Carbon Cycling in Terrestrial Ecosystems
Research Challenges and Opportunities

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With contributions from Markus Kleber, Michael Schmidt, Eoin Brodie, Peter Nico, and Janet Jansson

March 31, 2010
Subsurface Biogeochemical Research Workshop
Challenges and Opportunities

Carbon Cycle is central to Climate Change problem

Soils are key yet poorly understood

Our understanding of soil carbon cycle is changing

New insights, from new tools, are challenging the old models

We need new experiments and models

The fundamental challenge is integration and prediction at large scales
The Global Carbon Cycle

- Photosynthesis: 122 Gt/yr
- Deforestation: 0.9 Gt/yr
- Respiration: 60 Gt/yr
- Atmospheric CO₂: 800 Gt

Stocks:
- Fossil: 4,200 Gt
- Carbonates: 60,000,000 Gt
- Kerogens: 15,000,000 Gt

Flows:
- Rivers: 0.8 Gt/yr
- Ocean: 36,000 Gt
- CH₄: 960 Gt C

- Flow from Fossil to CH₄: 10 Gt/yr
Future Climate
Depends on Radiative Forcing

IPCC 2007

Emissions Scenarios

Global surface warming (°C)

Year

1900 2000 2100
Fossil Fuel Emissions: Actual vs. IPCC Scenarios

Raupach et al. 2007, PNAS, updated; Le Quéré et al. 2009, Nature Geoscience; International Monetary Fund 2009
Global Change and the Terrestrial Carbon Cycle

- **Carbon Sink.** Mechanisms, Variability, and Trends
- **Climate Feedbacks.** Sign, magnitude, and timing
- **Biofuels.** C balance for land management, conversion
- **Sequestration.** How and how much C storage
Carbon Sink: Fate of Anthropogenic CO$_2$ Emissions (2000-2007)

1.5 Pg C $\cdot$ y$^{-1}$

4.2 Pg $\cdot$ y$^{-1}$ Atmosphere 46%

7.5 Pg C $\cdot$ y$^{-1}$

2.6 Pg $\cdot$ y$^{-1}$ Land 29%

2.3 Pg $\cdot$ y$^{-1}$ Oceans 26%

8.7 Pg C $\cdot$ y$^{-1}$ in 2008

Canadell et al. 2007, PNAS (updated)
Carbon Sink: Airborne Fraction

Fraction of total CO\(_2\) emissions that remains in the atmosphere

Airborne fraction is going up.

Land and ocean sinks are not keeping pace with emissions

Le Quéré et al. 2009, Nature Geoscience; Canadell et al. 2007, PNAS; Raupach et al. 2008, Biogeosciences
Climate-Ecosystem Feedbacks: Paleo

Ice core evidence for positive feedback

EPICA Ice Core 650,000 year record

All coupled climate-carbon models showed increased atm CO₂ with warming (positive feedback)

The magnitude of feedback depends on tropical forests and global soil responses

Biofuels

• Important climate mitigation
• Climate benefits depend on land use carbon balance
• Soil carbon release
• Tropical deforestation

Ag conversion, tillage
FAO

Deforestation (NASA)

www.noble.org/
CO$_2$ emissions from conversion of Forest and Grassland to Agriculture

Countries/Regions

- Rest of World
- United States
- Southeast Asia
- China/India/Pakistan
- Developed Pacific
- North Africa and Middle East
- Latin America
- Soviet Union
- Europe
- Africa
- Canada

Mg CO$_2$ / ha

Grassland emissions
Forest emissions

Andy Jones, from Houghton data
Carbon sequestration

- Important for climate mitigation
- Up to 1 Gt/y (estimates vary 10-fold)
- Forest biomass and Soils

NPP variation = $10 \times$

Microbial metabolism and synthesis

C Residence time Variation = $1000\times$
Terrestrial Carbon Cycle Basics

Adapted from Paul and Clark 1996
Stock depends on **Inputs** and $\tau$

(production and decomposition)

\[
\frac{dC(t)}{dt} = I - \frac{C}{\tau} = 0
\]

at steady state

\[
C = I\tau
\]

$\tau$ = turnover time, residence time
State of understanding

Historic view of soil carbon dominated by concept of recalcitrance

This view has profoundly shaped current numerical simulation models of ecosystems

New insights, from new tools, are challenging these old models
Historic Focus on Soil C Cycling

- Litter decay & Surface soil (20 cm)
- Recalcitrance is main control
  - Selective preservation
  - Humics (large, synthesized)
- Microbes are black box
- Inputs: Litter, DOC, roots, Black C
- Physical protection:
  - Texture, aggregation, minerals

? Depth
? Priming
? Transport: erosion, leaching
Numerical ecosystem models

- CENTURY
- CN (in CCSM)
- CASA
- RothC
- LPJ
- IBIS (~CENTURY)
- Orchidee (~CENTURY)
CENTURY Model

Live Plant

Dead Plant

Organic Matter incl microbes

Parton et al.
CENTURY Model

- Model Structure
  - Soil C in 2-4 pools

- Turnover time ($\tau$)
  - Litter chemistry (lignin:N)
  - Soil texture (clay + silt)
  - Soil temperature, moisture

- Designed for surface horizon; 1-2 layers

Parton et al.
# New insights from new tools: 5 examples

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Isotopically labelled substrates used to study transformations and fate

Example:
Quantifying lignin turnover using $^{13}$C-labelled inputs

Track label into: specific compounds, $^{13}$C-PLFA, microbial DNA/RNA, soil carbon fractions, DOC, respired $^{13}$CO$_2$
Bulk soil: New, $^{13}$C-labelled SOC replaces old SOC

- 32 field experiments (FACE or C$_3$/C$_4$)
- 2 - 33 years
- N. America, Europe (23 papers 1980 - 2007)
- Carbon (0.8 – 4.2% C)
- pH (5.6 - 7.6)

$1/k = 40$ years, $R^2 = 0.6$

filled symbols: 7 sites used for compound-specific data, next slide
Compounds replaced faster than bulk C

Does Lignin turnover faster or slower than other compounds?

Compounds replaced slower than bulk C
Lignin compounds are replaced more rapidly than is bulk soil organic matter.
Is black carbon “recalcitrant” in soil?

Natural Experiment
100 years w/o fire

- Sites sampled in 1900 and 1997
- BC quantified with BPCA (Benzene polycarboxylic acids)


Torn et al. 2002. Global Biogeochemical Cycles

Photos: Andrei Lapenis, Karen Hammes
• Soil BC stocks decreased 25% from 1900 to 2000

• BC turnover time ~ 300 y (210-540 y)

\[
\tau = \frac{-t}{\ln(f - b) / (f - 1)}
\]

Turnover time
\(\tau = f\) (reduction in BC input, years between sampling)

• Total org C stock did not change.
• BC comprised ~ 8% of total C

\(^{14}\text{C} \text{ measurements \& modeling show that bulk soil organic matter had turnover time > 1000 years.}\)
BPCA are molecular markers for stability of BC

First test of BPCAs as molecular markers for BC dynamics.

B3,4,5CA $\tau \sim 83$ y
B6CA no change

(increased substitution with C-atoms)
Increasing resistance against degradation?

Oxidation (HNO$_3$
65%, 170°C, 8h)
Error bars = analytical error
Implications of Lignin and Black Carbon studies

- There may be no universally recalcitrant SOC
- Mechanisms of SOC persistence vary with environment and disturbance.
- Current model reliance on “recalcitrance” is unjustified, but compound chemistry does matter
- Black Carbon and lignin may not be as effective for sequestration as hoped

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.”

Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions – a review. Priority Program 1090 of the German Research Foundation
New insights from new tools:
5 examples

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And many more sites

Carbon stocks and turnover time correlated with reactive minerals, not texture!
Advanced Capabilities for studying Mechanisms of Soil Carbon Stabilization

**Advanced Light Source**
soft x-ray synchrotron

- **FTIR:** 1.4.3, 5.4.4 confocal-Raman (commissioning)
- **STXM/ NEXAFS:** 11.0.2, 5.3.2.0, 5.3.2.1 (under construction)
- **LBNL Molecular Foundry**
- **Nano-SIMS** Imaging Stable Isotope Labels
- **Natural abundance $^{14}$C
- **EMSL**

**Chemical form and spatial associations of key C cycle elements, C, O, N, P, Si, Al on nanometer scale**

**Live cell imaging and carbon chemistry on micron scale**

**SEM, TEM, AFM, XPS, optical microscopy**
Imaging micro aggregate structure and formation

Peter Nico, Jennifer Pett-Ridge, Markus Kleber, Peter Weber, Delphine Derrien, Bernd Zeller
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Microbial Communities

1. How are microbial communities affected by climate?
2. Do altered communities affect carbon-cycling rates, pathways, or by-products?

natural climate gradient

Six Ecosystems
MAP: 94 - 480 cm
MAT: 10.7 – 22 °C

Rainfall
Low  Ambient  High

Mary Firestone, David Ackerly, Gary Andersen, Margaret Torn,
Eoin Brodie, Cristina Castanha, Marc Fisher, Don Herman,
Francesca Hopkins, Sarah Placella, Sam St. Clair, Rohit Salve,
Erika Sudderth, Stephanie Swarbreck (née Bernard),
Eric Dubinsky, Eoin Brodie, Mary Firestone, et al.
across natural climate gradient

Soil moisture explains almost all variance in community structure

NMDS ordination of community data

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<th>R²</th>
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<tr>
<td>Soil moisture</td>
<td>0.85</td>
</tr>
<tr>
<td>MAP</td>
<td>0.82</td>
</tr>
<tr>
<td>MAT</td>
<td>0.65</td>
</tr>
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Dry-adapted taxa are phylogenetically clustered. Drying increases relatedness (lower diversity).

Increasing soil moisture →

High

Ambient

Low

Climate Gradient

Climate Experiment

Pseudomonadaceae
Comamonadaceae
Sphingomonadaceae
Actinomycetales
Bacillaceae

Bacillaceae
Actinomycetales

Correlations to soil moisture

Relatedness

Increasing soil moisture →

Relatedness

Low

Ambient

High
The physiological basis for climate response suggests there could be biogeochemical impacts on carbon cycling rates, processes, and/or by-products.

Evidence that microbes need to be included in models explicitly.

*At what resolution do we need to represent microbes in terrestrial biogeochemical models?*

*Does functional redundancy compensate for community shifts?*
METAGENOMICS PROJECTS ARE UNDERWAY

The Great Prairie Soil Metagenome Flagship project

JGI Permafrost metagenome

Approximately 40 billion bases of sequence data

Largest environmental sequencing project to date!!

Both microbial identities and functions revealed
## Emerging Views of Soil C Cycling

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<th>Old Conceptual Model</th>
<th>New Concepts</th>
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<tr>
<td>Lignin is recalcitrant</td>
<td>not recalcitrant</td>
</tr>
<tr>
<td>Humic acids are main source of very stable material</td>
<td>Not important in soil</td>
</tr>
<tr>
<td>Texture</td>
<td>reactive interfaces</td>
</tr>
<tr>
<td>Focus on surface soil</td>
<td>Deep soil C matters</td>
</tr>
<tr>
<td>Fire-derived carbon is inert</td>
<td>Some degrades quickly</td>
</tr>
<tr>
<td>Intrinsic chemical recalcitrance</td>
<td>Environment-specific</td>
</tr>
<tr>
<td>Litter / DOC input</td>
<td>Root input</td>
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- **Temperature (Q$_{10}$)**
  - Complex Relationship, Moisture is integral

- 1 micron
- Image 1
- Image 2
- Image 3
- Image 4
A new conceptual model

Lake Constance
ESF workshop
October 2009

Mechanisms
- Diffusion
- Desorption
- Depolymerization
- Absent complexation
- Bioturbation

Non-assimilable C
- Chemical-physical form of soil organic matter

Assimilable C
- Soil Environment
  - Microbes
  - pH
  - O₂
  - Minerals
  - Climate

Leaves & needles
Wood
Roots
Black carbon
CO₂
Soil Carbon Modeling
from Mechanisms to Models

Step 1. Identify pathways and controls

Step 2. Express mechanisms as equations that explain significant variation.

Step 3. Create functions based variables that can be derived for many sites (e.g., FAO soil map, ISRIC database, USDA STATGO), so that application is practical.

Step 4. Scale to m² and to Primary Productivity

Step 5. Explore, Validate, Incorporate
Understanding and Prediction at Large Scales

Ecosystem Disturbance

State Factors

Geostatistics

Hans Jenny
c/o Jen Harden

Erosion
15% of land area

10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

SOC Samples
Land use
Rainfall
Temperature
DEM
Need models that are mechanistic enough to:

- Test hypotheses
- Predict influence of conditions outside our datasets
  - Spatial extrapolation
  - Climate change
The Challenges Ahead

We need new experiments to clarify unknowns

We need new models that incorporate new understanding and meet new goals

New ecosystem models need to be tested, offline and coupled to climate models

Fundamental challenge is integration and prediction across spatial and temporal scales
Carbon Cycle is central to Climate Change problem

Soils are key yet poorly understood

Our understanding of soil carbon cycle is changing

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We need new experiments and models

The fundamental challenge is integration and prediction at large scales
Thank you

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European Science Foundation