Radiocarbon constraints on the carbon cycle

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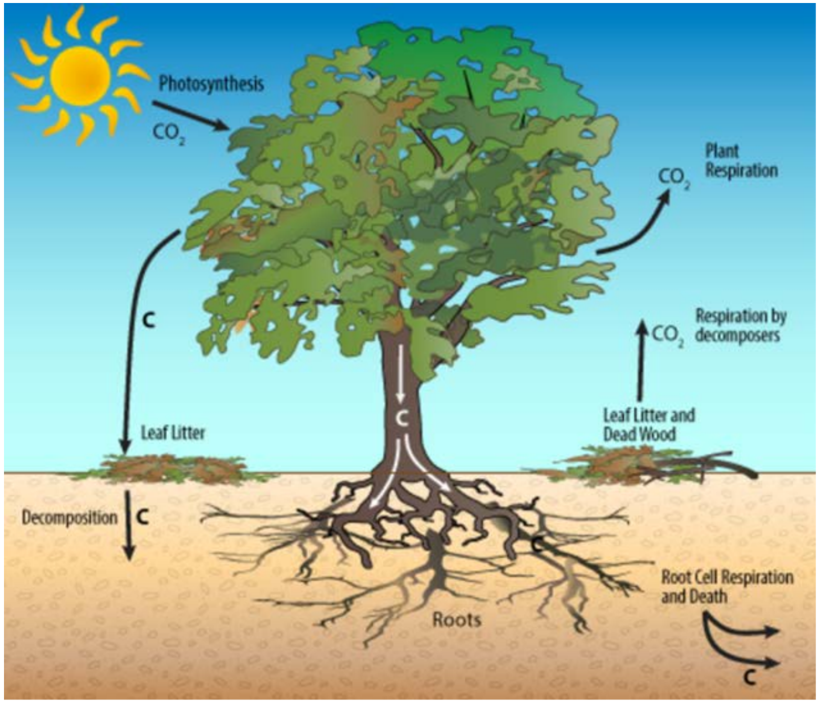
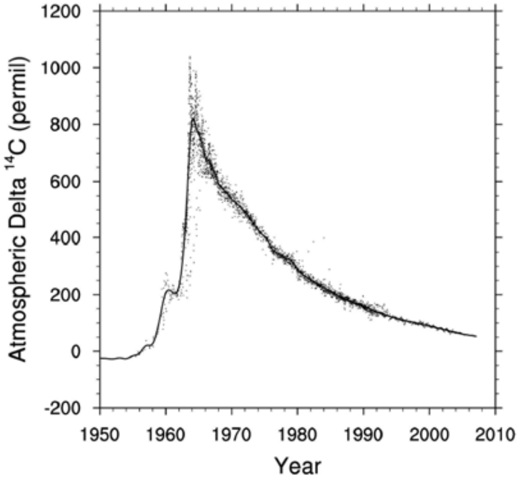
outline

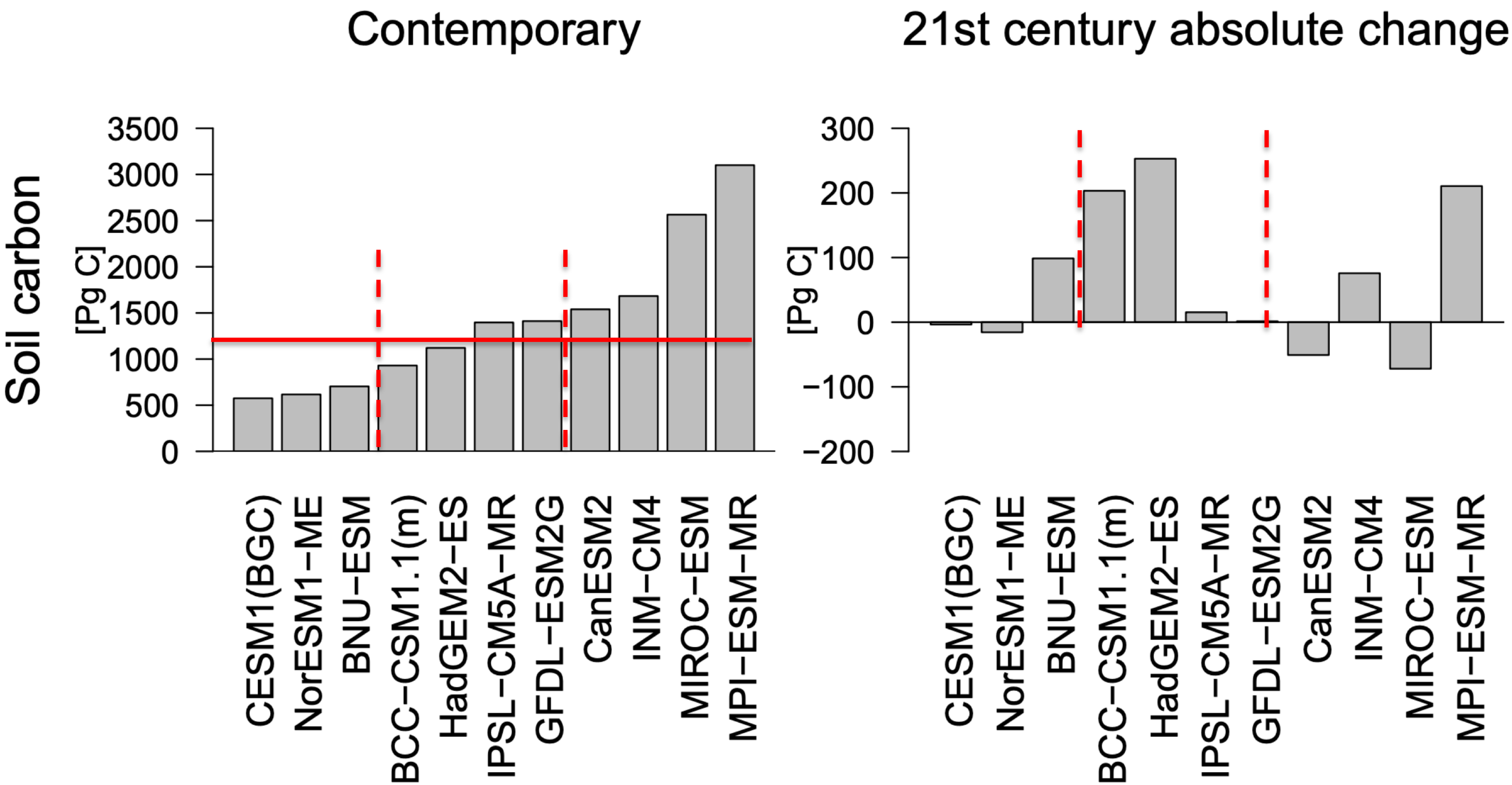
1. Terrestrial ^{12}C cycle and ^{14}C signal constraints on ^{12}C cycle
2. ^{14}C in E3SM land model (Chen et al. 2019)
3. ^{14}C for CMIP5/CMIP6 ESMs (Metzler et al., review at JAMES)

- Major processes
  - Photosynthesis
  - Plant respiration
  - Litter input
  - Soil turnover



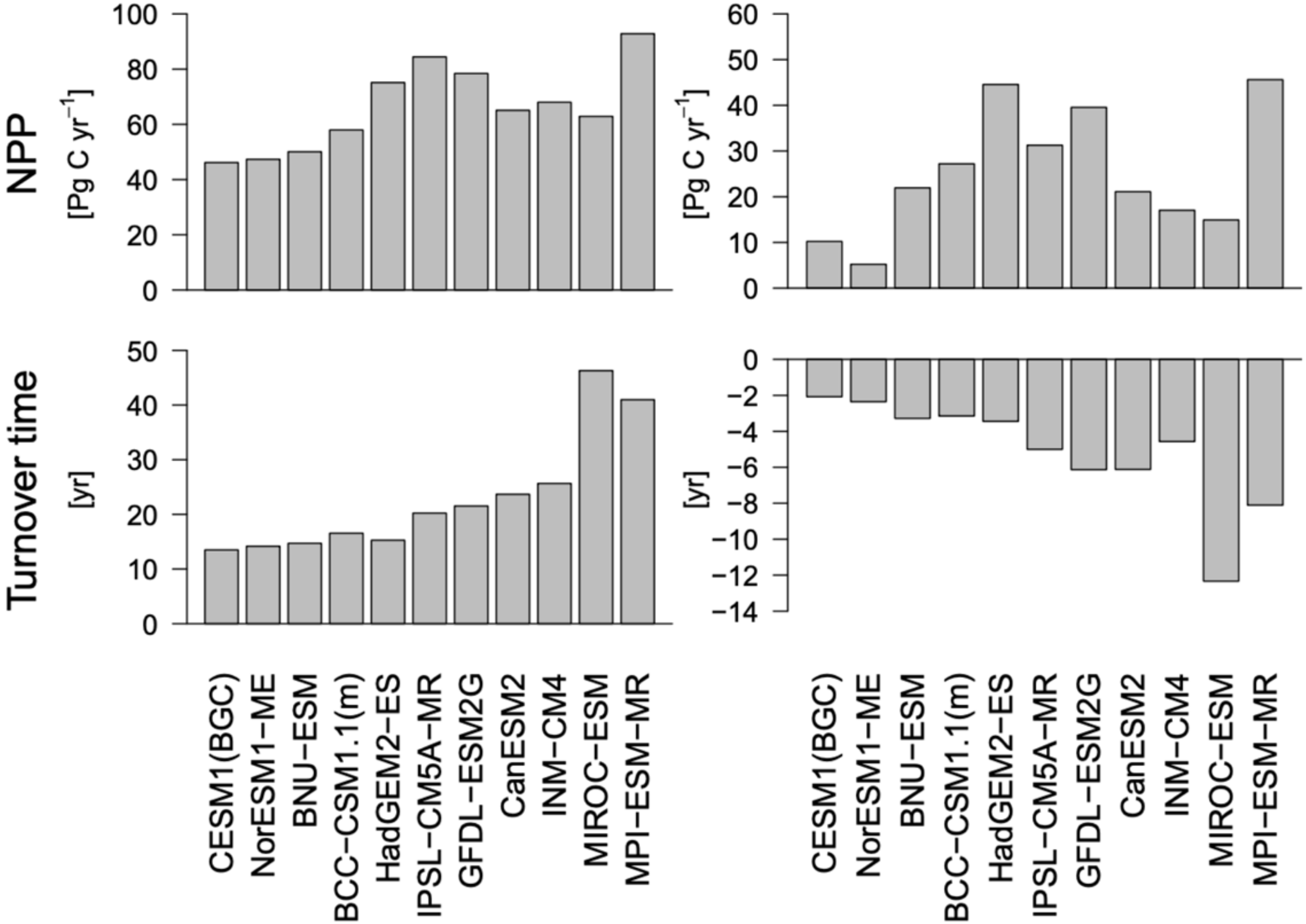
- Soil has larger potential to store C than vegetation
- Soil carbon residence time could be very long





Todd-Brown et al., 2014

Q1: How do ESM simulate SOC stock?
Q2: Better SOC estimate -> reliable future projection?



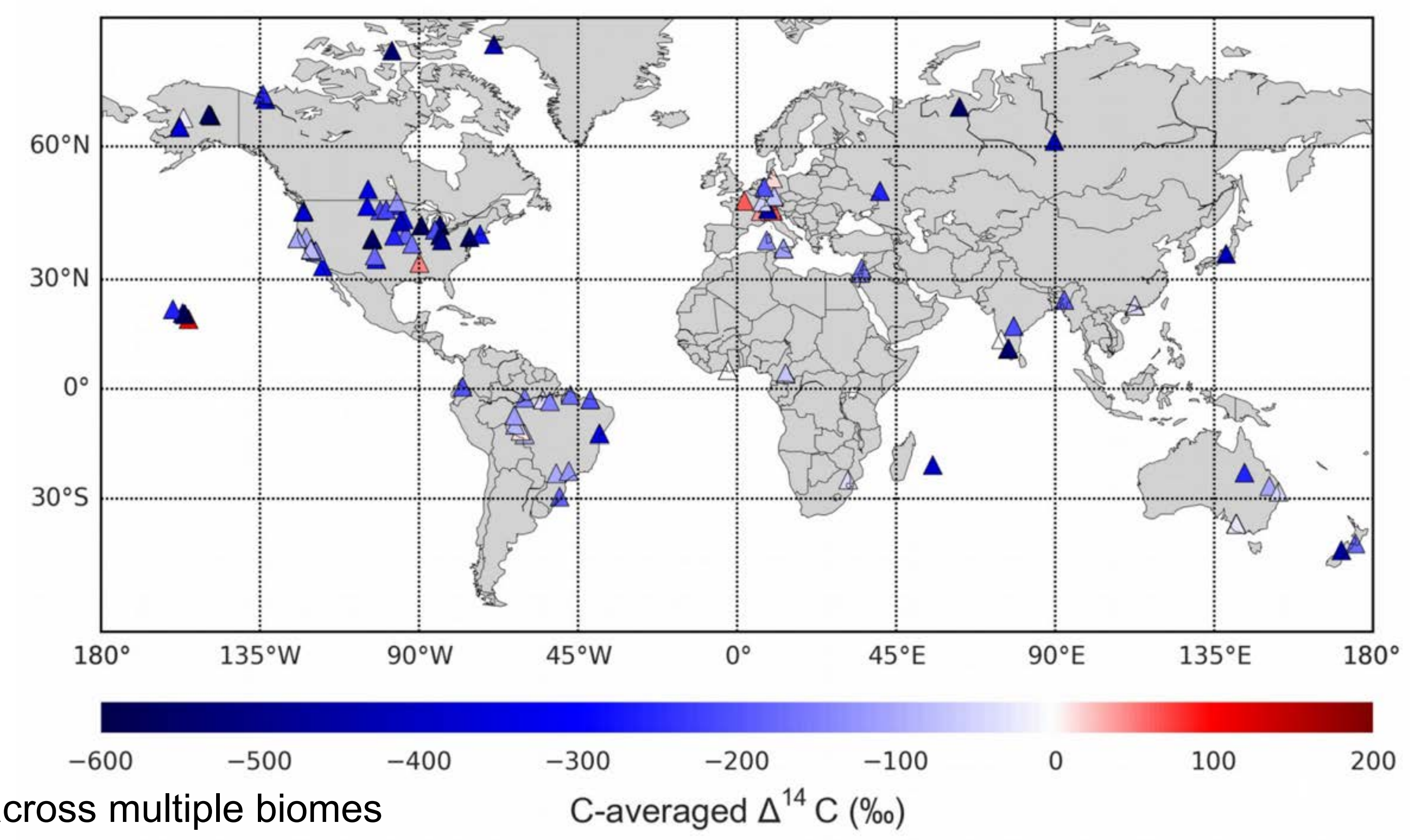
C Input: gross input, depth-distribution, …

Turnover: decomposability, T sensitivity, …

How to use observational data to constrain the C cycle in Earth System Model?

SOC stock	Inputs	turnover
Harmonized World Soil Database	GPP, CUE	Soil ^{14}C profile
SoilGrid	Long-term plots	Soil Incubation
Northern Circumpolar Soil Carbon Database		

Radiocarbon (14C) data

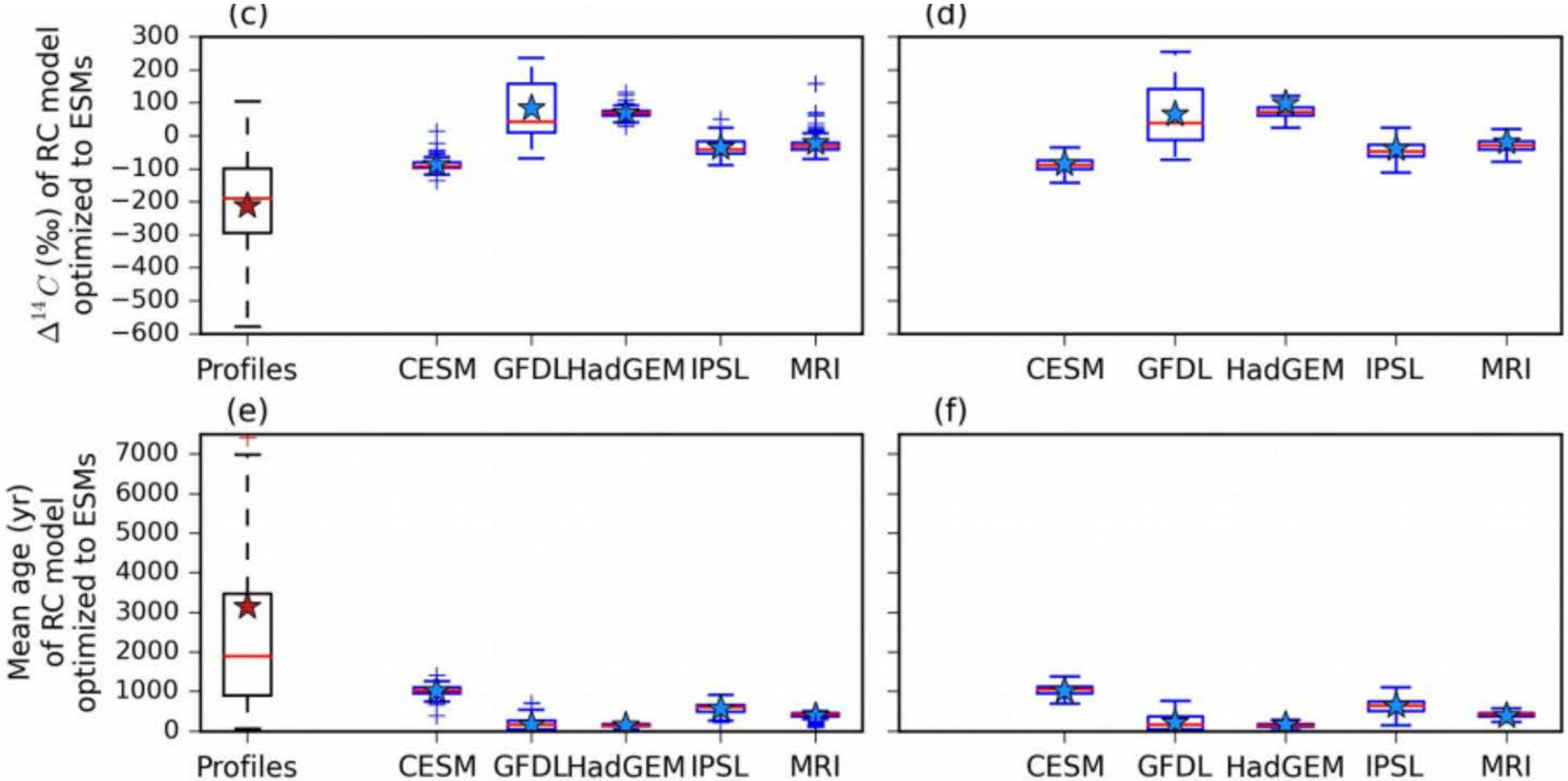


157 sites across multiple biomes

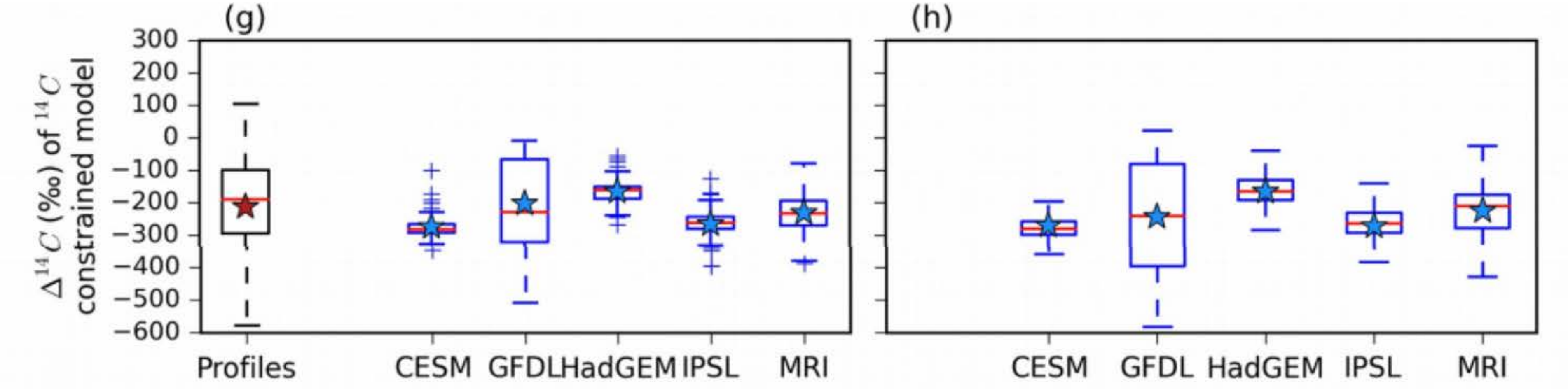
He et al., 2016

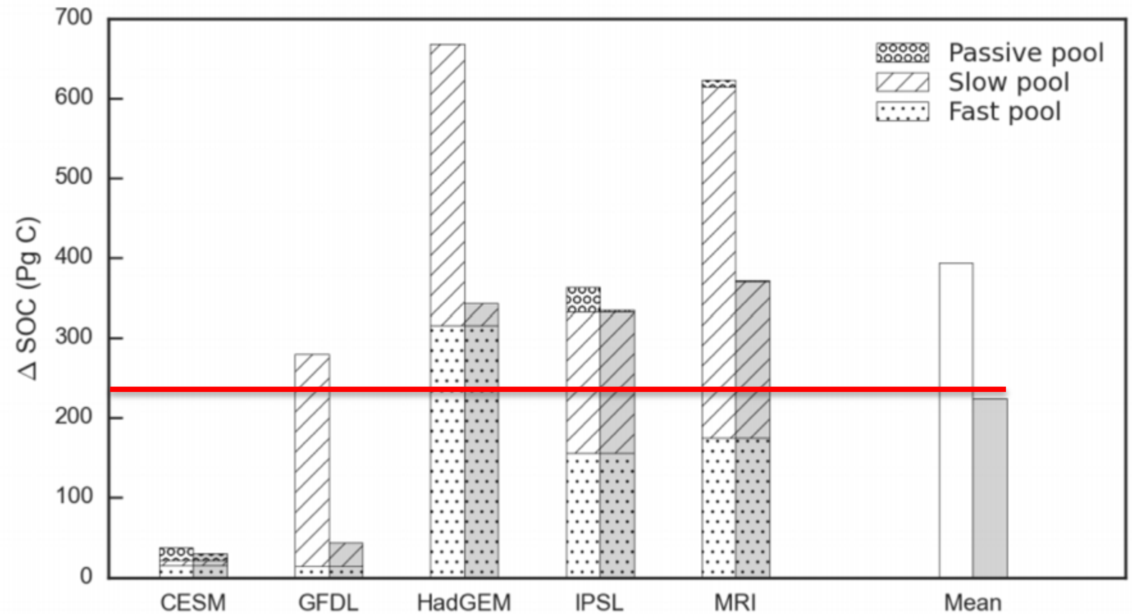
How do ESMs represent soil age (turnover time)?

Radiocarbon (^{14}C) in ESM



He et al., 2016


(g)
(h)
$\Delta^{14}C$ (‰) of ^{14}C constrained model
300
200
100
0
−100
−200
−300
−400
−500
−600
Profiles
CESM
GFDL
HadGEM
IPSL
MRI


Δ SOC (Pg C)
700
600
500
400
300
200
100
0
Passive pool
Slow pool
Fast pool
CESM
GFDL
HadGEM
IPSL
MRI
Mean

He et al., 2016

International-Soil-Radiocarbon-Database/ISRaD

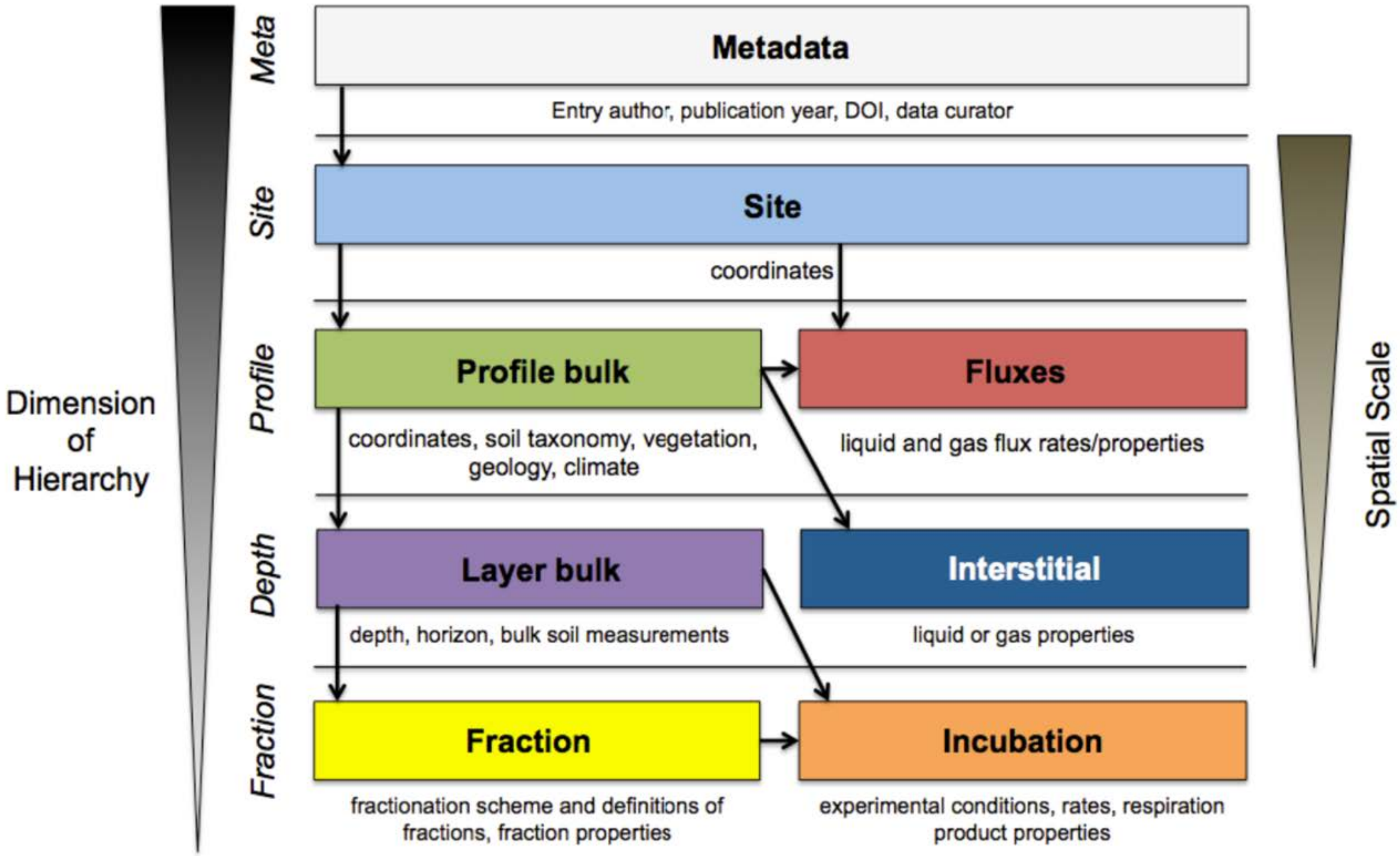
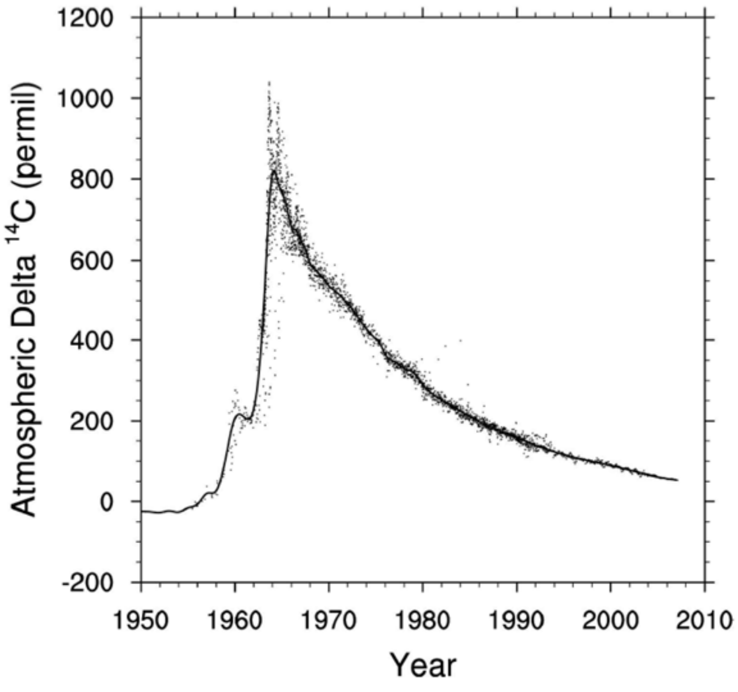
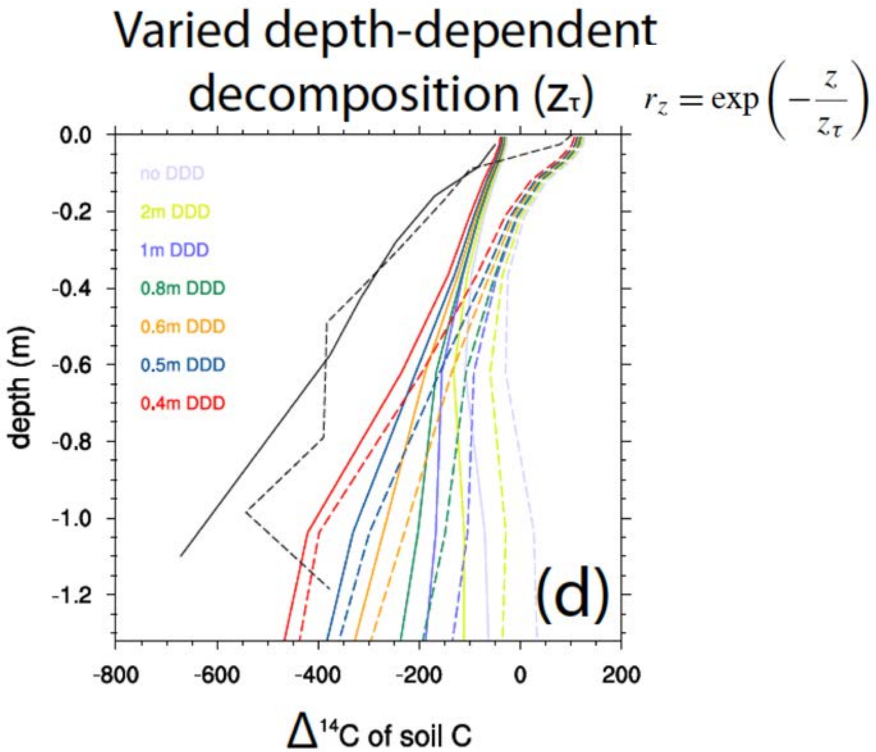


Fig. 1 Conceptual diagram of an entry in ISRaD. Each box represents a table in an entry; the horizontal bars distinguish the hierarchical levels of the database, and arrows show the hierarchical linkages among the tables.

Radiocarbon (^{14}C) in CLM





Koven et al., 2013

Summary: background

1. Soil ^{14}C signal is controlled by radioactive decay and perturbed by "nuclear bomb"

2. ^{14}C is powerful constraint on soil C cycle, in additional to ^{12}C SOC stock

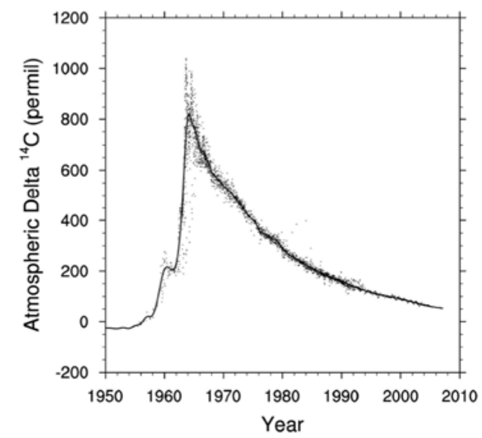
3. ^{14}C is largely biased (too young) in current generation of ESM

Challenges & Research Questions

1. How do we effectively use ^{14}C soil profile data (in situ) to constrain ESM (100kmx100km gridcell)?

2. How can ^{14}C data inform ^{12}C soil carbon model development?

Case #1: ^{14}C in E3SM



Model: ELM-ECA (Zhu et al., 2019)

Modeling protocol:

0 per mil — **Accelerated spinup** → 0 per mil — **Regular spinup** → Bomb spike — **Transient simulation**

14C radioactive decay half life ~ 5700yr

Grid cell selection:

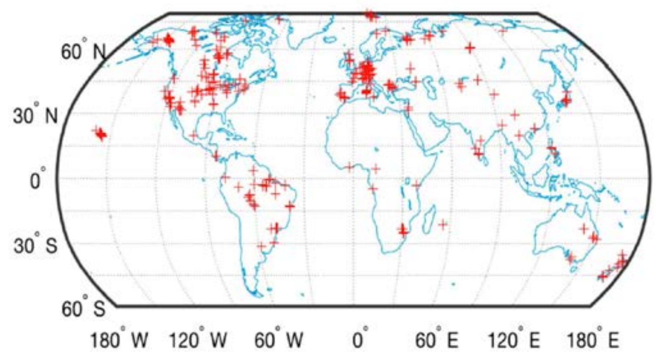
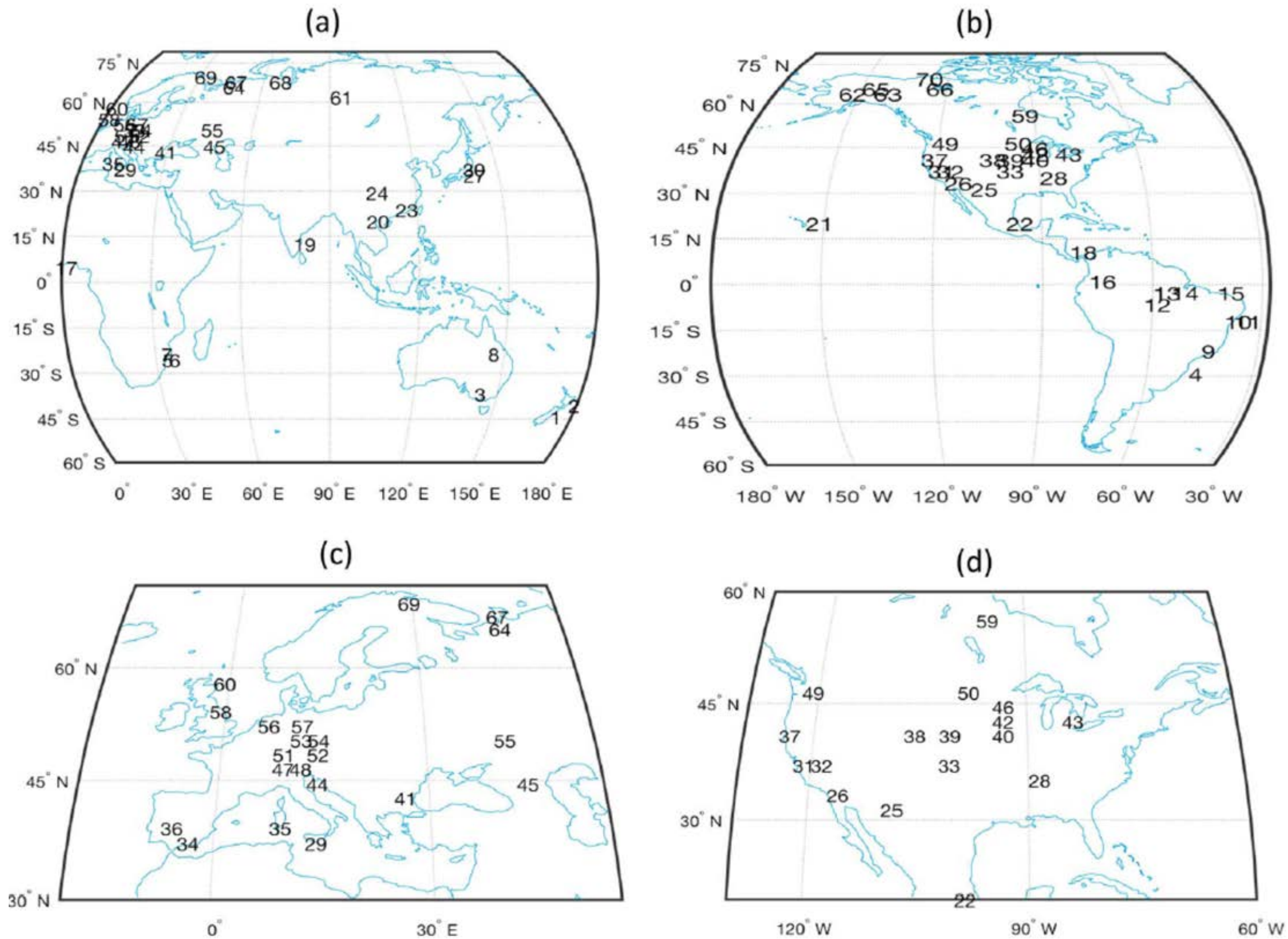


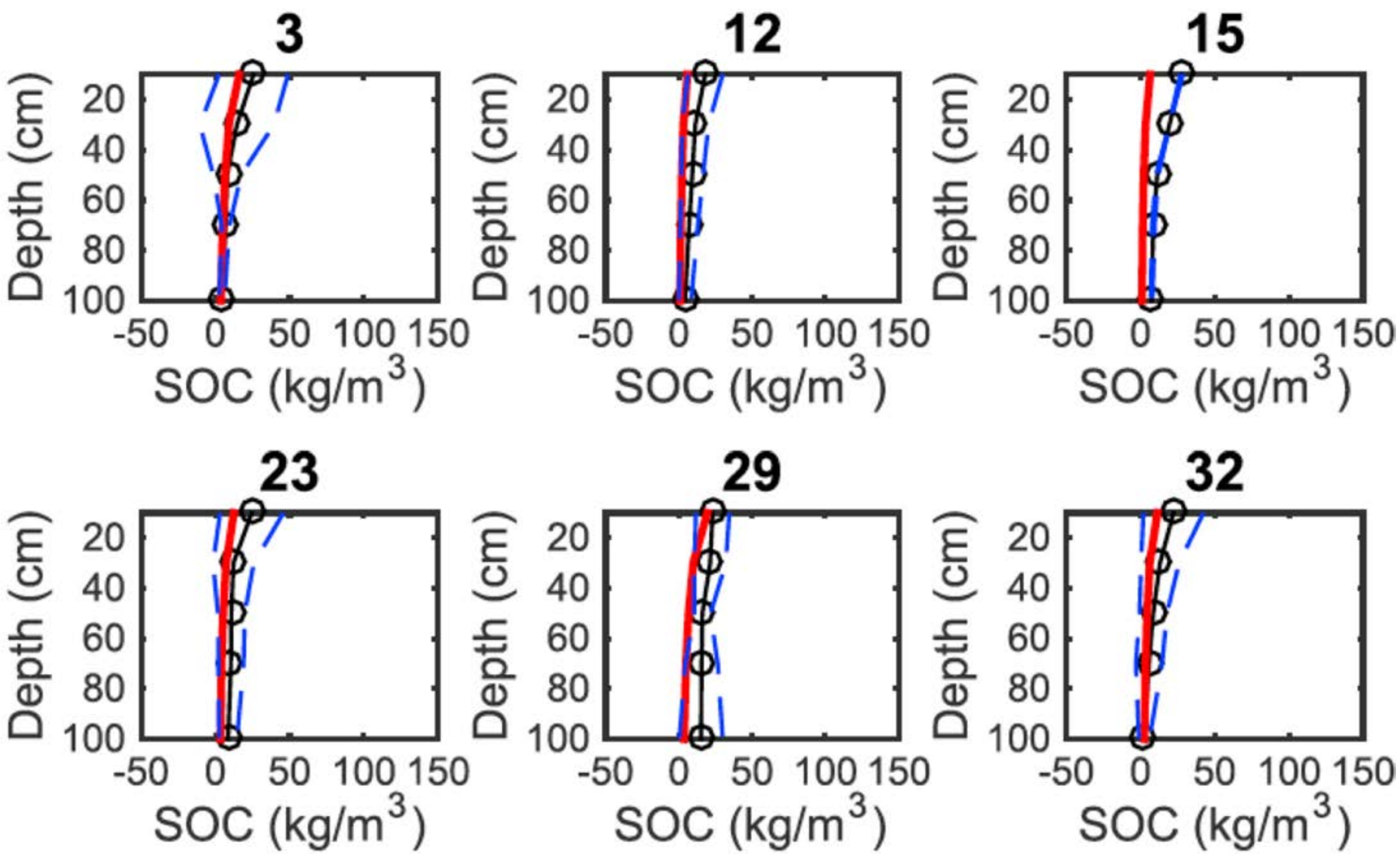
Figure 1. Locations of global soil radiocarbon observation sites (red plus signs). There are 671 sites in total around the global.

Case #1: ^{14}C in E3SM

70 ESM gridcells

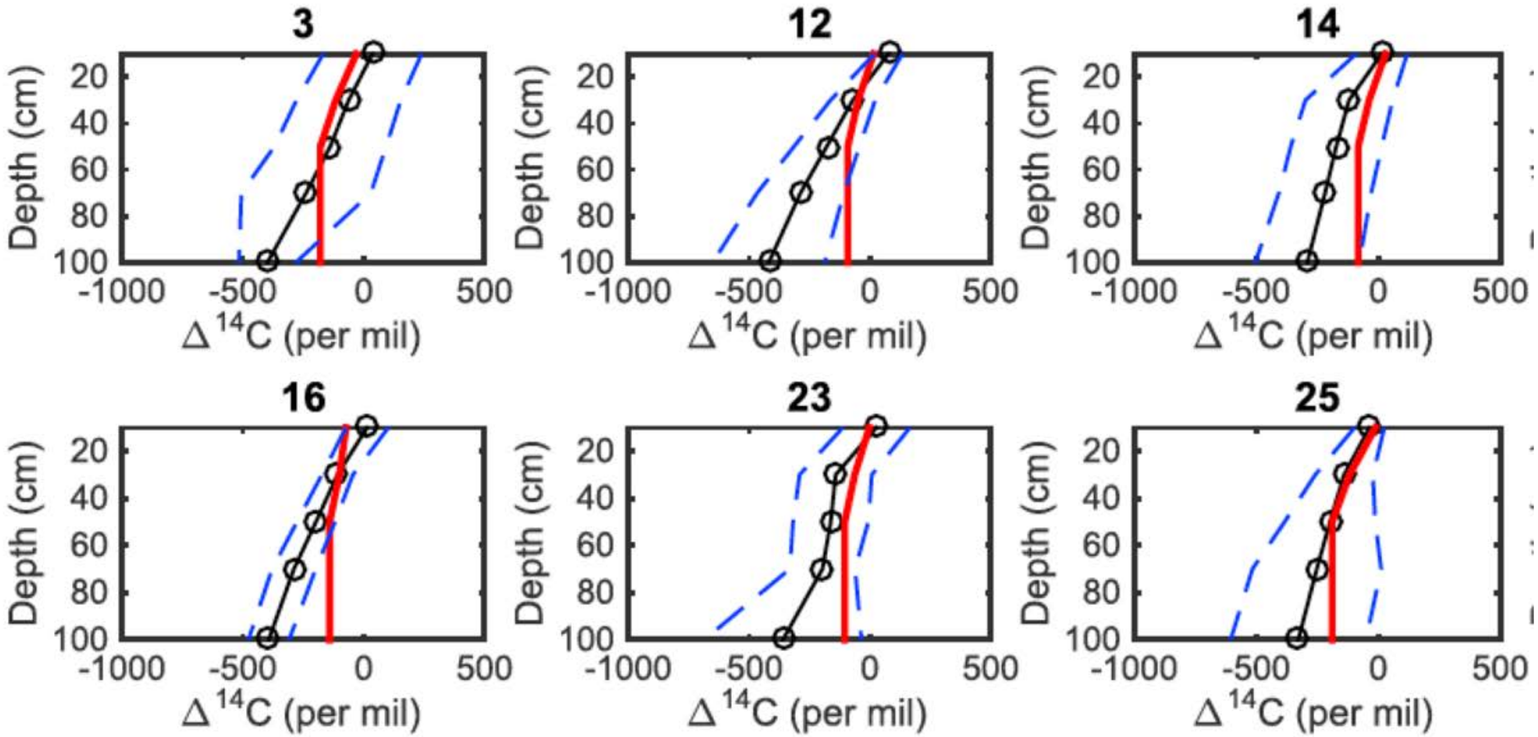


Grid cell level comparison



Chen et al., 2019

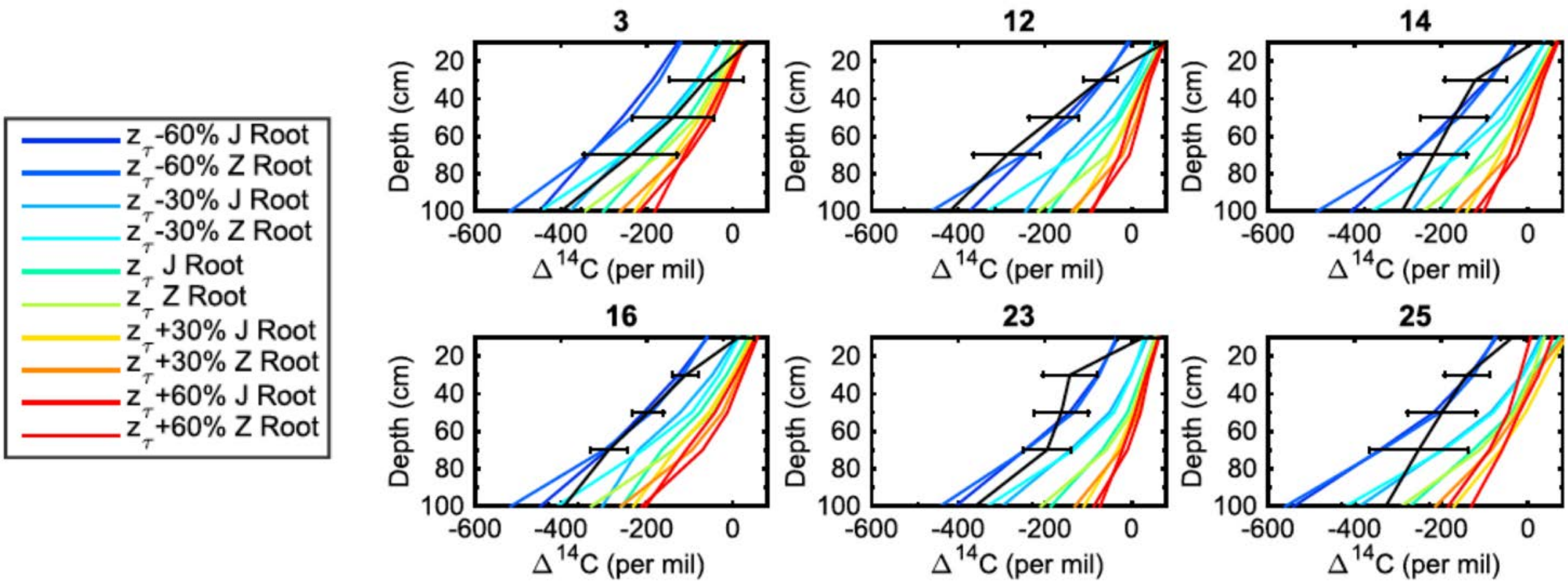
Grid cell level comparison



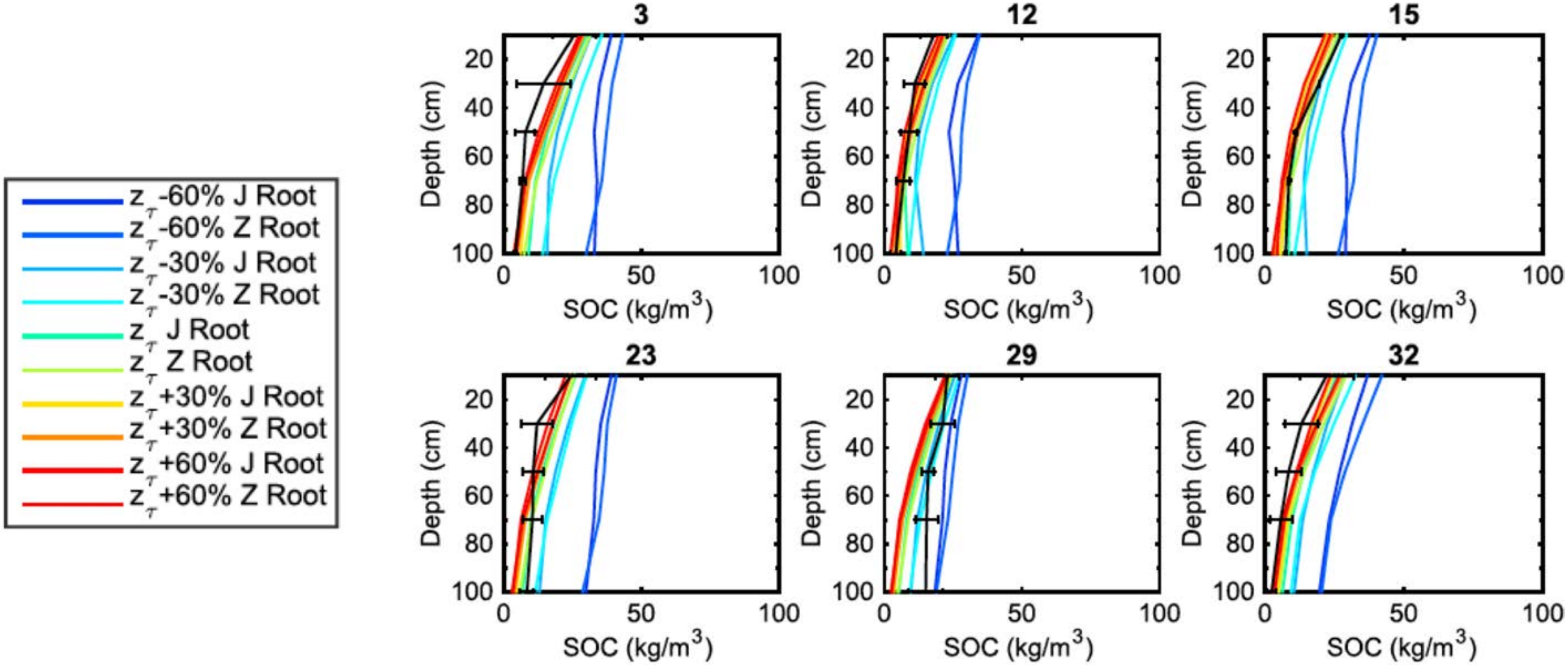
Chen et al., 2019

Hypothesis: soil decomposability parameterization bias leads to the young soil at deep soil layers
Hypothesis: fresh carbon input (root below 50cm) at deep layers is too large

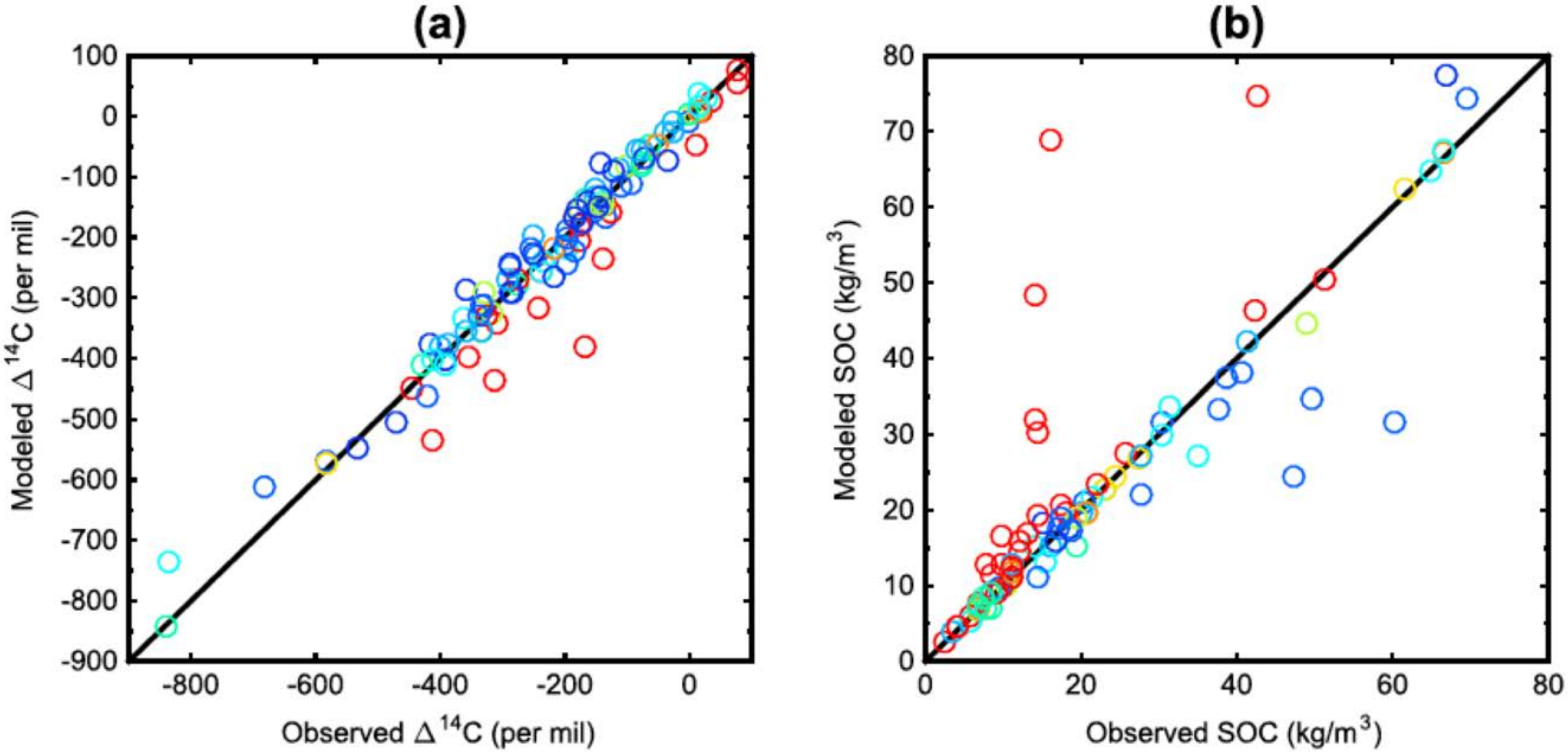
Sensitivity analysis



Sensitivity analysis



Best model-data fit

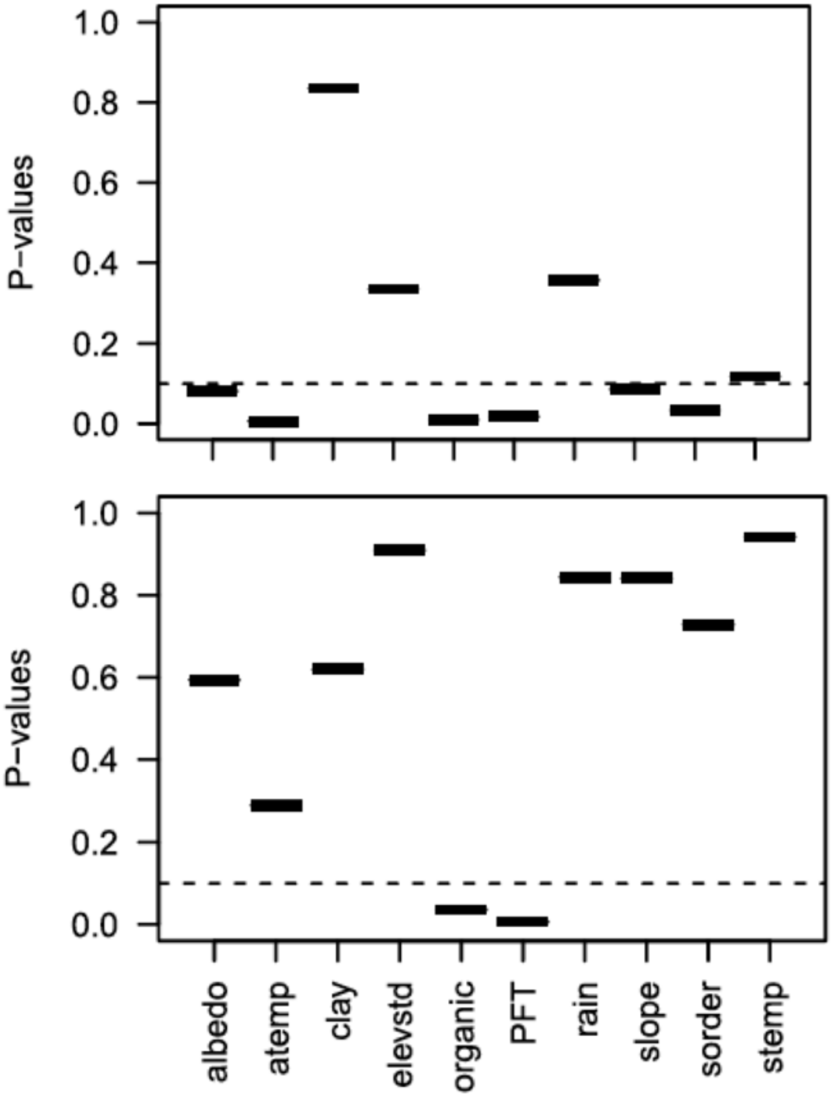


- z_tau means to represent "unconsidered factors" on soil decomposability across depth
- Heterogeneous z_tau benefit model-data fit

Machine learning approach for bias analysis

10 cm:
air temperature, organic matter density, PFT, soil order

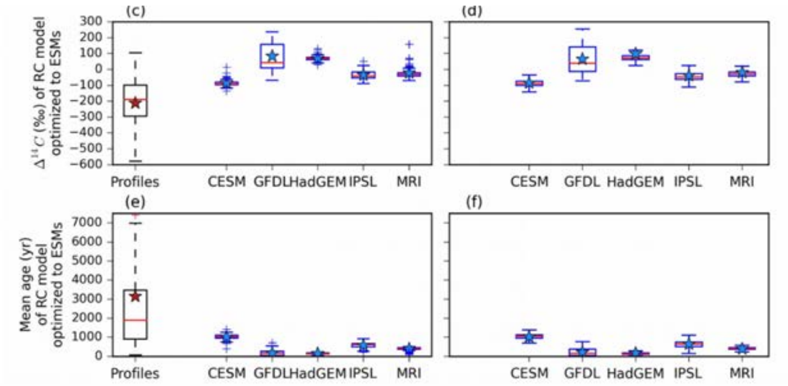
70 cm:
organic matter density, PFT



Summary: case study 1

1. ELM deep soil carbon is “too young”
2. After tuning, SOC and delta^{14}C bias are largely removed
3. SOC and ^{14}C are sensitive to z_tau, rooting depth profile
4. Heterogeneous z_tau at different depth
5. Shallow and deep soils are controlled by different factors

Case #2: ^{14}C for ESM



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Accelerated spinup →	Regular spinup →	Transient simulation

14C radioactive decay half life ~ 5700yr

Q: Can we reconstruct ^{14}C, given only ^{12}C output variables?

Carbon cycle models are subject to the law of mass conservation

represented as compartmental systems (Anderson, 1983)

Compartmental system

$$\frac{\mathrm{d}}{\mathrm{d}t}\,\mathbf{C}(t) = \mathrm{B}(\mathbf{C}(t),t)\,\mathbf{C}(t) + \mathbf{u}(\mathbf{C}(t),t), \quad t > t_0,$$

$$\mathbf{C}(t_0) = \mathbf{C}^0.$$

Semi-analytic solution

$$\mathbf{C}(t) = \Phi(t,t_0)\,\mathbf{C}^0 + \int_{t_0}^{t} \Phi(t,\tau)\,\mathbf{u}(\tau)\,\mathrm{d}\tau.$$

Transition matrix

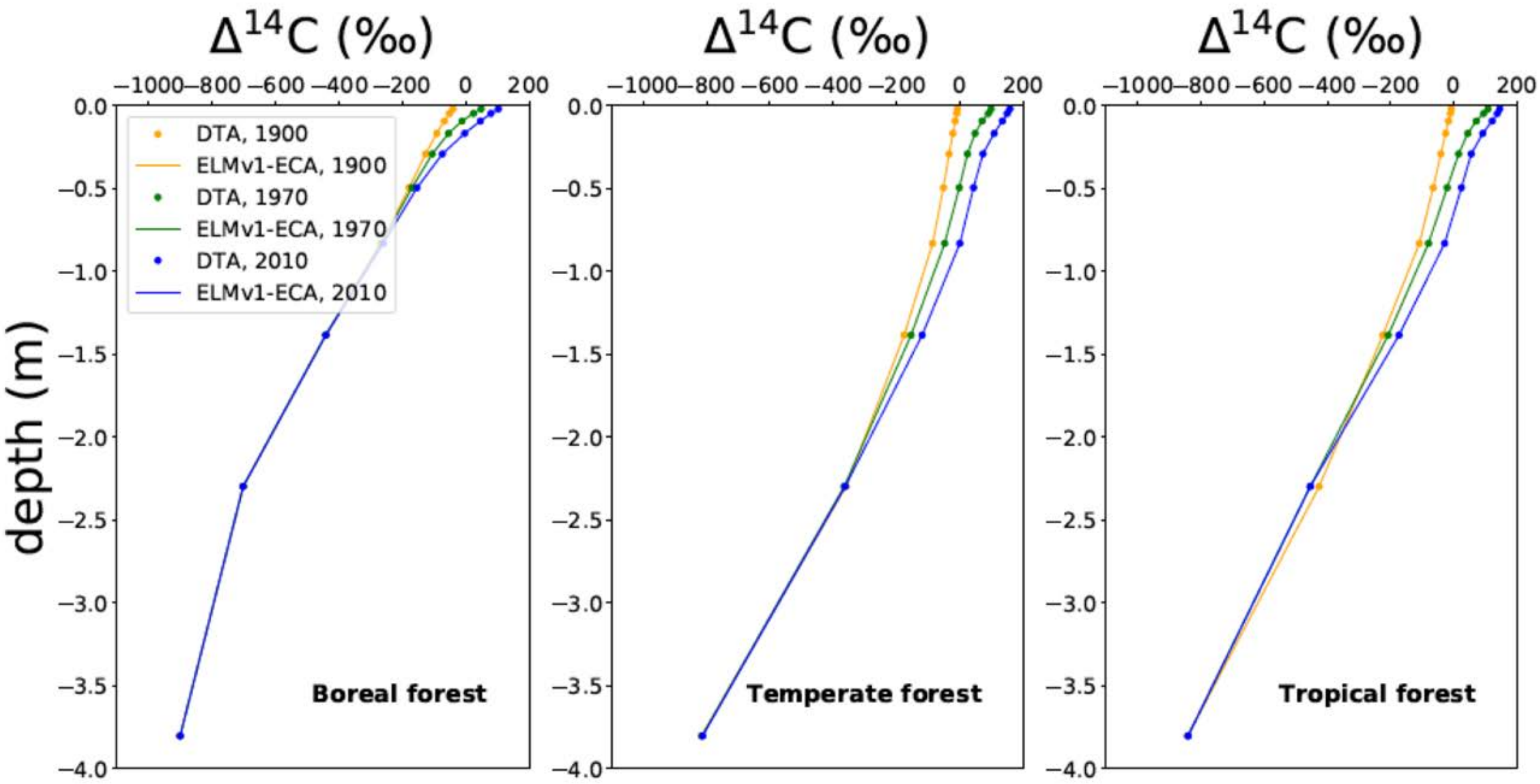
$$\frac{\mathrm{d}}{\mathrm{d}t}\,\Phi(t,t_0) = \mathrm{B}(t)\,\Phi(t,t_0), \quad t > t_0$$

$$\Phi(t_0,t_0) = \mathrm{Id},$$

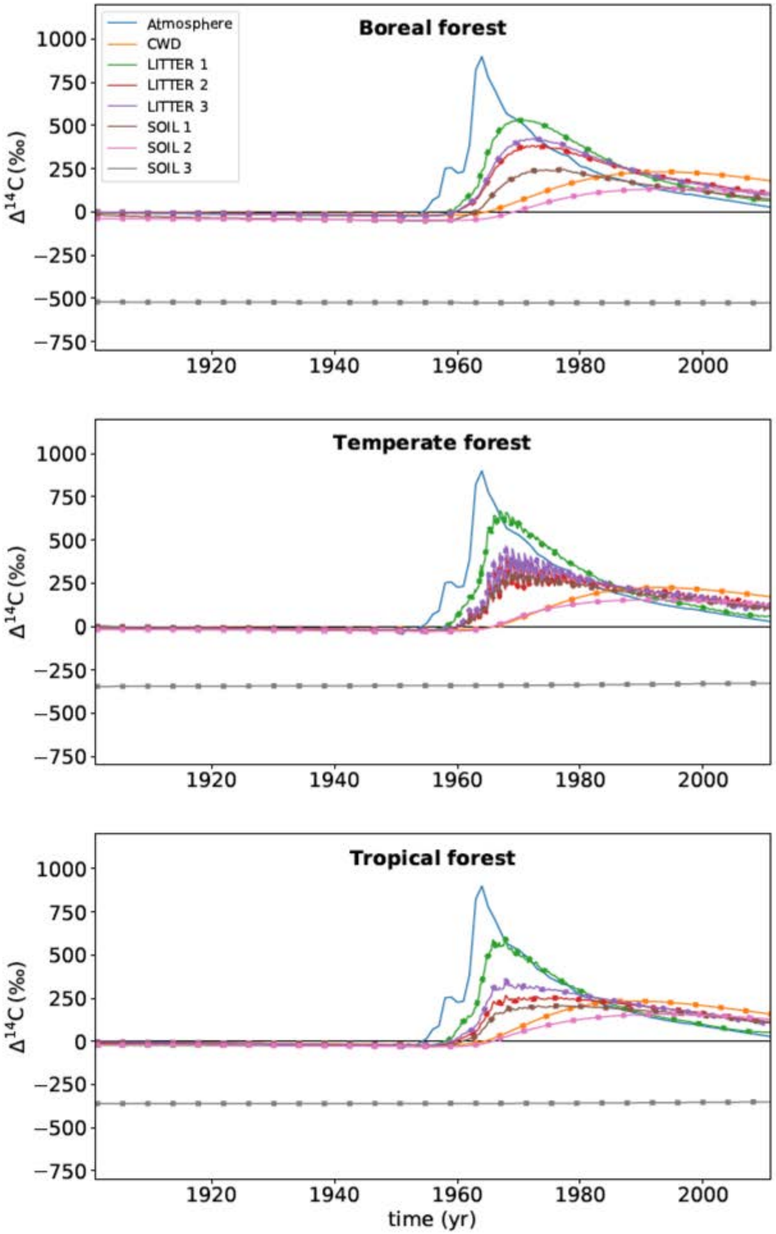
^{14}C and ^{12}C shares the same governing matrix ***B***

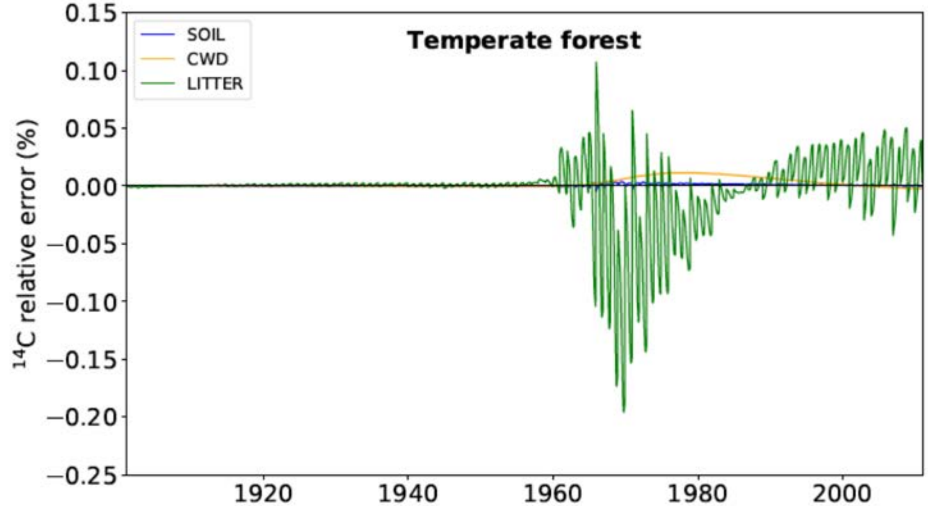
$$^{14}\mathrm{B}(\mathbf{C}(t),t) := \mathrm{B}(\mathbf{C}(t),t) - \lambda\,\mathrm{Id}$$

Transition matrix $$^{14}\Phi(t,t_0) = \Phi(t,t_0)\,e^{-\lambda\,(t-t_0)}\,\mathrm{Id}, \quad t \geq t_0$$



Metzler et al., review at JAMES





High ^{14}C reconstruction accuracy (< 0.2%)

Potentials of ^{14}C reconstruction

- Reconstruct ^{14}C CMIP5/CMIP6 model with ^{12}C cycle
- Save ^{14}C physical model development efforts
- Benchmark/assess soil age, turnover time for any ESM with ^{12}C output

Conclusions

1. The growing ^{14}C database will be powerful tool for studying soil ^{12}C cycling
2. A "high fidelity" ESM need to get both ^{12}C and ^{14}C right
3. Shallow vs deep soil ^{12}C cycles are different
4. ESM ^{14}C dynamics could be accurately reconstructed using ^{12}C dynamics