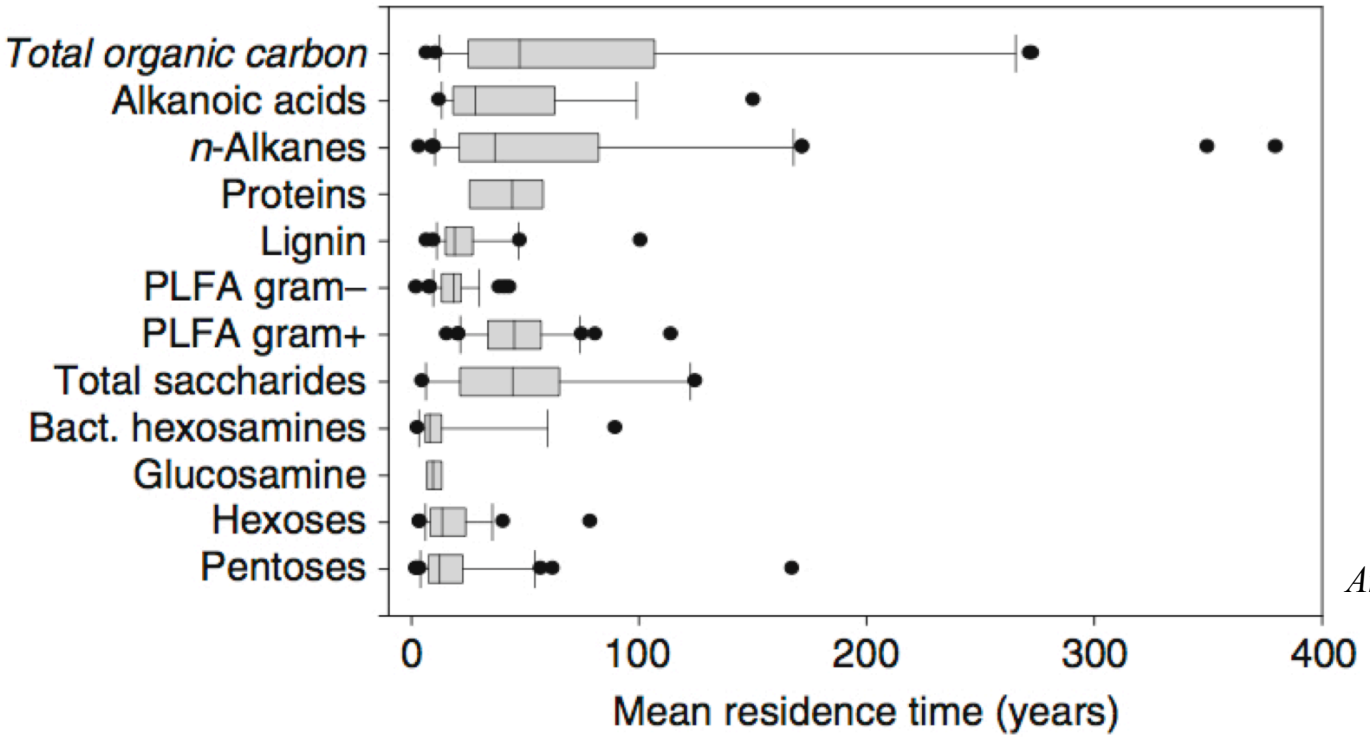


- ^{13}C analysis
- 7 FACE or C_3/C_4 expts
- 2 - 33 y
- N. America, Europe
- Carbon (0.8 – 4.2% C)
- pH (5.6 - 7.6)

Graph from Michael Schmidt.

Data from: Dignac et al. 2005; Heim & Schmidt 2006, 2007; Bahri et al. 2006, Hofmann et al. 2009.

^{13}C analysis to estimate residence time of C in different compounds



Amelung et al. 2008

- 20 long-term field expts (up to 23 y) using natural abundance ^{13}C labeling
- Even sugars turn over on the order of years - decades.
- Mechanisms other than chemical properties stabilize organic matter

New understandings from new tools and techniques:

II. Organo-Mineral Interactions

- Organo-mineral interactions important for long-term stabilization.
- Not represented by texture.
- Free iron and aluminum oxides

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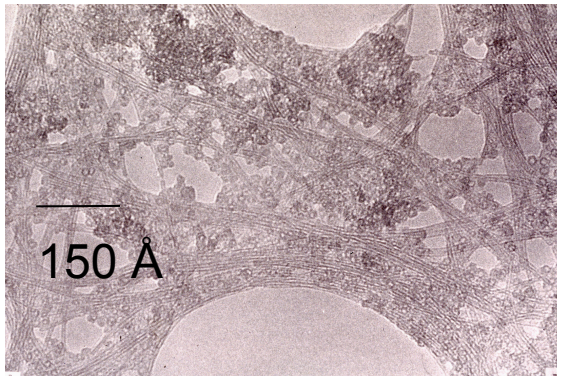
Imogolite
High charge
density

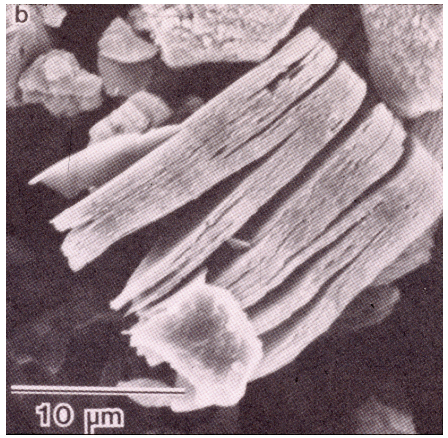


$^{+}H_3N—R—$

$^{+}H_3N—R—$

$^{+}H_3N—R—$

Kaolinite
Low charge
densityl



$^{+}H_3N—R—$

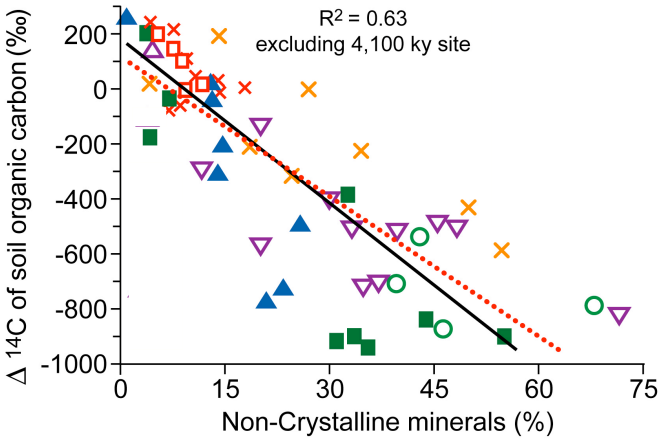
And many more sites...

Hawaiian Chronosequence
Volcanic Ash Soils

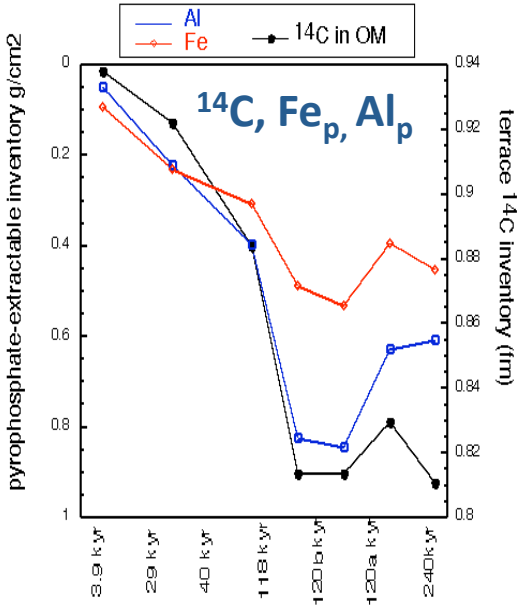
Carbon stocks and turnover time correlated with reactive minerals (not clay content or texture)

Sandstone
Chronosequence
California

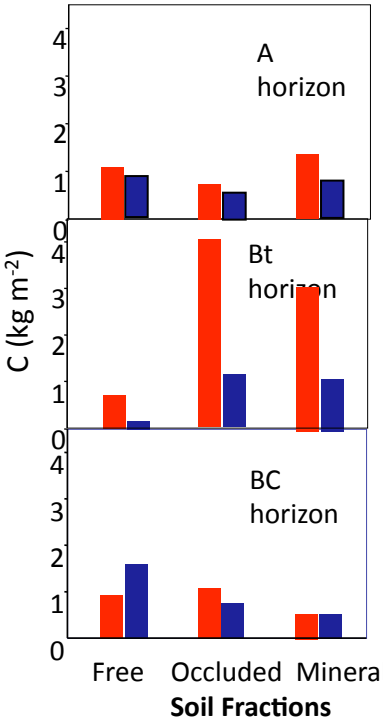
Sierra Nevada
Granite vs Andesite



Torn et al. 1997



Masiello et al. 2004

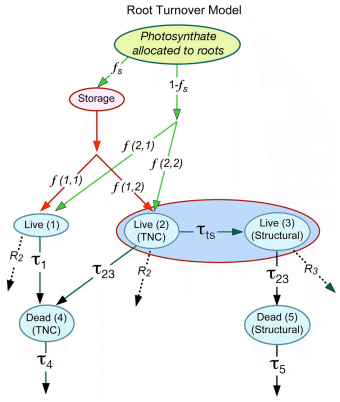


Rasmussen et al. 2005

New understandings from new tools and techniques:

III. Roots & Microbes

- Root and rhizosphere are important sources of SOC
- Root turnover is slower than modeled; temperate forest $\tau \sim 4$ y



(Riley et al. 2009)

- Soil organic matter can persist because of physical disconnect_between decomposesr and organic matter. How to represent this in models?

- Priming. Easy to represent. How important is it?

- How explicitly and at what taxonomic resolution do we need to represent microbial communities and functions?

- **Reconsider effect of vegetation change on SOC dynamics: Roots, litter quality, Priming**

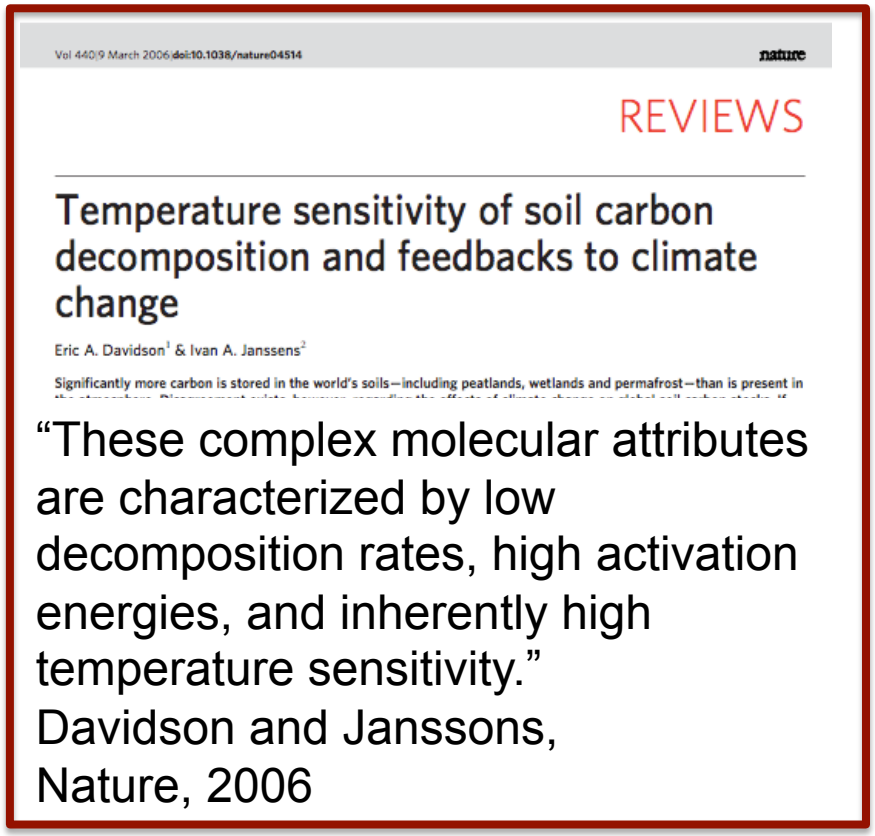
-

What if Recalcitrance is not the basis for Temperature Sensitivity?

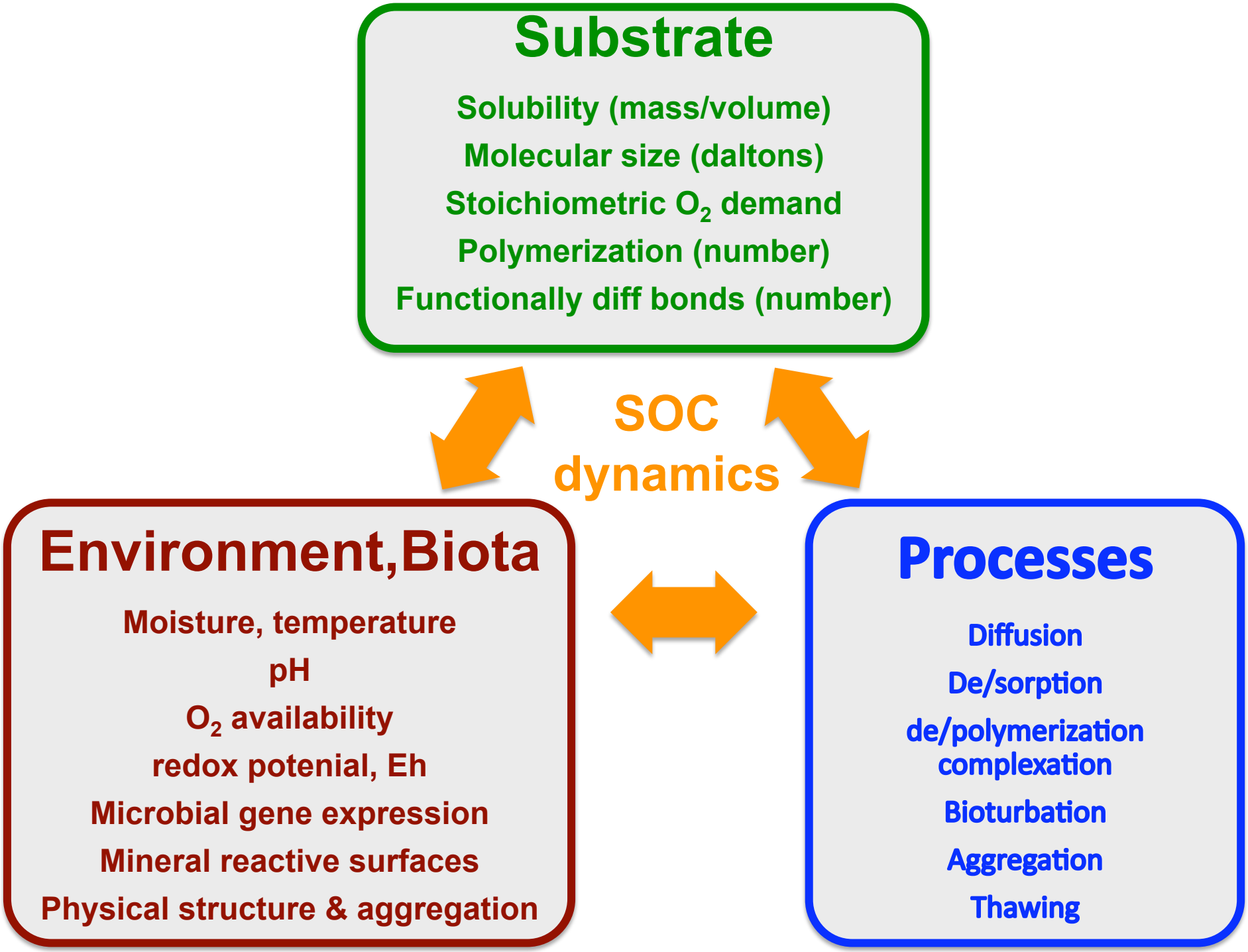
"As ...most SOM is of high age and stability, the temperature dependence of stable SOM pools is the central question that determines C stocks and stock changes under global warming." *--Von Lutzow and Kögel-Knabner, 2009*

The carbon quality-temperature (CQT) theory of temperature sensitivity links the temperature sensitivity of old organic carbon to an increase in molecular complexity.

The findings on recalcitrance challenge the scientific basis of the CQT theory



"These complex molecular attributes are characterized by low decomposition rates, high activation energies, and inherently high temperature sensitivity."
Davidson and Janssons, Nature, 2006


Substrate
Solubility (mass/volume)
Molecular size (daltons)
Stoichiometric O_2 demand
Polymerization (number)
Functionally diff bonds (number)
SOC dynamics
Environment,Biota
Moisture, temperature
pH
O_2 availability
redox potenial, Eh
Microbial gene expression
Mineral reactive surfaces
Physical structure & aggregation
Processes
Diffusion
De/sorption
de/polymerization complexation
Bioturbation
Aggregation
Thawing

A proposal

- **Integrate new mechanisms and processes**
  - Near term: O_2 limitation, mineral proxy, root inputs
  - Replace litter chemistry and recalcitrance as major influences
  - Develop new temperature response functions
- **Use appropriate information to develop parameters**
  - Be cautious about relying on incubations and sorption experiments
- **Increase capability of land surface model**
  - ^{14}C, depth, O_2 diffusion/consumption, sub-grid hydrology

Criteria for Success

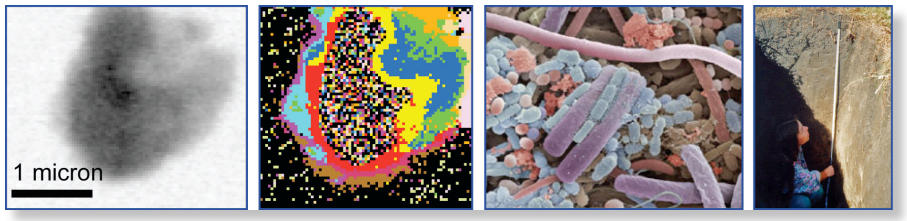
1. **Predictive Capability**
   - Requires the mechanisms that drive change
   - Testing is difficult. (Longterm expts, gradients)
2. **Can be run globally.**
   - Tension between mechanistic detail and global coverage

Code Development and Capabilities Needed

- Tracers—each variable needs a tracer element
- Depth-resolved transport and reactions
- Depth-resolved oxygen diffusion
- TOUGH type numerical solvers
- If model uses discrete C pools, treat each one as a distribution of turnover times rather than a single turnover time.
- Subgridscale hydrology

Thank you

U.S. Department of Energy, Office of Science
National Science Foundation
U.S. Department of Agriculture
Deutsche Forschungsgemeinschaft
European Science Foundation

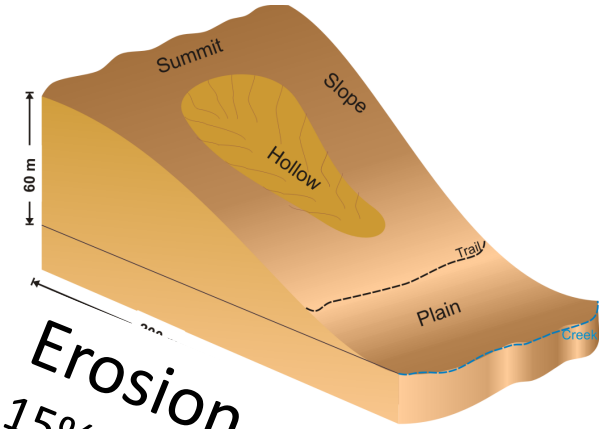


Implications for SOC Modeling

- SOC dynamics determined by interaction among substrates, microbes, and environment
- Cannot assume the same chemistry will have the same effect on τ in all soils.
- Mumerical models of soil carbon cycling are missing important mechanisms
- Recalcitrance/molecular complexity are not basis of temperature sensitivity
- Need new approach to temperature sensitivity
- Reconsider effect of vegetation change on SOC dynamics: Roots, litter quality, Priming

Missing Processes and Mechanisms

- Vertical Transport and Diffusion in BGC
- Mineral interactions and surface chemistry
- Microbial functional groups and physiology
- Microbial transformations of SOM
- Oxygen limitation
- Interaction among controls (e.g., temperature and moisture)



Erosion
15% of land

Landscape Scale Processes

Ecosystem Disturbance

Humic Polymer Model vs. Molecular Aggregate Model

(from *Kleber and Johnson 2010*)

Humic Polymer Model:

- **Molecular structure** = Fragments are re-synthesized by strong covalent bonds.

  SOM molecules are produced by secondary syntheses reactions from degradation products, Large, covalently bonded ('humic") polymers with unique chemical structures that are different from those of the starting materials.
- **Implication for stability** = The humic polymer model implies inherent resistance to decomposition, also called recalcitrance
- Experimental evidence from the recent past fails to identify humic molecules in soils or in alkali-extracted humic substances
- *(Sutton and Sposito 2005, Kelleher and Simpson 2006, Lehmann et al 2008)*.

New understandings from new tools and techniques:

I. Recalcitrance

"…..recalcitrance alone cannot explain long-term stabilization and is not the major driving force of passive C-pool formation. This implies a reconsideration of the basic concepts underlying most actual compartment and cohort models. "

Koegel-Knabner et al 2008