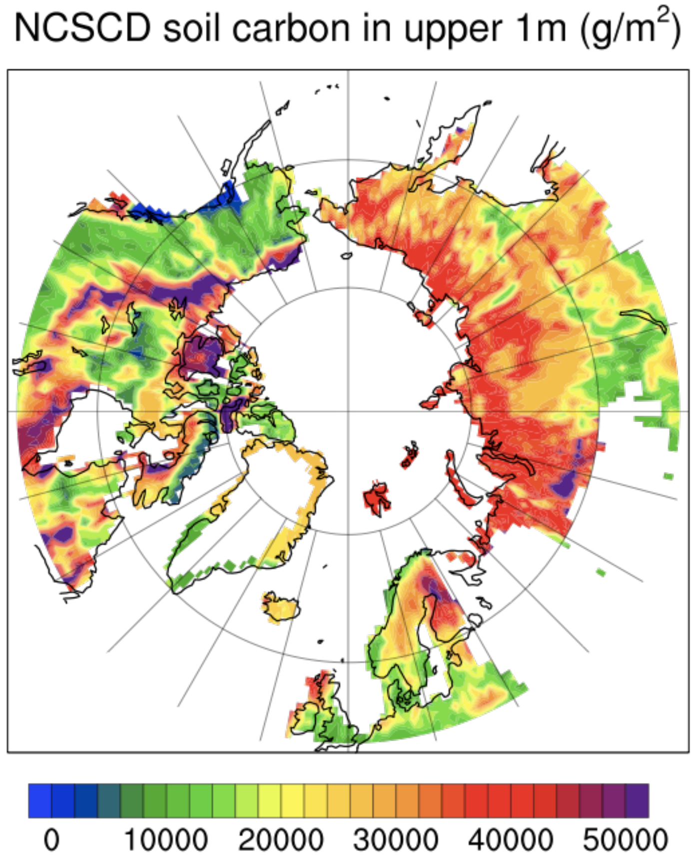
Permafrost C and N Dynamics in CLM4

Charles D. Koven[1], William J. Riley[1], Zachary M. Subin[1], Jinyun Tang[1], Margaret Torn[1], Jennifer Harden[2], David Lawrence[3], Gordon Bonan[3], Sean Swenson[3]

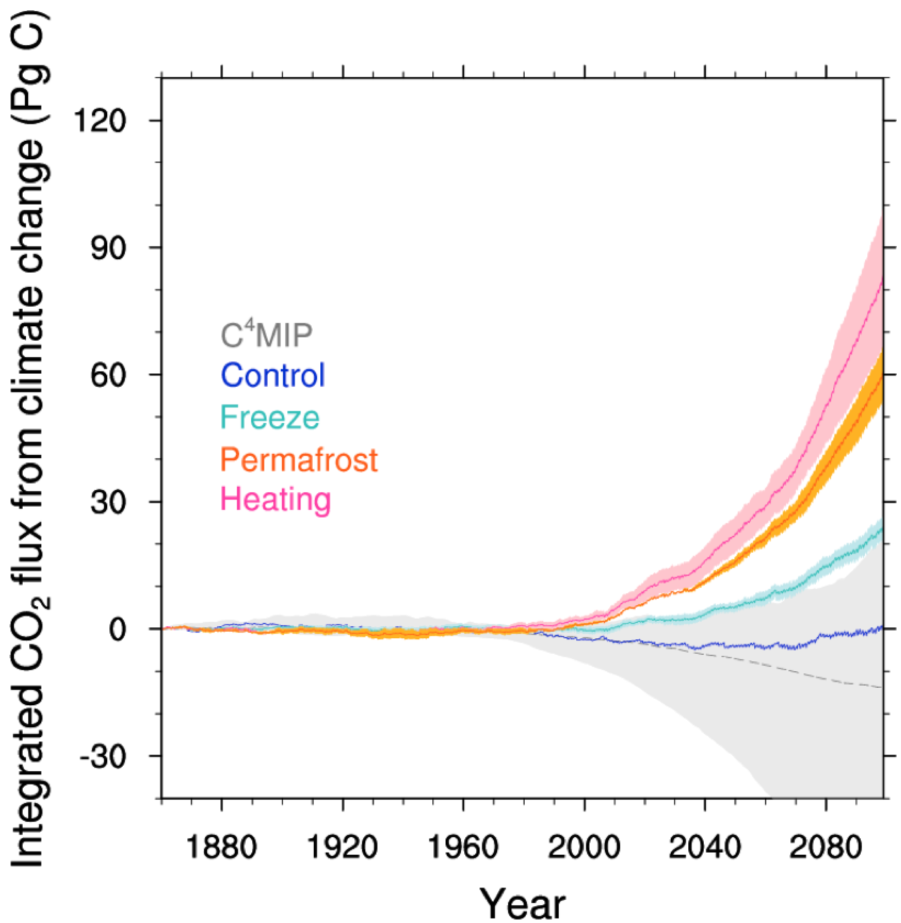
1. Lawrence Berkeley National Lab, Berkeley, CA
2. United States Geological Survey, Menlo Park, CA
3. National Center for Atmospheric Research, Boulder, CO

High-latitude terrestrial ecosystems store a vast amount (>1000 Pg in top 3 meters of permafrost soils) of soil C.



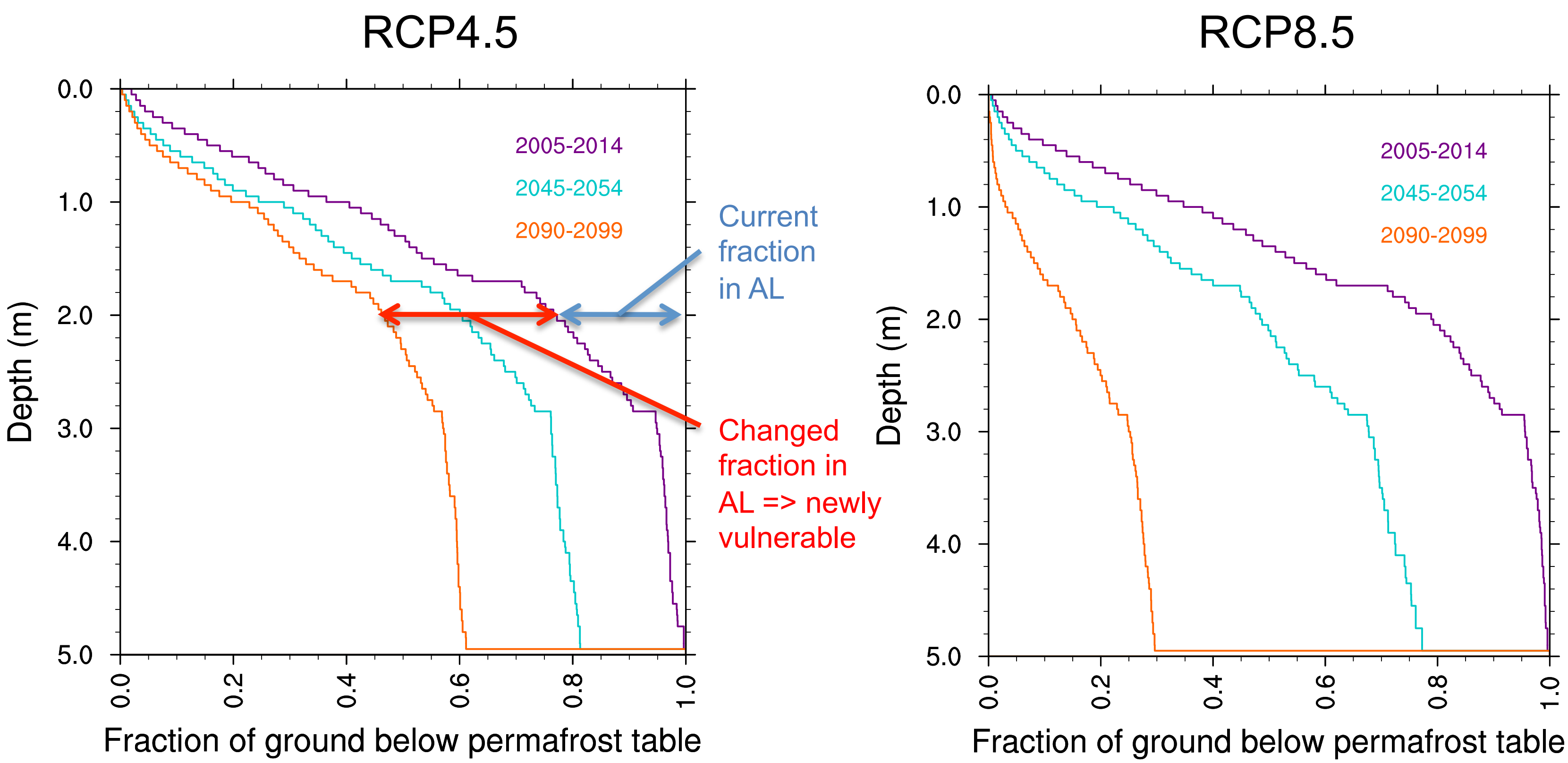
Northern Circumpolar Soil Carbon Database (Tarnocai et al., 2007)

Problem: We want to include permafrost C processes into ESMs, as they can change sign of C feedback to warming at high latitudes; huge uncertainties remain on the nature of response



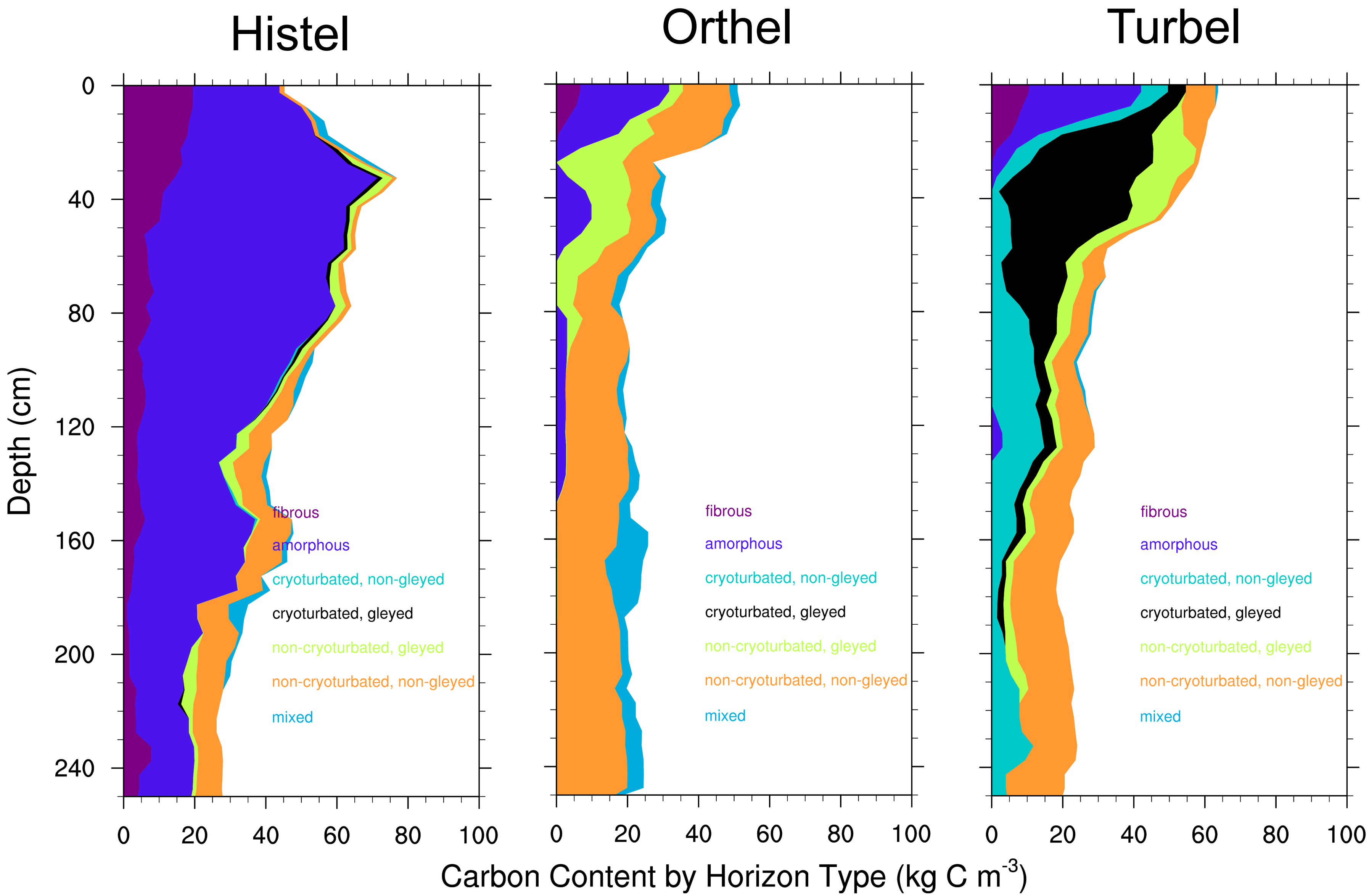
Koven et al., (2011)

Vulnerability of permafrost C stocks is a function of depth



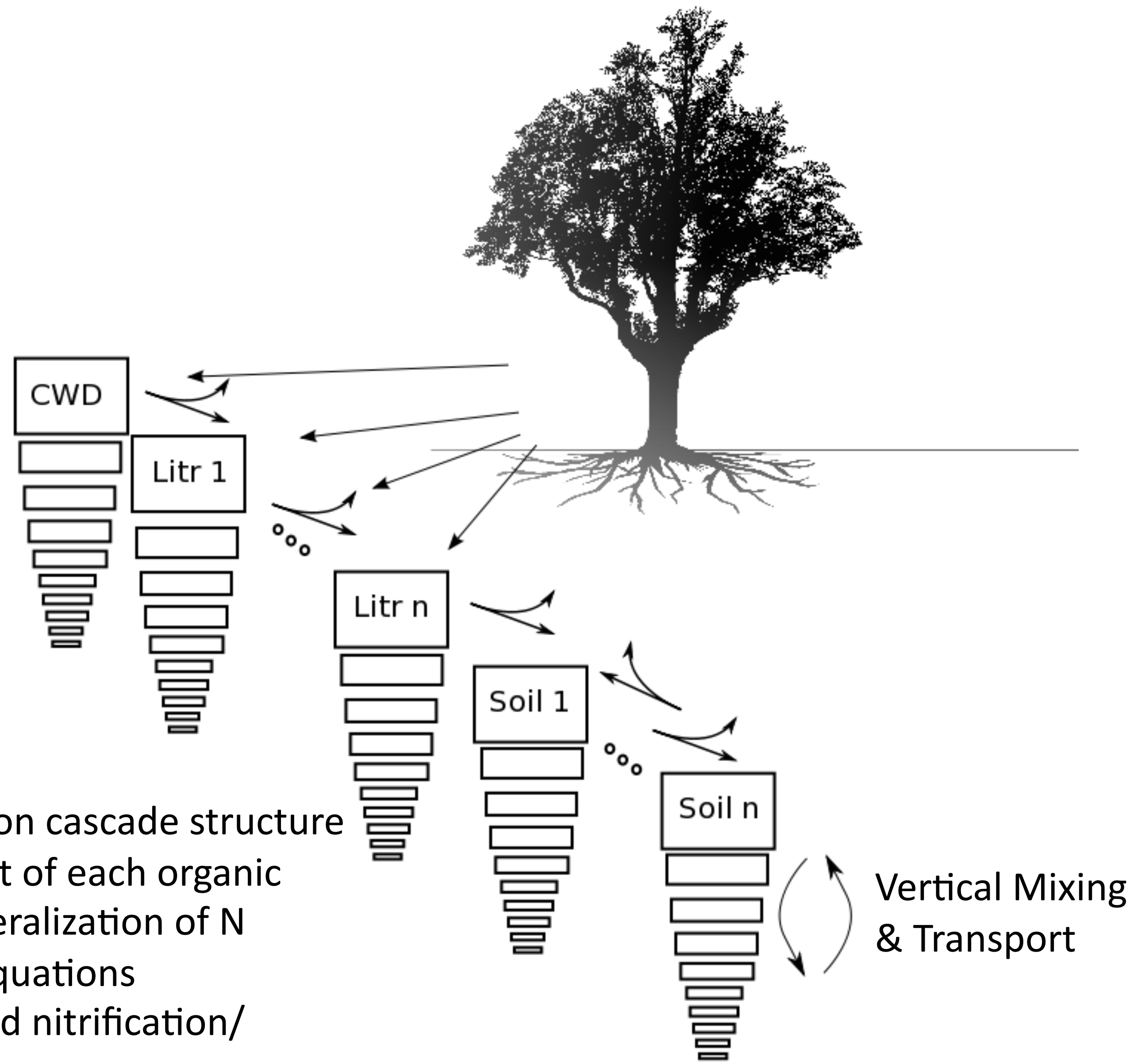
At, e.g., 2 meter depth, CCSM4 predicts that the fraction of the present-day total permafrost area that is within active layer will shift from 20% (current) to 40% by 2050, and 60% by 2095, based on CCSM4 in RCP 4.5, meaning that 40% of the carbon at 2m depth will be newly vulnerable to decomposition

Permafrost C profiles by depth and horizon type



Pedon data from Permafrost RCN members

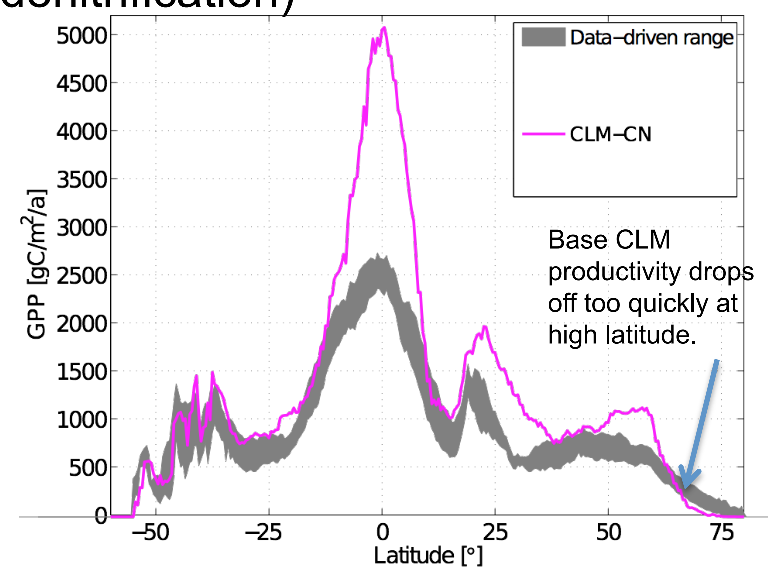
CLM4-V Soil Model Structure



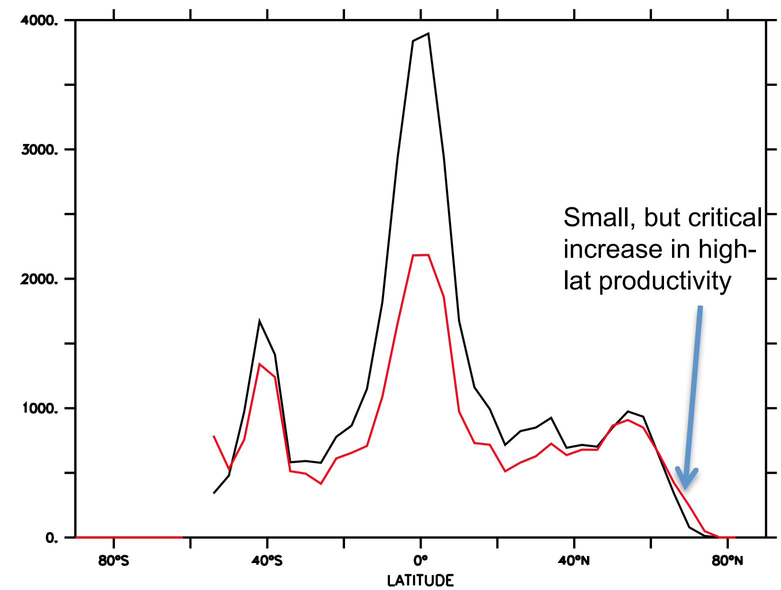
- Generalized decomposition cascade structure
- Track C, ^{14}C and N content of each organic pool; immobilization/mineralization of N following standard CLM equations
- Inorganic N speciation and nitrification/ denitrification

Replace inorganic N cycle and Nitrification/Denitrification

- Base CLM4 has first-order decay of any unused mineral N at each timestep with rapid loss to denitrification
- Replaced this with nitrification/denitrification based on CENTURY approach
  - Nitrification occurs as first-order decay of NH_4 pool, with same temperature and moisture limitations as decomposition
  - Denitrification is co-limited by C decomposition and NO_3 availability
  - Explicit O_2 concentration from CH_4 submodel, with anoxic microsite parameterization and denitrification occuring only in anoxic soil fraction
- Leads to decreased tropical productivity; increased high latitude productivity; better agreement with observations
- CLM very sensitive to poorly-constrained slow N cycle processes (N fixation, denitrification)

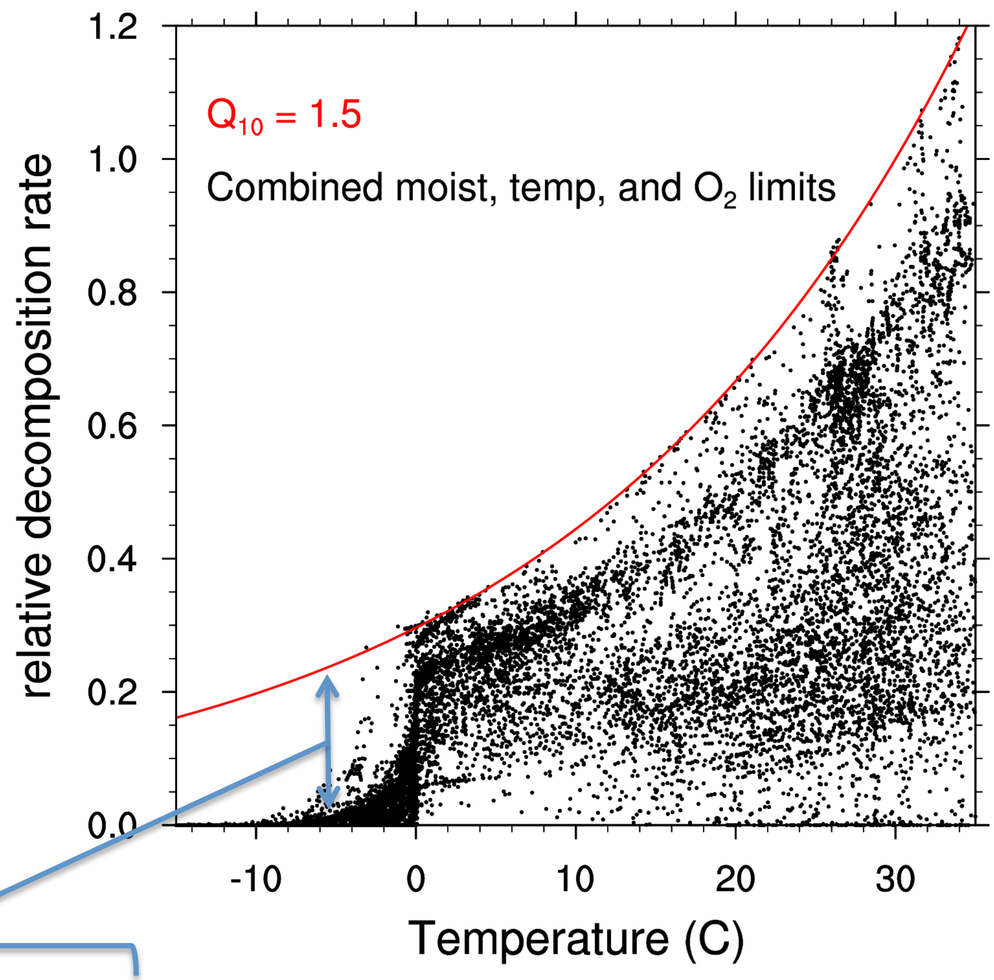


Modified from Beer et al., *Science* 2010, fig. S26



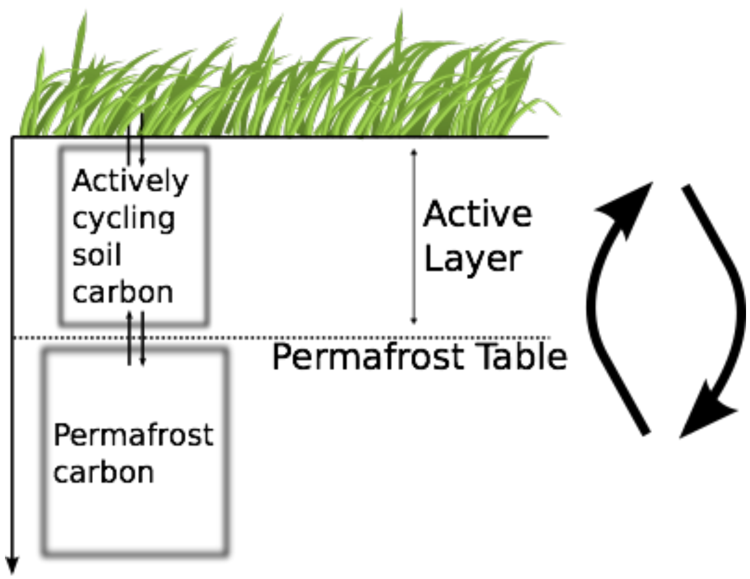
Black: CLM4, Red: CLM4-Vertical

Sharp reduction in modeled decomposition rates across freeze/thaw boundary due to moisture limitation



Limitation by (unfrozen) water

Vertical mixing by cryoturbation modeled as diffusive transport



$$\frac{\partial C_i}{\partial t} = D\frac{\partial^2 C_i}{\partial z^2}$$

- Carbon input, based on rooting profile, only in the active layer
- Mixing below active layer allows carbon to be subducted into upper permafrost

What about vertical mixing rates?

Temperate/tropical soils:

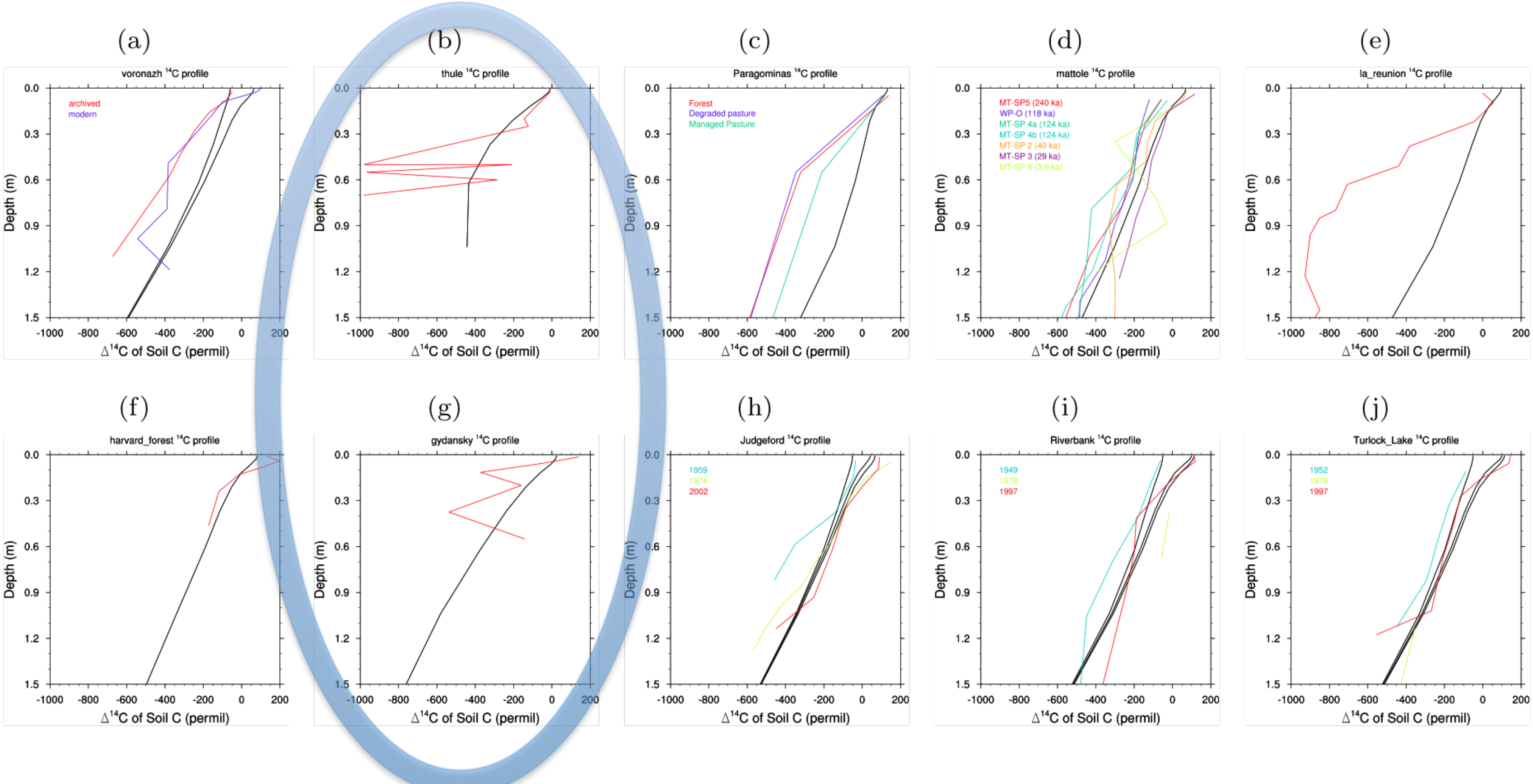
Reference	diffusion rate	advection rate	location	depth	ecosystem	process	how inferred
Elzein and Balesdent 1995	5.15 $cm^2\ yr^{-1}$	0.13 mm yr^{-1}	Kattinkar, India		forest	bioturbation	^{14}C
Elzein and Balesdent 1995	16.58 $cm^2\ yr^{-1}$	0.34 mm yr^{-1}	Para, Brazil		forest	bioturbation	^{14}C
Elzein and Balesdent 1995	5.29 $cm^2\ yr^{-1}$	0.48 mm yr^{-1}	Bahia, Brazil		forest	bioturbation	^{14}C
Elzein and Balesdent 1995	0.94 $cm^2\ yr^{-1}$	0.6 mm yr^{-1}	Bezange, France		forest	bioturbation	^{14}C
Elzein and Balesdent 1995	1.48 $cm^2\ yr^{-1}$	0.42 mm yr^{-1}	Marly, France		forest	bioturbation	^{14}C
Bruun et al. 2007	0.71 cm^2/ yr	0.081 mm yr^{-1}	Sweden				^{14}C
O'Brien and Stout 1978	13 $cm^2\ yr^{-1}$		New Zealand	0-1m	pasture		^{14}C
Jarvis et al. 2010	0.3 $cm^2\ yr^{-1}$		Sweden	0-50 cm	forest	bioturbation	^{137}Cs
Baisden et al. 2002		0.01-0.4 cm yr^{-1}	California		grassland	bioturbation	^{14}C
Baisden and Parfitt 2007		0.6, 0.09, 0.019	California		grassland	bioturbation	^{14}C
Baisden and Parfitt 2007		0.06, 0.13, 0.025	California		grassland	bioturbation	^{14}C
Baisden and Parfitt 2007		0.05 cm yr^{-1}	New Zealand		grassland	bioturbation	^{14}C
Yoo et al. 2011		1-5 cm yr^{-1}	Delaware	surface	agro	tillage	^{210}Pb
Yoo et al. 2011		0.6-1 cm yr^{-1}	Delaware	20 cm	agro	tillage	^{210}Pb
Yoo et al. 2011		0.5-0.7 cm yr^{-1}	Delaware	surface	forest	bioturbation	^{210}Pb
Yoo et al. 2011		2.2-3.2 cm yr^{-1}	Delaware	10 cm	forest	bioturbation	^{210}Pb
Heimsath et al. 2002		0.007-0.026 cm yr^{-1}	Australia	10-85 cm	forest	hillslope creep	OSL
Kaste et al. 2007	1-2 $cm^2\ yr^{-1}$		Australia and California		grassland	bioturbation	^{7}Be and ^{210}Pb
Richards and Humphreys 2010		0.025-0.04 cm yr^{-1}	Australia	0-5 cm	forest	bioturbation	tile burial

Permafrost soils:

???

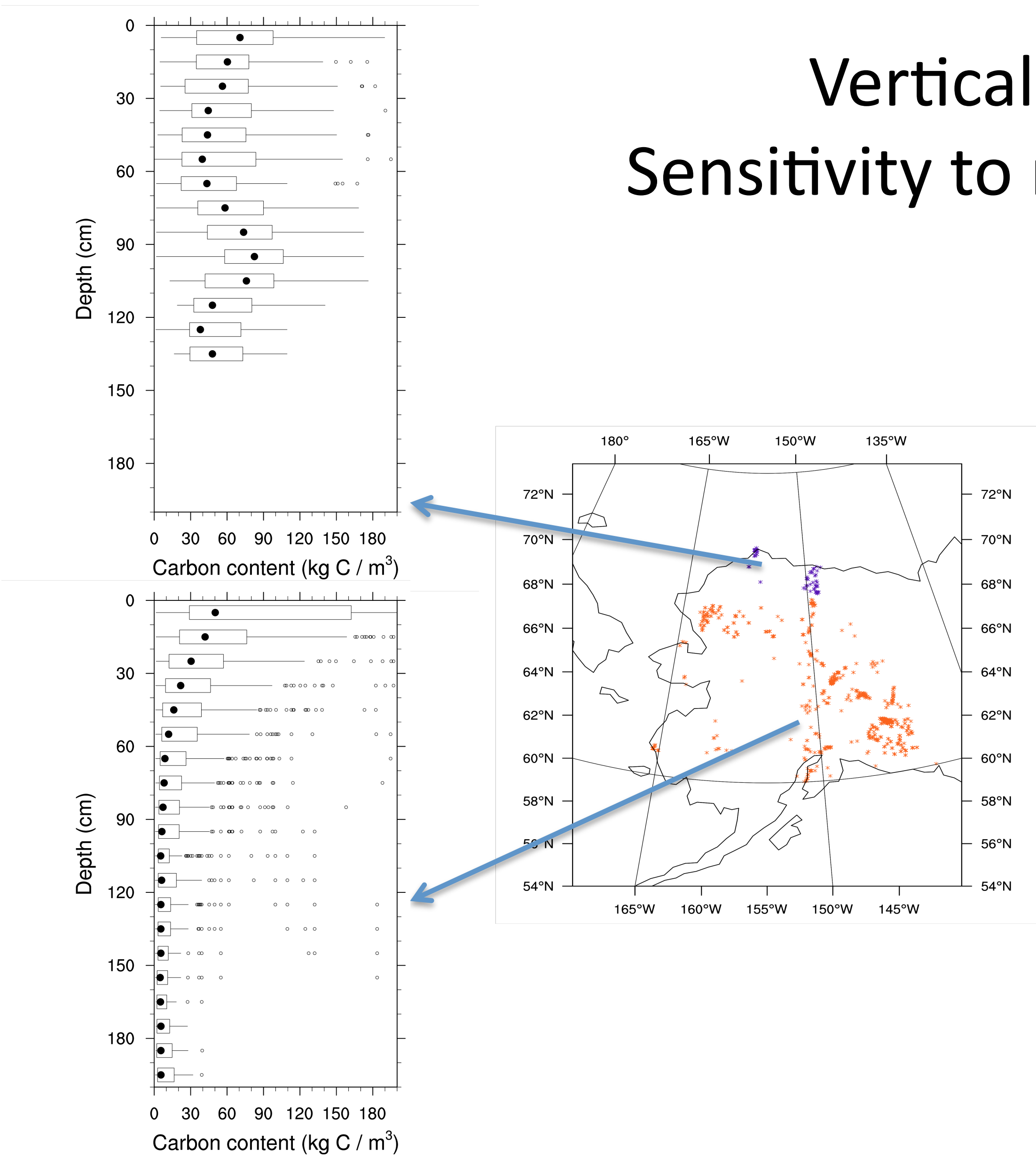
Comparison of modelled and observed ^{14}C profiles of SOM

Permafrost



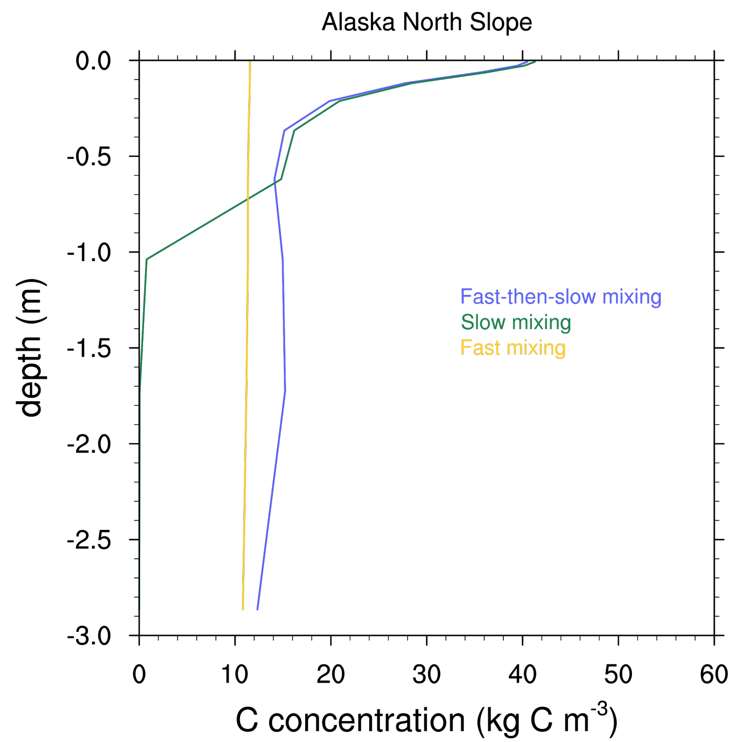
^{14}C data: Torn (2002), Horwath (2008), Trumbore (1995), Masiello (2004), Basile-Doelsch (2005), Gaudinski (2000), Kaiser (2007), Baisden (2007)

Vertical profiles of SOM: Sensitivity to mixing rate and history



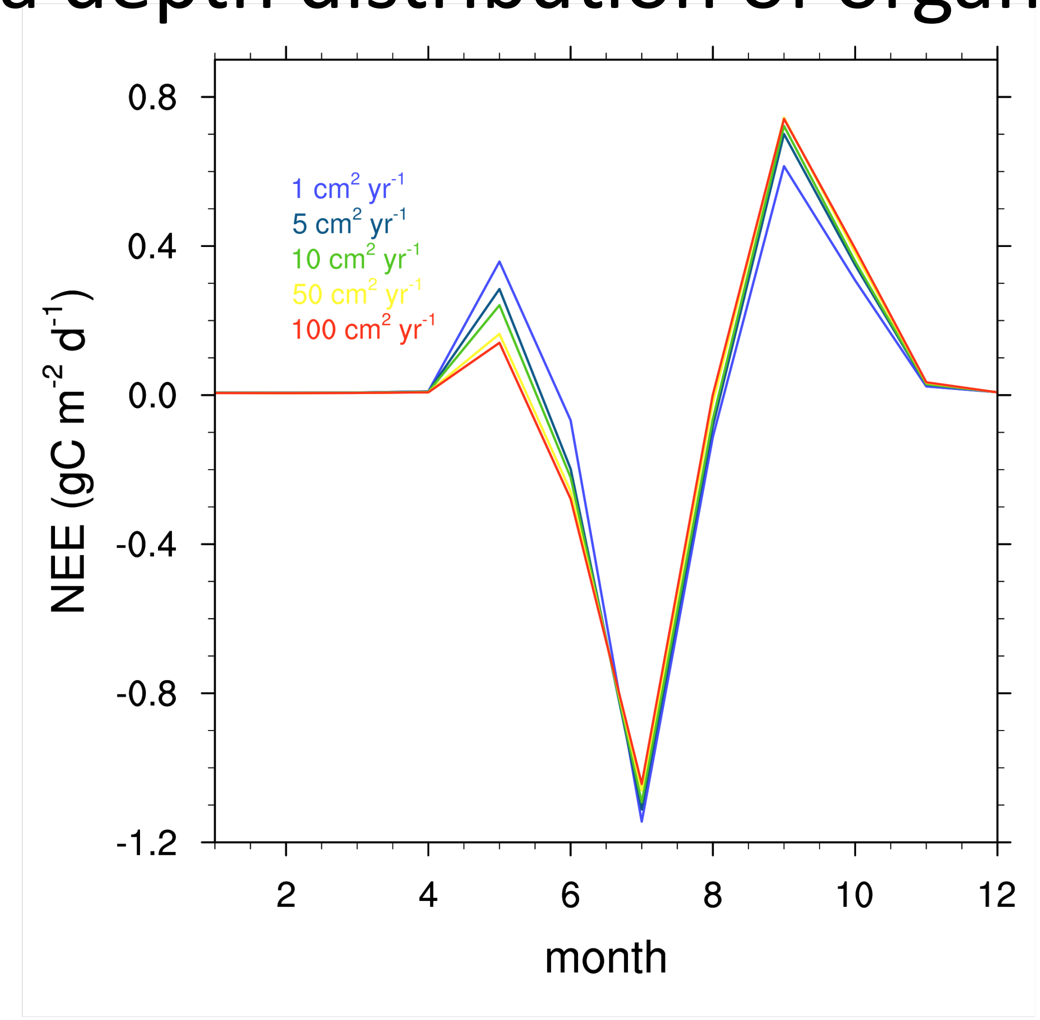
Carbon concentration data:
National Soil Carbon Network, 2011

CLM4 with vertical mixing



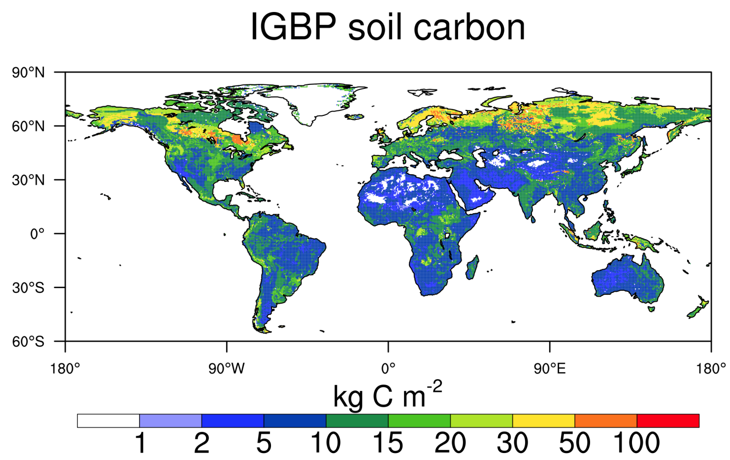
Green: Slow mixing
Yellow: Fast mixing
Blue: Fast-then-slow mixing

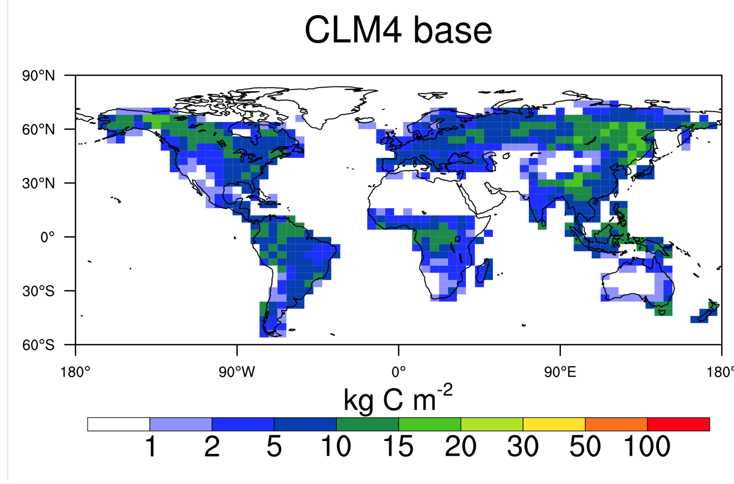
Seasonal CO_2 flux cycle dependent on mixing rate via depth distribution of organic matter

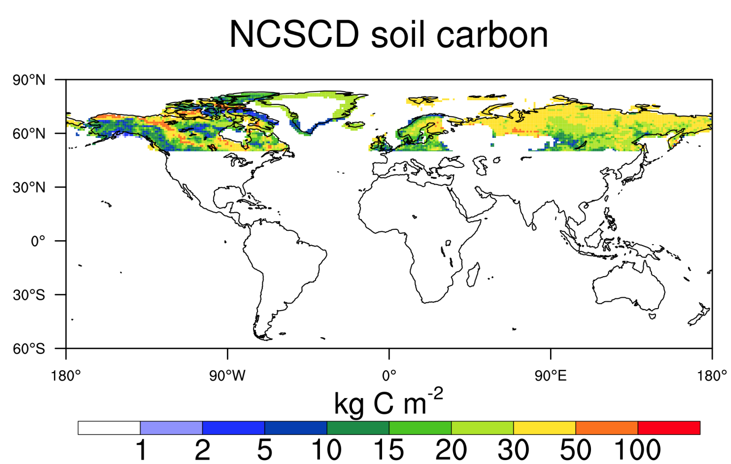


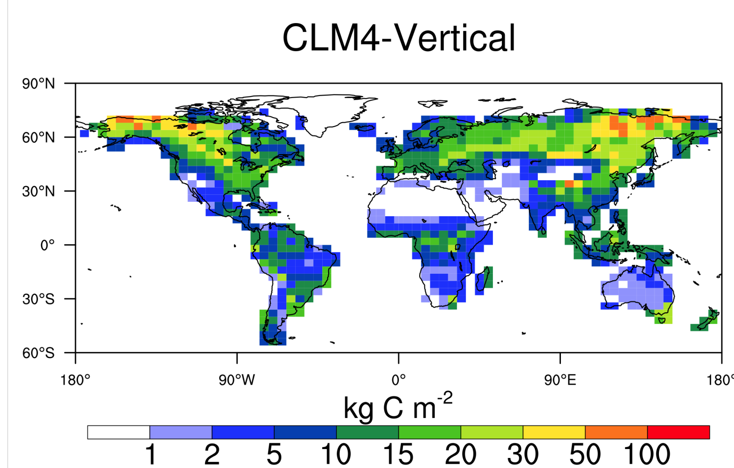
Asymmetric response of shoulder-season respiration, due to time-lag resulting from deeper profile of SOM

Soil C stocks to 1 m

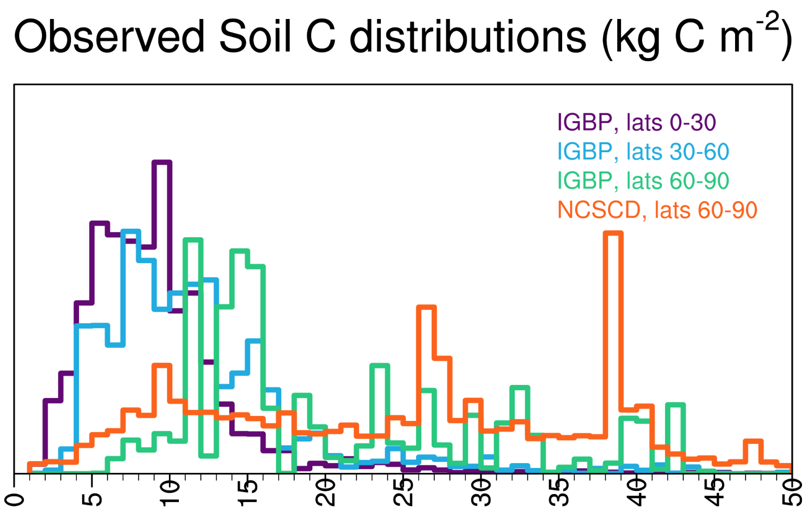


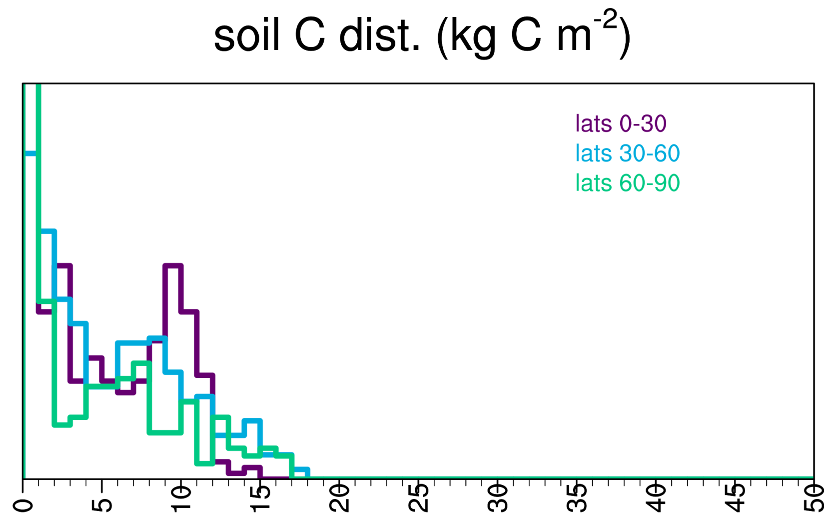


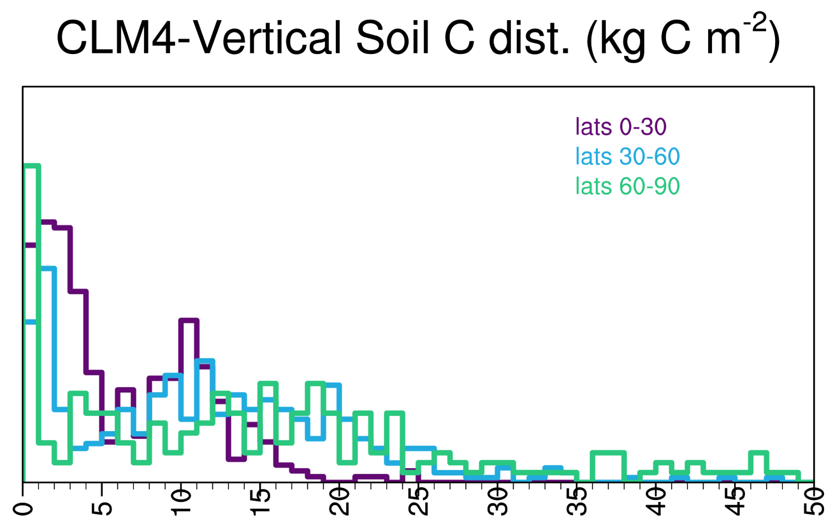




Soil C distributions







Conclusions and future work

- Including depth-resolved soil C allows model to have more realistic high-latitude C stocks
- Large uncertainty remains in depth distribution of soil C and its effect on lability and vulnerability
  – Possible constraints include observed soil C depth distributions, ^{14}C, and seasonal cycle in respiration
- Next steps: evaluate model responses to perturbations
- C decomposition and N mineralization feedbacks with warming

Thanks

- **Organizers and contributors to National Soil Carbon Network database**
- **Members and leaders of Permafrost RCN**
- **Many researchers for published 14C data**
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