Soil biogeochemistry in a changing world
Will Wieder
2019 CTSM Tutorial
Soils Store Carbon

CO₂  CH₄

C

Arrow pointing upwards from C to CO₂ and CH₄.
Soils Store Carbon and Nitrogen
soil biogeochemical models

Input – Climate hypothesis
Time to rethink soil biogeochemical models?

$I = \text{NPP}$

$\dot{C} = \frac{I}{\tau}$

$\varepsilon = f(S)$

$\tau = f(T, M, S, \ldots)$

Input – Climate hypothesis
Rate constant ($\tau$)
- Water function
- Temperature function
- Transfer coefficients (among pools & respiration)

Stoichiometry

\[ C:N \]

\[ \tau = f(T,M,S,...) \]

\[ E = f(S) \]
Code base: src/soilbiogeochem
esp. SoilBiogeochemDecompCascadeBGCMod.F90
Technical note 2.21: Decomposition

Rate constant ($\tau$)
- Water function
- Temperature function
- Transfer coefficients (among pools & respiration)

Stoichiometry

Parameter file
- tau_l1, tau_s1, tau_s2, etc.
- rf_l1s1_bgc, rf_s1s2_bgc
- cn_l1_bgc, cn_s1_bgc, etc.
Code base: src/soilbiogeochem
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Technical note 2.21: Decomposition

Century Soil C pool structure

CLM-CN Soil C pool structure

Koven et al. 2013
Biogeoosciences
Code base: src/soilbiogeochem
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Technical note 2.21: Decomposition

Parameter file

Rate constant (τ)
Water function
Temperature function
Transfer coefficients

minpsi_hr = -2 CLM5 & -10 CLM4.5
q10_hr = 1.5

Yizhao et al.
2015 Sci Reports
Global soil biogeochemical models
CMIP5 Models = 6x variation

\[ \hat{C} = \frac{I}{k} \]

*Obs. CMIP5 MODELS*

- Tropical rainforest
- Cropland and urban
- Desert and shrublands
- Grasslands and savanna
- Temperate forest
- Boreal forest
- Tundra
- Permanent wetlands

*Todd-Brown et al. Biogeosciences 2013, Friedlingstein et al. 2006; Jones et al. 2003*
CMIP5 Models RCP8.5

Contemporary

21st century absolute change

Soil carbon

[

NPP

[
Pg C yr^{-1}]

0

50

100

150

200

250

300

350

400

0

50

100

150

200

CMIP5 Models RCP8.5

Todd-Brown et al. Biogeosciences 2014
Permafrost C in models

Todd-Brown et al. Biogeosciences 2013
Permafrost C “observations”
Permafrost soils CLM4.5bgc & 5.0

Carbon rich
Vertically complex

CENTURY-like soil biogeochemistry

Koven et al. *Biogeosciences* 2013
Permafrost soils CLM4.5bgc

(a) IGBP

(b) NCSCD

(c) CLM4.0-CN

(g) CLM4.5-biogeophysics/biogeochemistry

Fig. 5. Maps of soil C. (a, b) Observed soil C databases: (a) IGBP-DIS dataset (Global Soil Data Task Group, 2000); (b) NCSCD, (Tarnocai et al., 2007; Hugelius et al., 2013). (c–g) Modeled soil C for various cases: (c) base CLM4.0-CN; (d) CLM4.5-biogeophysics; (e) single-level biogeochemistry (BGC), Century-based decomposition; (f) multi-level BGC, Century-based decomposition, C N denitrification; (g) multi-level BGC, Century-based decomposition and nitrification/denitrification (CLM4.5-biogeophysics/biogeochemistry). For observations and multi-level model, data here is for upper 1 m of soil. Note quasi-logarithmic scale bar. – to observations from sites where C and $^{14}$C depth profiles have been measured and reported: V oronazh, Russia (Torn et al., 2002); Thule, Greenland (Horwath et al., 2008); Paragominas, Brazil (Trumbore et al., 1995); Mattole, California (Masiello et al., 2004); La Reunion, South Pacific (Basile-Doelsch et al., 2005); Harvard Forest, Massachusetts (Gaudinski et al., 2000); Gydansky, Western Siberia (Kaiser et al., 2007); and Judgeford, New Zealand; Riverbank, California; and Turlock Lake, California (Baisden and Parfitt, 2007). These site-level comparisons show that C and $^{14}$C profiles can be reasonably well simulated across a variety of ecosystems using the new vertically resolved Century-like C decomposition, imposed additional vertically resolved C
Turnover times

**Figure 1** Global distributions of the inferred apparent turnover time (\( \tau_{\text{app}} \)) (a) (inferred from MODIS MODIS NPP) and (b) (inferred from MODIS MODIS NPP) as a function of climatological temperature. Each gridcell is plotted as function of mean annual air temperature (MAAT). Each gridcell is colored by climatological precipitation. The residual two-fold variation in turnover times (residual variance in being diagnosed as those where the climatological temperature over the interval, with stronger sensitivity in cold climates than in warm climates. We note, however, that considerable variation remains.

**Figure 2** The residual two-fold variation in turnover times (residual variance in being diagnosed based on \( \tau_{\text{app}} \)) versus MAAT, with 50% prediction intervals shown. Best-fit regression curve in the sensitivity of inferred potential evapotranspiration calculated as the ratio of carbon stocks (\( \text{Soil carbon to 1 m (kg C m}^{-2} \)) to 1 m (kg C m\(^{-2} \)) beyond the simple climate metrics used here. We recognize that further research diagnosing the mechanisms responsible for this variation is critical, but here we focus on the central feature of the data, and this may be driven by mineralogical or biochemical differences.

**Equation 1**

\[
\tau_{\text{app}} = \frac{C}{\rho \cdot \epsilon} \left(1 + k \cdot T\right)
\]

\( C \) is calculated from the derivative of the regression curve in the sensitivity of inferred potential evapotranspiration calculated as the ratio of carbon stocks (\( \text{Soil carbon to 1 m (kg C m}^{-2} \)) to 1 m (kg C m\(^{-2} \)) beyond the simple climate metrics used here. We recognize that further research diagnosing the mechanisms responsible for this variation is critical, but here we focus on the central feature of the data, and this may be driven by mineralogical or biochemical differences.

**Supplementary Table 1**

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<td>Cold-climate</td>
<td>( \tau_{\text{app}} &gt; 100 \text{ yr} )</td>
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**Emergent Domains**

Emergent domains are characterized by high-climatic sensitivity, while non-emergent domains have low-climatic sensitivity. The climatic sensitivity is determined by the ratio of temperature sensitivity to climatological temperature over the interval, with stronger sensitivity in cold climates than in warm climates. We note, however, that considerable variation remains.

**Figure 3** The residual two-fold variation in turnover times (residual variance in being diagnosed based on \( \tau_{\text{app}} \)) versus MAAT, with 50% prediction intervals shown. Best-fit regression curve in the sensitivity of inferred potential evapotranspiration calculated as the ratio of carbon stocks (\( \text{Soil carbon to 1 m (kg C m}^{-2} \)) to 1 m (kg C m\(^{-2} \)) beyond the simple climate metrics used here. We recognize that further research diagnosing the mechanisms responsible for this variation is critical, but here we focus on the central feature of the data, and this may be driven by mineralogical or biochemical differences.

**Equation 2**

\[
\tau_{\text{app}} = \frac{C}{\rho \cdot \epsilon} \left(1 + k \cdot T\right)
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**Figure 4** The residual two-fold variation in turnover times (residual variance in being diagnosed based on \( \tau_{\text{app}} \)) versus MAAT, with 50% prediction intervals shown. Best-fit regression curve in the sensitivity of inferred potential evapotranspiration calculated as the ratio of carbon stocks (\( \text{Soil carbon to 1 m (kg C m}^{-2} \)) to 1 m (kg C m\(^{-2} \)) beyond the simple climate metrics used here. We recognize that further research diagnosing the mechanisms responsible for this variation is critical, but here we focus on the central feature of the data, and this may be driven by mineralogical or biochemical differences.

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**Figure 5** The residual two-fold variation in turnover times (residual variance in being diagnosed based on \( \tau_{\text{app}} \)) versus MAAT, with 50% prediction intervals shown. Best-fit regression curve in the sensitivity of inferred potential evapotranspiration calculated as the ratio of carbon stocks (\( \text{Soil carbon to 1 m (kg C m}^{-2} \)) to 1 m (kg C m\(^{-2} \)) beyond the simple climate metrics used here. We recognize that further research diagnosing the mechanisms responsible for this variation is critical, but here we focus on the central feature of the data, and this may be driven by mineralogical or biochemical differences.

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Turnover times

Figure 4 | A comparison of relationships between soil turnover times and climate as predicted by a suite of ESMs and offline models.

Inferred turnover time, $\tau$, calculated as in Fig. 1 and coloured by precipitation as in Fig. 1c, from soil models used in ESMs.

- a–f, CMIP5 models, each of which (other than GFDL-ESM2G) use single-layer soil temperature control on soil carbon turnover.
- g, h, CLM4.5, which calculates vertically resolved decomposition rates. These differ by varying a parameter ($Z_\tau$) that controls decomposition rates with depth independently from resolved temperature, moisture, and oxygen controls.
- i, MIMICS, which treats decomposition as a microbially enabled and mineral-resolved nonlinear model, shows the wide scatter in moist tropical climates as observed, due to its consideration of mineralogical control on decomposition.

$k$ approximates the observed relationship suggests that, at least in the near surface, such transport processes are sufficiently fast over long timescales for the soil to act as a well-mixed reservoir through which respiration can occur at any depth within the 0–1 m interval.

We contend that the climatological sensitivity of soil C to historical climate (Fig. 1d) is an emergent ecosystem property that models should be expected to replicate. To test whether ESMs are able to match these qualitative patterns, we compare predictions of $\tau$ from models used in the CMIP5 carbon cycle experiments (Fig. 4a–f and Supplementary Table 2). Most models show a linear relationship between log($\tau$) and mean annual air temperature (MAAT), as would result from using fixed $Q_{10}$ and a single-layer model that diagnoses $k$ values from near-surface temperatures. Some models show other sets and emergent behaviour, but none are able to qualitatively capture both the increase in temperature sensitivity through the entire range of cold climates as well as the reduction in temperature sensitivity in tropical climates shown by the global data. The inability of the models to match spatial gradients implies that the transient response to warming will likewise be...
Permafrost soils CLM4.5bgc & 5.0

Stoichiometry
Rate constant (k)
Water function
Temperature function
Transfer coefficients
(among pools & respiration)

O₂ function
Advection
Diffusion
E-folding depth
(depth dependence of turnover)

Koven et al. Biogeosciences 2013
Permafrost soil C loss

![Graph showing PF Domain Soil C loss over time with different labels for soil depth: Z_T = 0.5m, Z_T = 1.0m, Z_T = 10m.](image)

**Permafrost soil C loss**

**PF Domain Soil C**

- **Δ Soil C (Pg)**: Change in soil carbon over time.
- **Year**: Time scale from 1900 to 2300.

### Key Observations

- **Z_T = 0.5m**: Slight reduction in soil carbon.
- **Z_T = 1.0m**: Moderate reduction in soil carbon.
- **Z_T = 10m**: Significant reduction in soil carbon.

**Notes**

- The graph illustrates the projected loss of soil carbon over time under different soil depth conditions (Z_T).
- The reduction in soil carbon is more pronounced with increasing soil depth (Z_T).
- The impact on soil carbon is critical for understanding carbon cycle responses to warming.
Coupled C:N Biogeochemistry

“N limitation of Decomposition fluxes”

Yes, that’s really a thing in CLM & other demand-based models
Coupled C:N Biogeochemistry

'donor'

$\frac{C}{N} = 50$

$\frac{N}{C} = 0.02$

$\varepsilon = 0.5$

$\frac{C}{N} = 25$

$\frac{N}{C} = 0.04$

N immobilization

'receiver'

$\frac{C}{N} = 10$

$\frac{N}{C} = 0.10$

Litter & Wood
**Coupled C:N Biogeochemistry**

- **Donor**
  - C:N = 50
  - N:C = 0.02
  - CO<sub>2</sub>
  - ε = 0.5

- **Receiver**
  - C:N = 25
  - N:C = 0.04
  - N Immobilization

- **Donor**
  - C:N = 15
  - N:C = 0.075
  - CO<sub>2</sub>
  - ε = 0.5

- **Receiver**
  - C:N = 7.5
  - N:C = 0.133
  - N Mineralization

- **Litter & Wood**
  - C:N = 16
  - N:C = 0.075

- **Soil**
  - C:N = 10
  - N:C = 0.10
N Demand

N Available

allocated proportional to demand
CLM 5 & beyond
Subgrid hillslope hydrology

NH$_3$ emissions

Levis et al. 2014 GMD

Riddick et al. (2016) BG
N uptake & competition

CLM4.0cn [inorganic N]
CLM4.5bgc [NH$_4^+$, NO$_3^-$]

Known Issues:
• High N fertilization effects
  Thomas et al (2013) GBC
• Huge denitrification fluxes
  Thomas et al. (2013) BG
  Houlton et al. (2015) NCC
• No leaching (or DON losses)
  Nevison et al. (2016) JAMES

[Diagram showing cycle of nitrogen uptake and competition]
N uptake & competition

CLM5 + ELM

Plants

Microbes

Nitrification

Microbes

Denitrification

Leaching

ECA approach

Zhu & Riley (2015) NCC
Zhu et al. (2016), BG
Soil Biogeochemistry in CLM 5+

Adding functionality & reality
**Rapid soil C turnover in CLM4.0-cn**

Bonan et al. Global Change Biology 2013
Absurd soil N behavior in CLM4.0-cn

(a) ACSA, 0.81 %N

(b) THPL, 0.62 %N

PIRE, 0.59 %N

TRAE, 0.38 %N

Fig. 11

As in Fig. 10, but for (a, b) Acer saccharum (ACSA), (c, d) Thuja plicata (THPL), (e, f) Pinus resinosa (PIRE), and (g, h) Triticum aestivum (TRAE) leaf litter. The low N simulation for CLM-cn segregates along three separate lines representing $f_{pi} = 0.20$, 0.10, and 0.05 (used in tropical forest, deciduous forest, and all other biomes, respectively).

© 2012 Blackwell Publishing Ltd, Global Change Biology, 19, 957–974

Bonan et al. Global Change Biology 2013
Soil C improved w/ DAYCENT?

Obs. (HWSD) 1259 Pg C

CLM4cn 502 Pg C, $r = 0.43$
Soil C improved w/ DAYCENT?

Obs. (HWSD) 1259 Pg C

CLM4cn* 746 Pg C, $r = 0.61$

DAYCENT* $\S 978$ Pg C, $r = 0.61$

* Analytical Solution
“observed” litter inputs

$\S$Modified to simulate soil 0-1 m

Wieder et al. GBC 2014