Soil dynamics in a changing world

Will Wieder
2014 CLM Tutorial
How does an ecologist use and improve CLM?
Observations \rightarrow Theory \rightarrow Models \rightarrow Observations
Perspectives on the C cycle

1. Global C cycle (esp. soils)
2. CLM soil biogeochemistry:
   - Past
   - Present &
   - Future
Terrestrial Carbon Cycle (Observations)
Terrestrial Carbon Cycle (Models)
What happens when a leaf falls in the forest?
What happens if MORE leaves fall in a WARMER forest?
Soils Store Carbon
CMIP5 Models = 6x variation

Todd-Brown et al. Biogeosciences 2013, Friedlingstein et al. 2006; Jones et al. 2003
CLM4.0-cn (CLM “past”)

Obs. (HWSD) 1259 Pg C

CLM4cn 502 Pg C, $r = 0.43$

Fast

Slow

$\text{CO}_2$

$\text{CO}_2$
Using data to evaluate models
Climate matters

Parton et al. Science 2007

Chemistry matters

Wieder et al. Ecology 2009
Which model looks more like reality?

CLM4.0-cn vs. LIDET

DAYCENT
Rapid soil C turnover in CLM4.0-cn

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?
Soil C improved w/ DAYCENT?

Obs. (HWSD) 1259 Pg C

CLM4cn* 746 Pg C, $r = 0.61$

* Analytical Solution
  “observed” litter inputs

§Modified to simulate soil 0-1 m

Wieder et al. GBC 2014
CONCLUSIONS

CLM4-cn: Anemic soil C pools
Rapid litter turnover

DAYCENT: Better litter turnover
Better soil C pools*

*with modifications for depth
CLM4.5bgc (CLM “present” )
Permafrost C “observations”

NCSCD from Hugelius et al. 2013
Permafrost C in models

Todd-Brown et al. Biogeosciences 2013
Permafrost soils CLM4.5bgc

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

Koven et al. Biogeosciences 2013
20th century land C sink

Fig. 12. Schematics of N cycle in base and updated versions of CLM4; numbers refer to the global mean slow N cycle source and sink terms for an 1850 control scenario.

(a) Terrestrial GPP
(b) Terrestrial NPP
(c) Change in total terrestrial C stocks. Observations in (c) are the sum of the land sink and land-use fluxes from the Global Carbon Project (Le Quere et al., 2013), with errors calculated assuming that within each year the land error equals the root-sum-of-squares of the ocean and fossil fuel errors, and that errors are correlated interannually, so are additive in time. Model versions are the CLM4.0-CN, CLM4.5-biogeophysics, and CLM4.5-biogeophysics/biogeochemistry.

The set of changes between the CLM4.0-CN and CLM4.5-biogeophysics lead to sharply reduced terrestrial gross primary productivity (GPP), from \( \approx 160 \) Pg C yr\(^{-1} \) to \( \approx 110 \) Pg C yr\(^{-1} \) (Fig. 13 a). Most of this reduction occurs in the tropical forests, which in CLM4.0-CN have unrealistically high GPP values (Beer et al., 2010), as a result of reduced photosynthesis following the revised calculations described in Bonan et al. (2011, 2012). Because tropical forests in CLM have relatively low carbon use efficiency (defined as the ratio of NPP to GPP), the reduced GPP in the tropical forests leads to a proportionally smaller decrease in the global NPP (Fig. 13 b). However, because the overall limitation by nitrogen is weakened due to the intrinsically lower photosynthetic uptake, the biosphere is more responsive to the increased temperature and CO\(_2\) concentrations, leading to a larger net uptake of carbon overall, which shifts the biosphere from a source to a weak sink of carbon (Fig. 13 c).

This shift can be seen by looking at the latitudinal profiles of the change in C pools (Fig. 14 a–b), in which the tropical vegetation transient increase is higher in the CLM4.5-biogeophysics simulation than the CLM4.0-CN simulation. There is larger storage in the litter and soil pools as well, despite the fact that the shift does not change the turnover times to these pools.

Koven et al. *Biogeosciences* 2013
CONCLUSIONS

CLM4.5bgc: Vertically resolved Large soil C pools 20th century land sink Permafrost dynamics
Microbial models (CLM “Future”)
What happens if MORE leaves fall in a WARMER forest?

GPP
R
A
R
HN
NEE
NPP
Wieder et al. GBC 2014
CLM4.0-cn
DAYCENT
Observations

Theory

Models
What are soils?
Biology in ESM C cycle?
Biological drivers of the terrestrial C cycle:

- Plant functional diversity
- Agriculture
- Soils...

Microbes
Microbial theory in models

The catalyst matters

CO₂

Microbes

Enzymes

DOC

SOC

Microbial theory in global models

Wieder et al. Nature Climate Change (2013)
Microbial models work at global scales

*All models w/ same forcing from CLM4.5 output*  

Wieder *et al.* Nature Climate Change 2013
Model structure matters  
(in global change settings)
Microbial theory in global models

Wang et al. Biogeosciences 2014
Biological drivers of the terrestrial C cycle:

Plant functional diversity  Agriculture

Soils...  Plants  Microbes  Minerals

**MIcrobial-MIneral Carbon Stabilization (MIMICS) model**

- **LIT** (Litter) 
  - $V_{max, K_m}$
  - $f_{i, met}$
  - $f_{i, struc}$

- **MIC** (Microbes) 
  - $f_p$
  - $f_c$

- **SOM** (Soil Organic Matter) 
  - $SOM_p$
  - $SOM_a$
  - $SOM_c$

- **Plants**: $f_{met}$

**Equations and Parameters**

- $f_{i, met}$
- $1 - \varepsilon$
- $\tau$

**POOLS**

- $SOM_p = $ generic physical protected pool
- $SOM_a = $ metabolically available SOM
- $SOM_c = $ chemically "protected" SOM

**FLUXES**

- What controls partitioning of turnover?
- What controls transfers to SOMa?
Validating MIMICS

Harvard Forest

Bonanza Creek

Mass remaining (%)

time (y)

Wieder et al. BGD (2014); see also Bonan et al. GCB (2013)
Validating MIMICS

* 0-100cm, all models w/ same forcing from CLM4.5 output
Model structure matters (increase litter quantity)

Change in total C (g C m$^{-2}$)

- DAY_clay
- DAY_sand
- MIM_clay
- MIM_sand
- CLM_mm

Wieder, unpublished
CONCLUSIONS

MIMICS: Microbial explicit
Microbial traits
Physical stabilization
Litter quality & quantity
More realistic?
New Directions

- Test ecological theory
- Evaluation & Validation
  - Functional traits (MGE, turnover)
  - Transient response
- Parameterization
  - scaling relationships (Climate, N, etc.)

LIT

MIC

SOM

POOLS

SOMp = generic physically protected pool
SOMa = metabolically available SOM
SOMc = chemically "protected" SOM

FLUXES

what controls partitioning of turnover?
what controls transfers to SOMa?
Thank you
CLM-microbial model
Model structure matters
(in global change settings)

Wieder et al. Nature Climate Change 2013
Model structure matters
(in global change settings)

Wieder et al. Nature Climate Change 2013
CMIP5 Models = 6x variation

Todd-Brown et al. Biogeosciences 2013, Friedlingstein et al. 2006; Jones et al. 2003
Permafrost soils CLM4.5bgc

Fig. 12. Schematics of N cycle in base and updated versions of CLM4; numbers refer to the global mean slow N cycle source and sink terms for an 1850 control scenario.

Fig. 13. Changes to global integrated carbon cycle quantities during a transient late-20th-century (1955–2005) model simulation forced by reanalysis meteorology and observed atmospheric CO$_2$ concentrations.

(a) Gross primary productivity (GPP).
(b) Net primary productivity (NPP).
(c) Change from initial total terrestrial carbon stocks. Observations in (c) are the sum of the land sink and land-use fluxes from the Global Carbon Project (Le Quere et al., 2013), with errors calculated assuming that within each year the land error equals the root-sum-of-squares of the ocean and fossil fuel errors, and that errors are correlated interannually, so are additive in time. Model versions are the CLM4.0-CN, CLM4.5-biogeophysics, and CLM4.5-biogeophysics/biogeochemistry.

The set of changes between the CLM4.0-CN and CLM4.5-biogeophysics lead to sharply reduced terrestrial gross primary productivity (GPP), from $\approx 160$ Pg C yr$^{-1}$ to $\approx 110$ Pg C yr$^{-1}$ (Fig. 13a). Most of this reduction occurs in the tropical forests, which in CLM4.0-CN have unrealistically high GPP values (Beer et al., 2010), as a result of reduced photosynthesis following the revised calculations described in Bonan et al. (2011, 2012). Because tropical forests in CLM have relatively low carbon use efficiency (defined as the ratio of NPP to GPP), the reduced GPP in the tropical forests leads to a proportionally smaller decrease in the global NPP (Fig. 13b). However, because the overall limitation by nitrogen is weakened due to the intrinsically lower photosynthetic uptake, the biosphere is more responsive to the increased temperature and CO$_2$ concentrations, leading to a larger net uptake of carbon overall, which shifts the biosphere from a source to a weak sink of carbon (Fig. 13c).

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Arctic SOC
Litter inputs (Pg C y^{-1})

CLM4.0 = 43
CLM4.5 = 49
Matthews = 45
“Old” SOC (Pg C)

HWSD = 1260

CLM4.0 = 1280

DAYCENT = 1710

*CLM4.5 litter fluxes
“New” SOC (Pg C)

HWSD = 1260
CLM4.5 = 2090
Microbial = 1420

*CLM4.5 litter fluxes