# Understanding and Modeling of Climate Feedbacks from Permafrost

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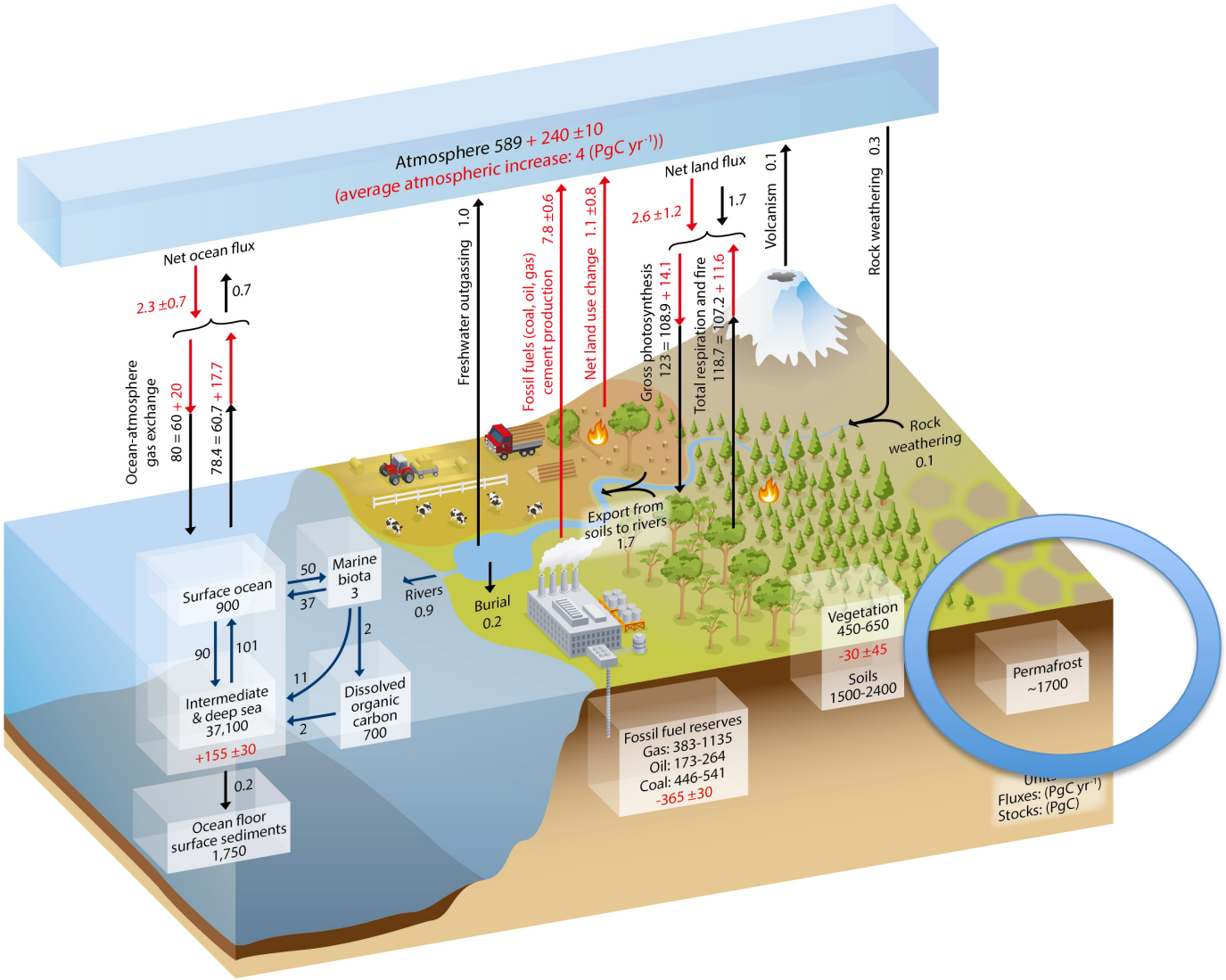
With many others: Bill Riley, Dave Lawrence, Jen Harden, Gustaf Hugelius, the CESM Land Model Working Group, and the Permafrost Carbon Network

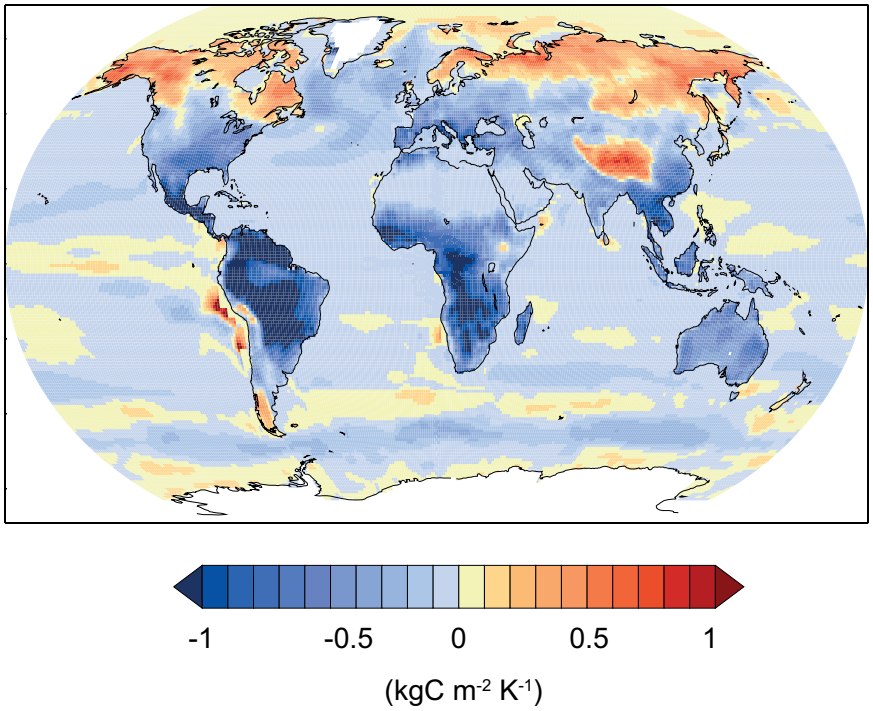
Thanks to DOE-BER support from Regional and Global Climate Modeling Program (BGC Feedbacks SFA), Terrestrial Ecosystem Science Program (NGEE Arctic), and Earth System Modeling Program (IMPACTS SFA)




IPCC-AR5 (Ciais et al., 2013)

# IPCC-AR5-WG1-Ch6 (Ciais et al., 2013)
# Estimates of carbon-cycle feedback parameters

Earth System Model (ESM) predictions of climate feedbacks, which don't include permafrost



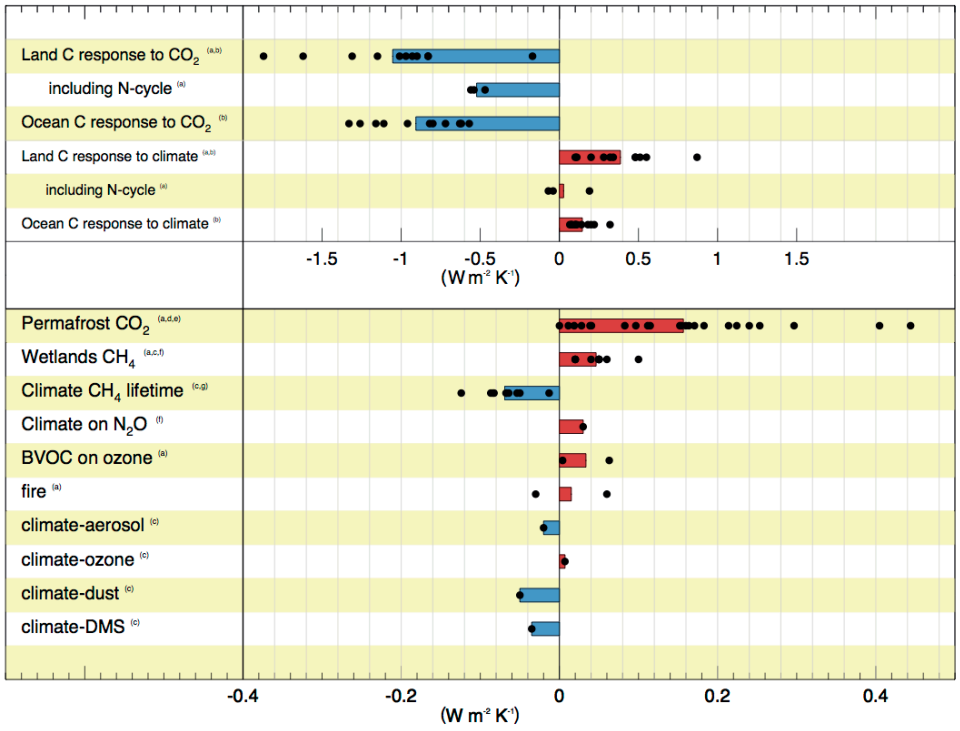
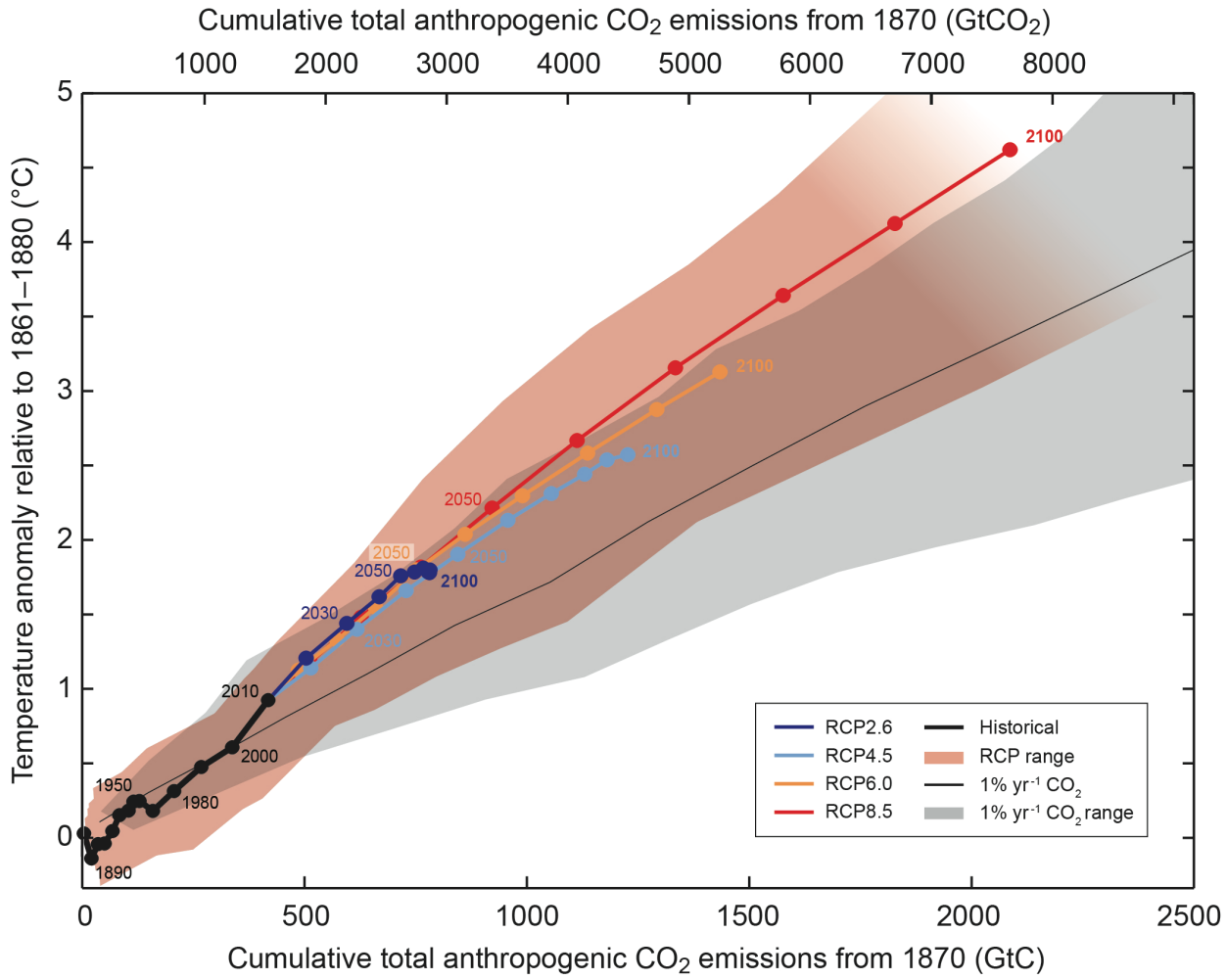



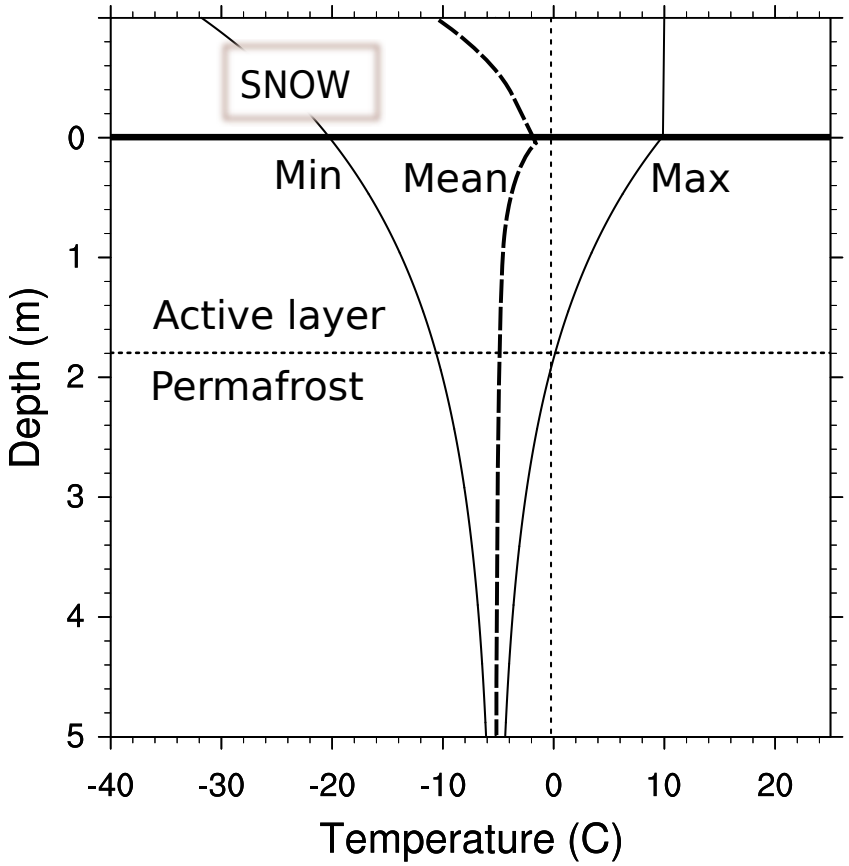

**Figure 6.20 |** A synthesis of the magnitude of biogeochemical feedbacks on climate. Gregory et al. (2009) proposed a framework for expressing non-climate feedbacks in common units (W m$^{-2}$ °C$^{-1}$) with physical feedbacks, and Arneth et al. (2010) extended this beyond carbon cycle feedbacks to other terrestrial biogeochemical feedbacks. The figure shows the results compiled by Arneth et al. (2010), with ocean carbon feedbacks from the C4MIP coupled climate–carbon models used for AR4 also added. Some further biogeochemical feedbacks are also shown but this list is not exhaustive. Black dots represent single estimates, and coloured bars denote the simple mean of the dots with no weighting or assessment being made to likelihood of any single estimate. There is *low confidence* in the magnitude of the feedbacks in the lower portion of the figure, especially for those with few, or only one, dot. The role of nitrogen limitation on terrestrial carbon sinks is also shown—this is not a separate feedback, but rather a modulation to the climate–carbon and concentration–carbon feedbacks. These feedback metrics are also to be state or scenario dependent and so cannot always be compared like-for-like (see Section 6.4.2.2). Results have been compiled from (a) Arneth et al. (2010), (b) Friedlingstein et al. (2006), (c) Hadley Centre Global Environmental Model 2-Earth System (HadGEM2-ES, Collins et al., 2011) simulations, (d) Burke et al. (2013), (e) von Deimling et al. (2012), (f) Stocker et al. (2013), (g) Stevenson et al. (2006). Note the different *x*-axis scale for the lower portion of the figure.

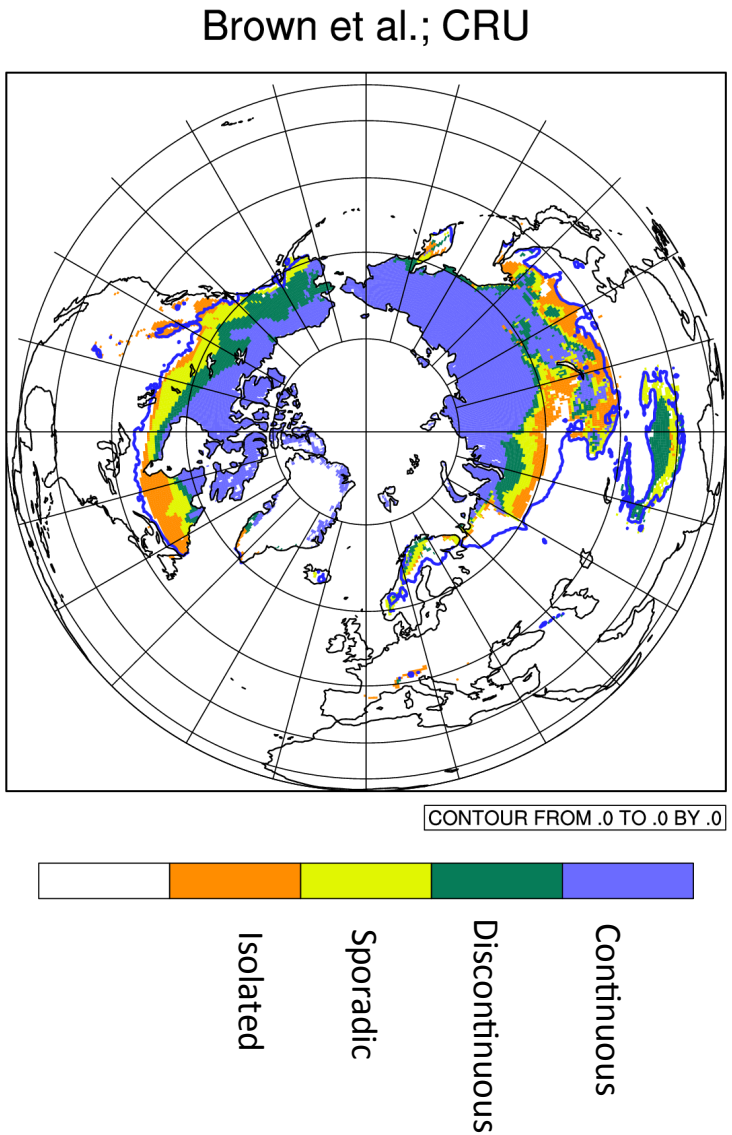
# Problem: Earth System Models (ESMs) are crucial tool for projecting climate change. But missing key permafrost processes. How to tractably include these?




IPCC AR5 Summary for Policymakers

# What and where is Permafrost?



# Permafrost soils characterized by some key processes: (1) Cryoturbation: Turbel soils

- Warping of soil horizons by freeze-thaw processes
- Buries surface organic material into permafrost layers
- Mixes organic and mineral soil material to make C-rich mineral soil layers
- Cover large area

Photo: *Soil Atlas of the Northern Circumpolar Region*

# Permafrost soils characterized by some key processes: (2) Peat Accumulation: Histosol, Histel soils

- Accumulation of organic matter in waterlogged and/or frozen soils
- Highest C contents, but smaller fraction of surface area
- Saturated soils are important $CH_4$ sources

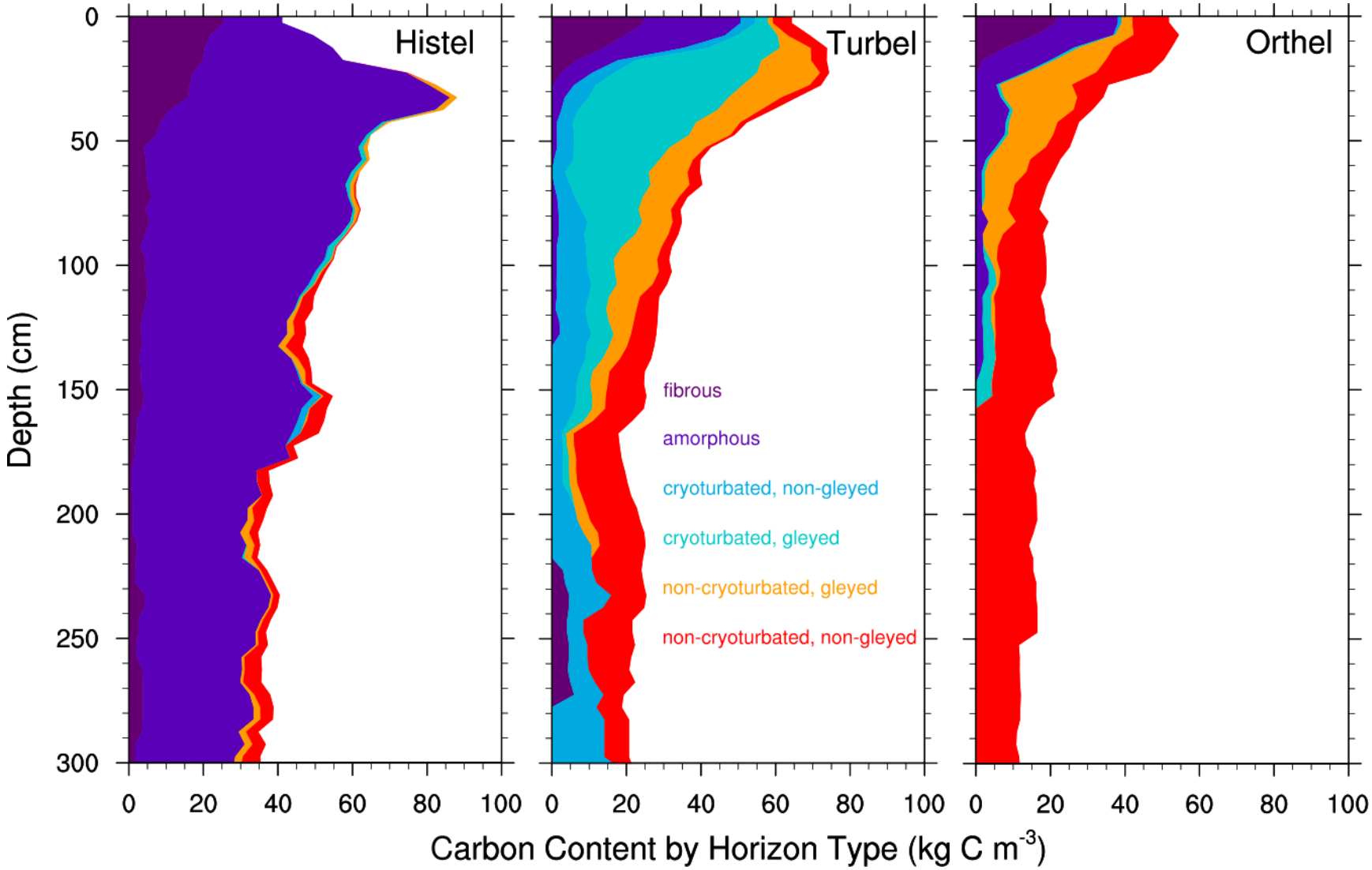
Photo: *Soil Atlas of the Northern Circumpolar Region*

# Permafrost soils characterized by some key processes: (3) Dust deposition and ice wedge growth in Yedoma

- Deep: can be 30m thick in places
- Very ice-rich
- Formed during glacial periods from wind- and river-transported sediments
- Deposits in interior Alaska and eastern Siberia
- Not included in soil C maps (which go to 1-3m)

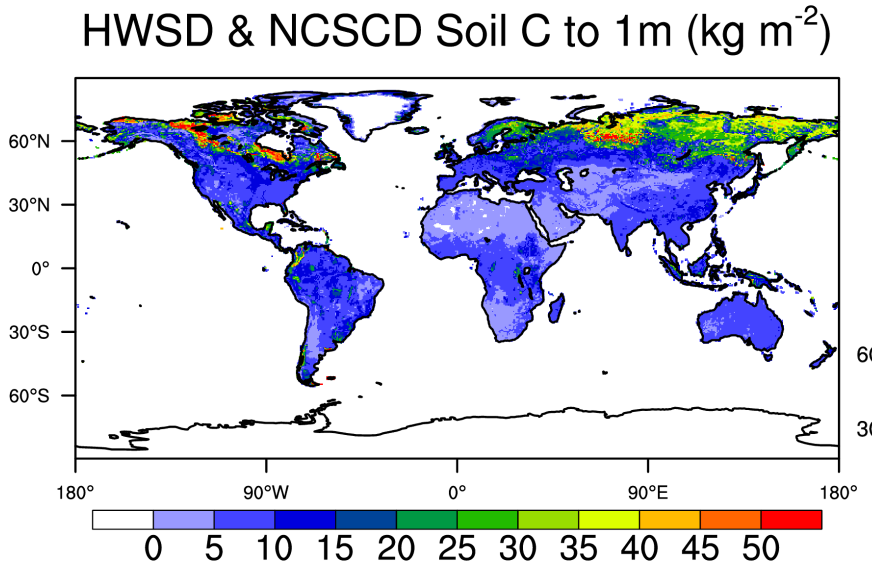
Photo: Katey Walter

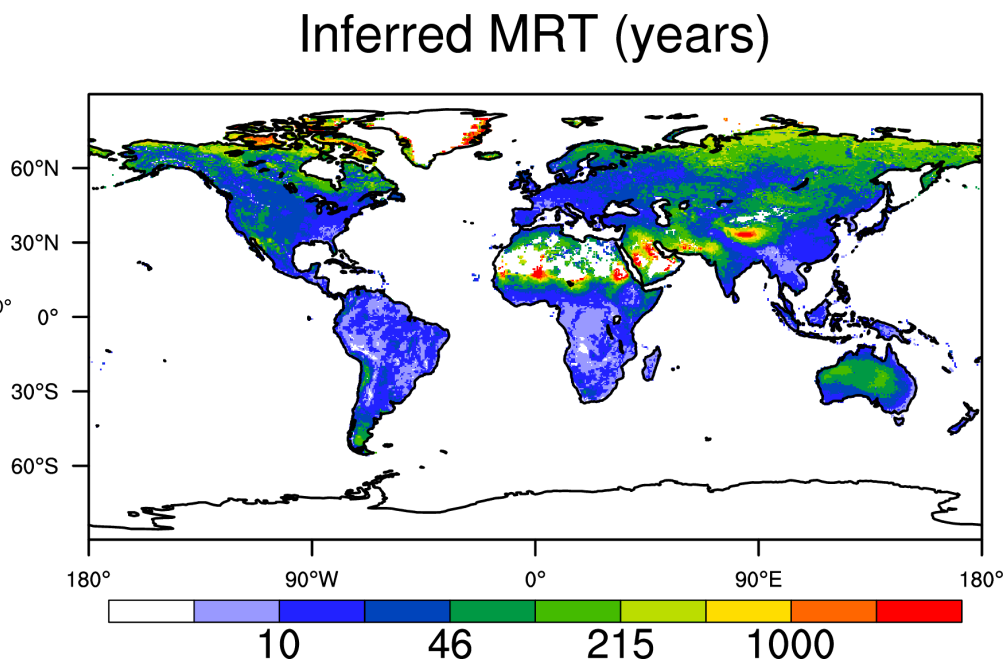
Of the three suborders of permafrost soils, largest amount of near-surface C is in turbel soils, because they are both C-rich and widespread.

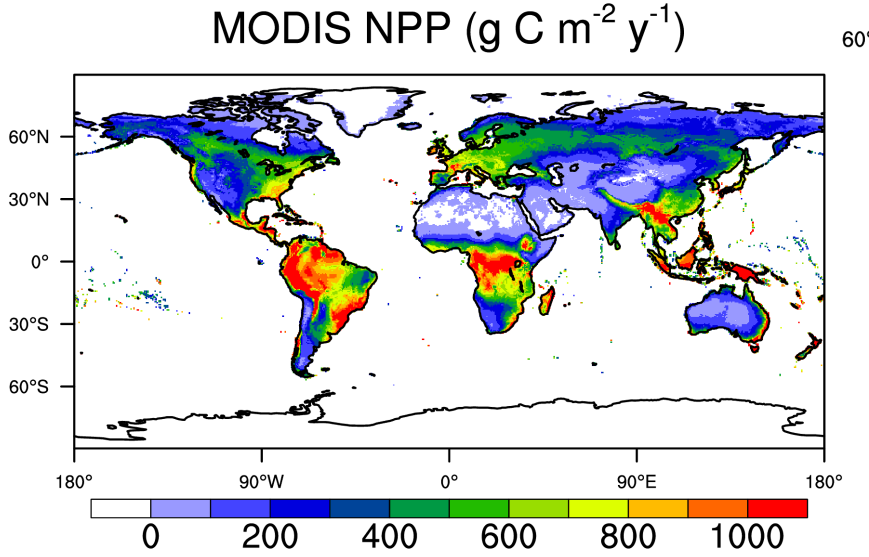



Harden, Koven, et al., 2012

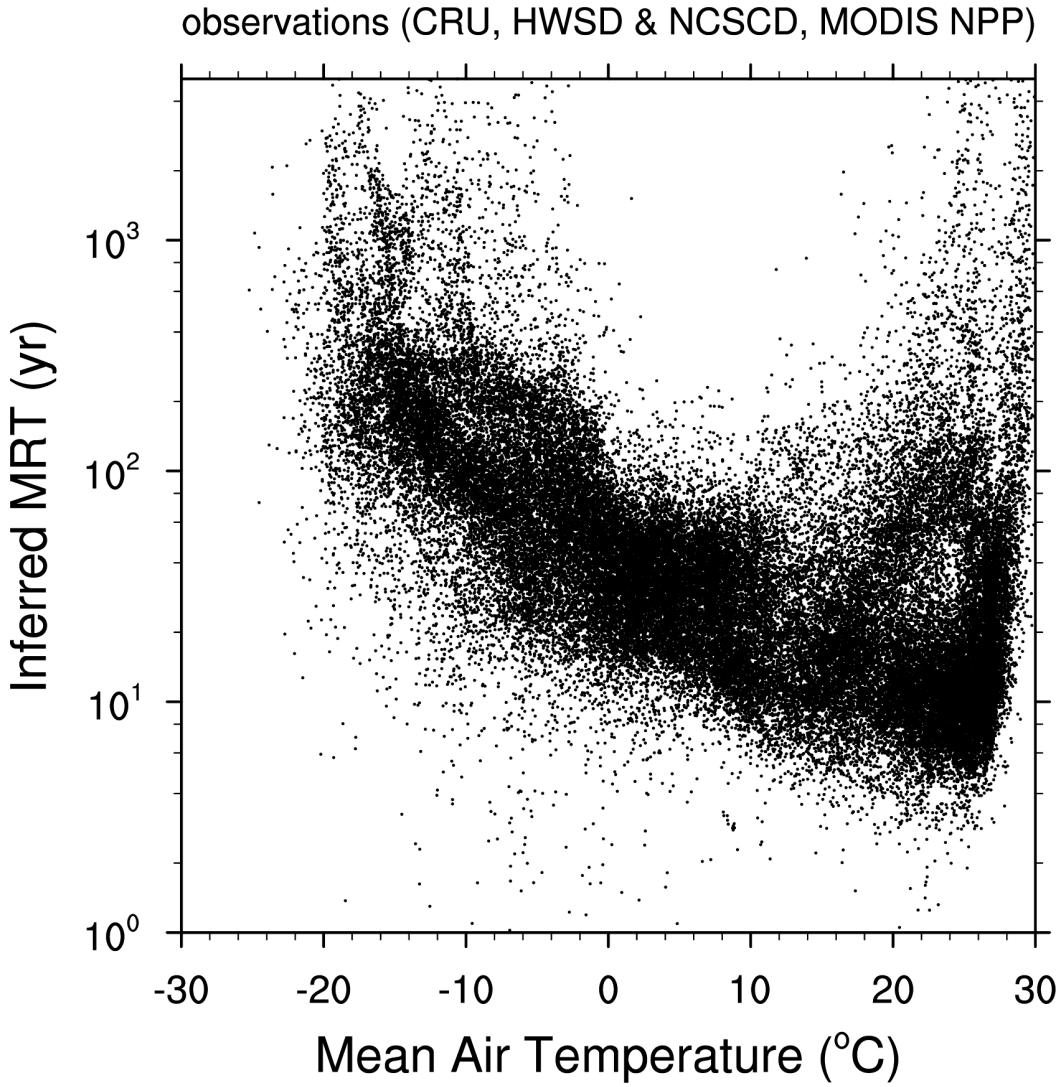
# The carbon signature of permafrost: high stocks, low inputs, therefore extremely long residence times



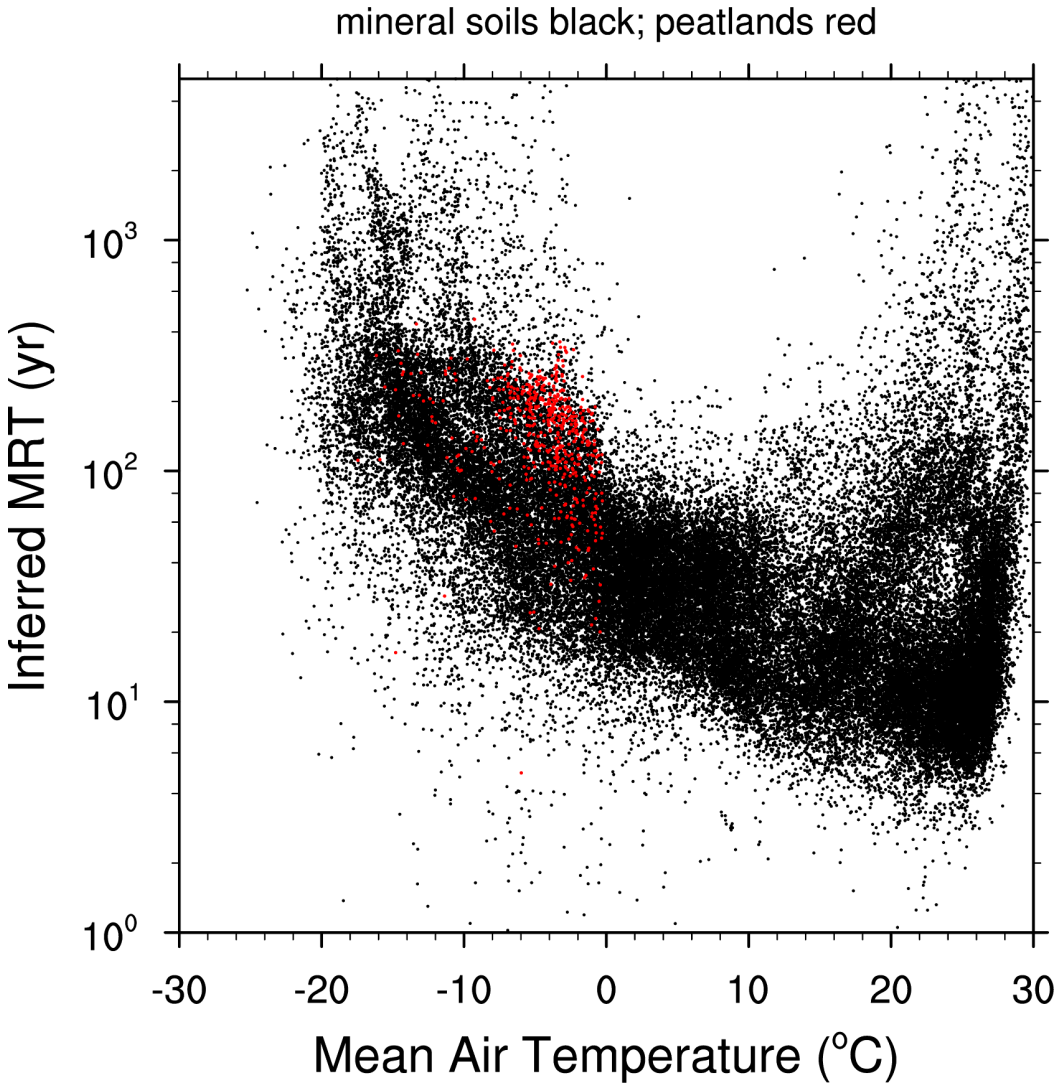



# What are global temperature controls on soil C turnover? Log-scaled Inferred Mean Residence Time (= SoilC / NPP) as function of Temperature



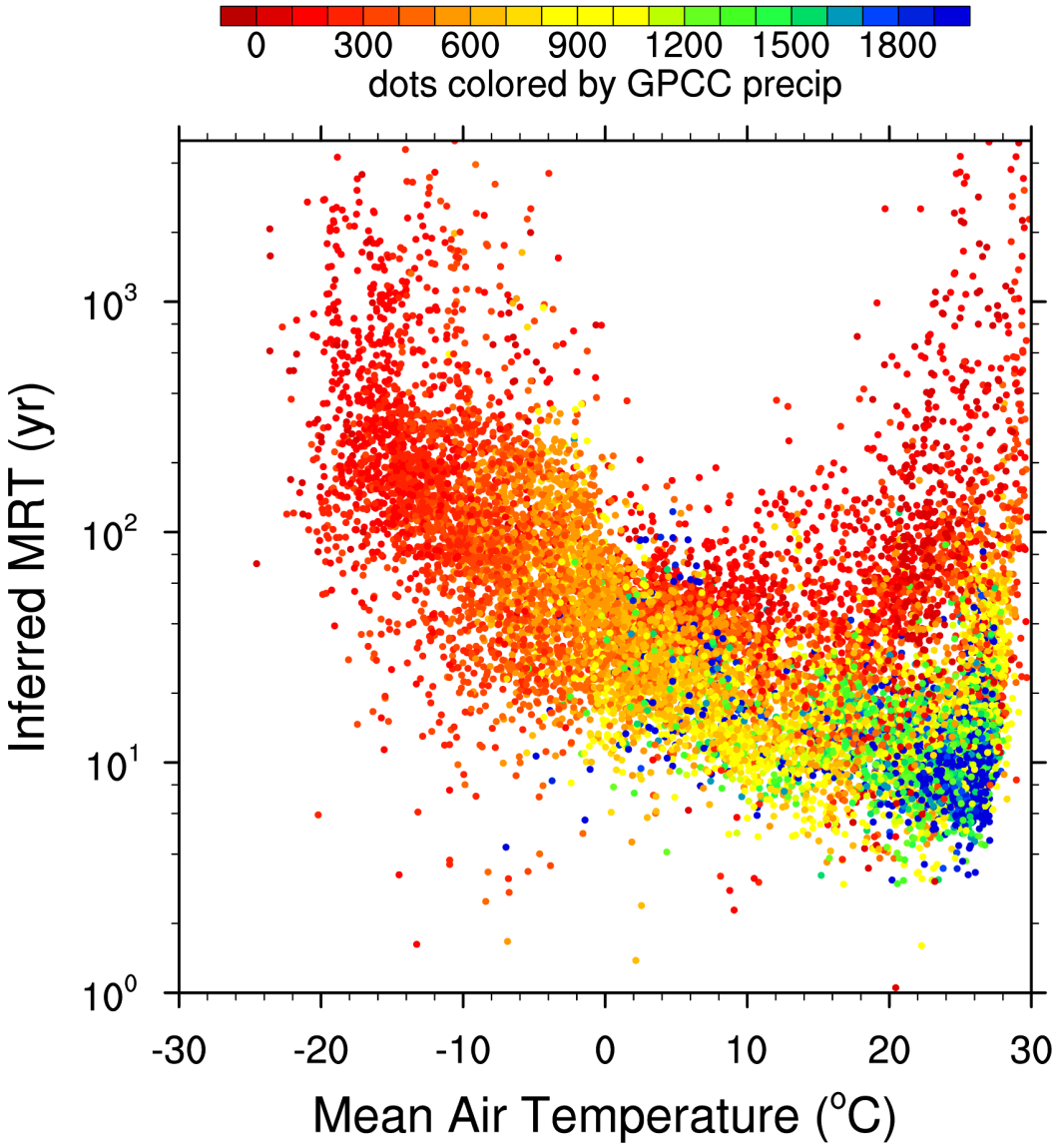

Koven et al., *in prep*

# Where are the peatland soils?



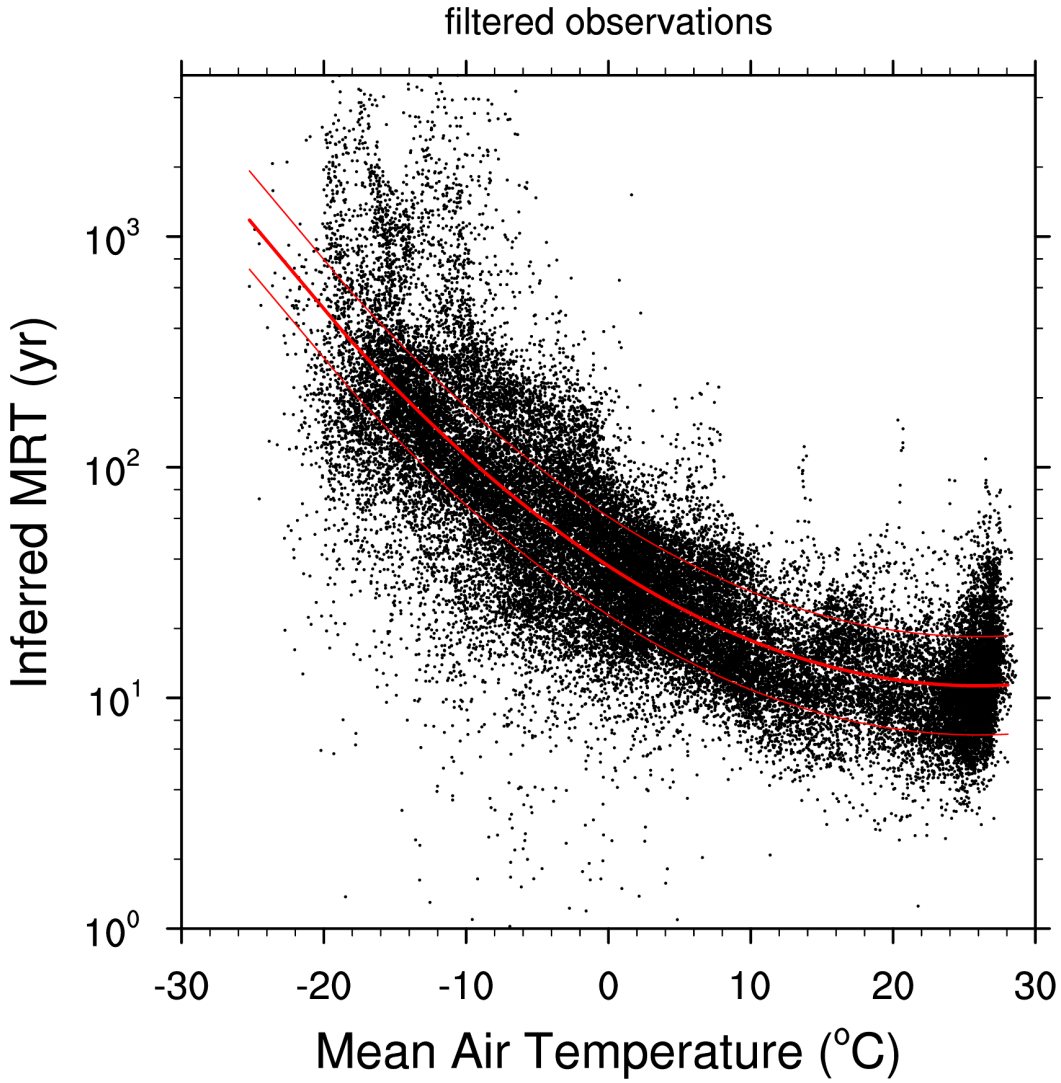

Koven et al., *in prep*

# What about moisture controls? Color by Precip…




Koven et al., *in prep*

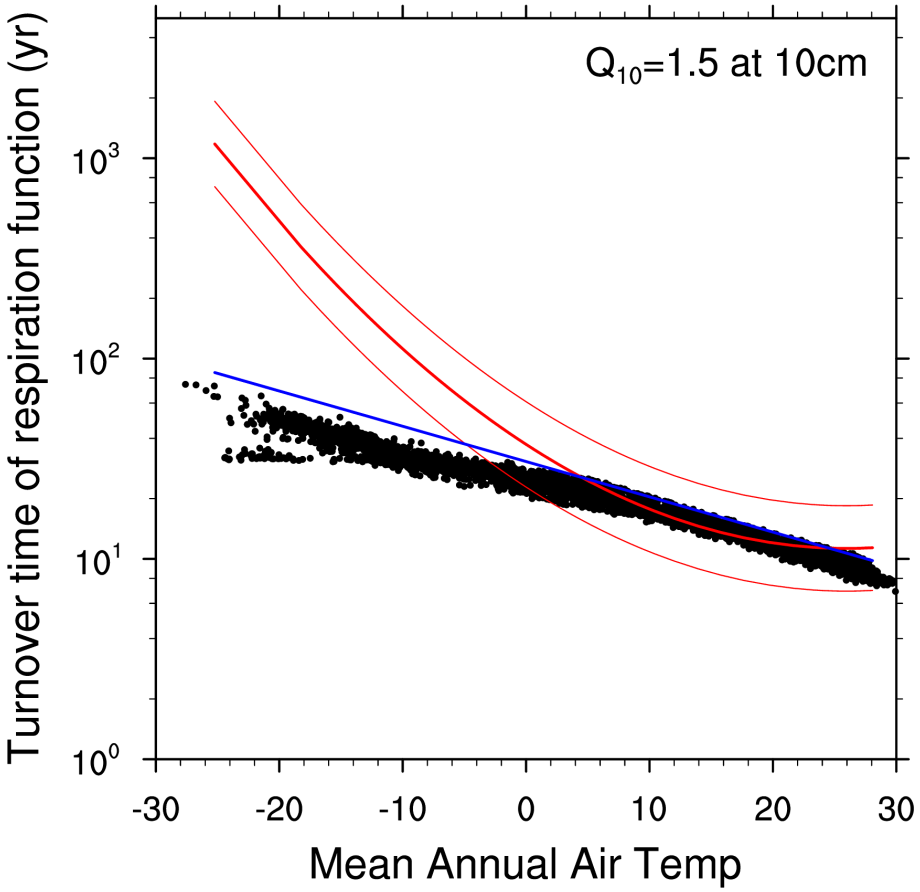
# Filter out all soils that are either too wet (peatlands) or too dry (precip minus potential ET < -1000 mm/yr) and regress temperature control on MRT




Koven et al., *in prep*

# Strawman model hierarchy:

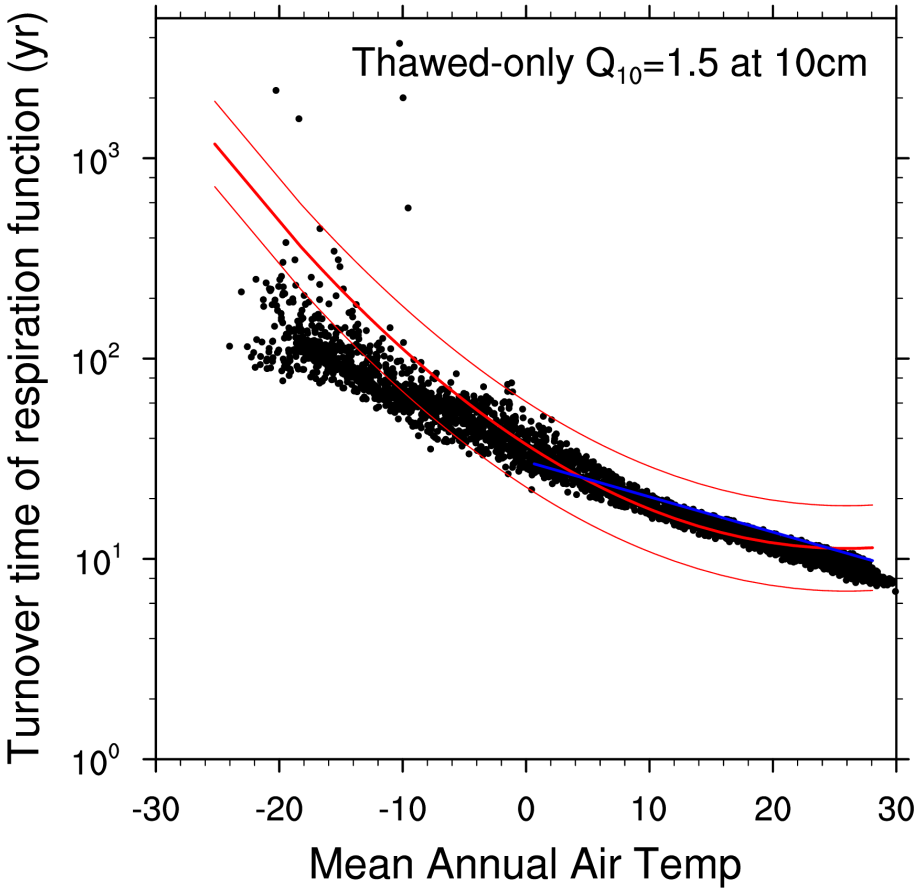
(1) Simplest possible model: evaluate $Q_{10}$ function (of 1.5) with arbitrary base turnover time using high-frequency soil temperature at 10cm depth (here using CLM temperatures), compare mean value to mean air temperature.




Koven et al., *in prep*

# Strawman model hierarchy:

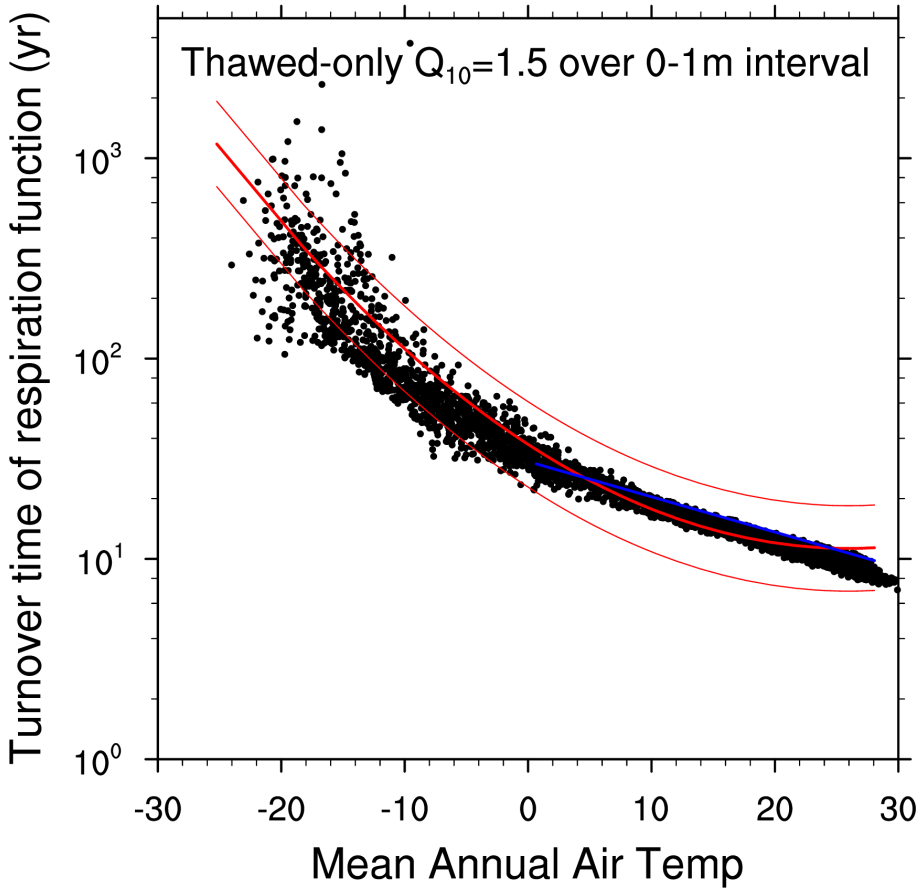
(2) Next simplest possible model; same $Q_{10}$ function, but now set equal to zero decomposition when Tsoil < 0°C




Koven et al., *in prep*

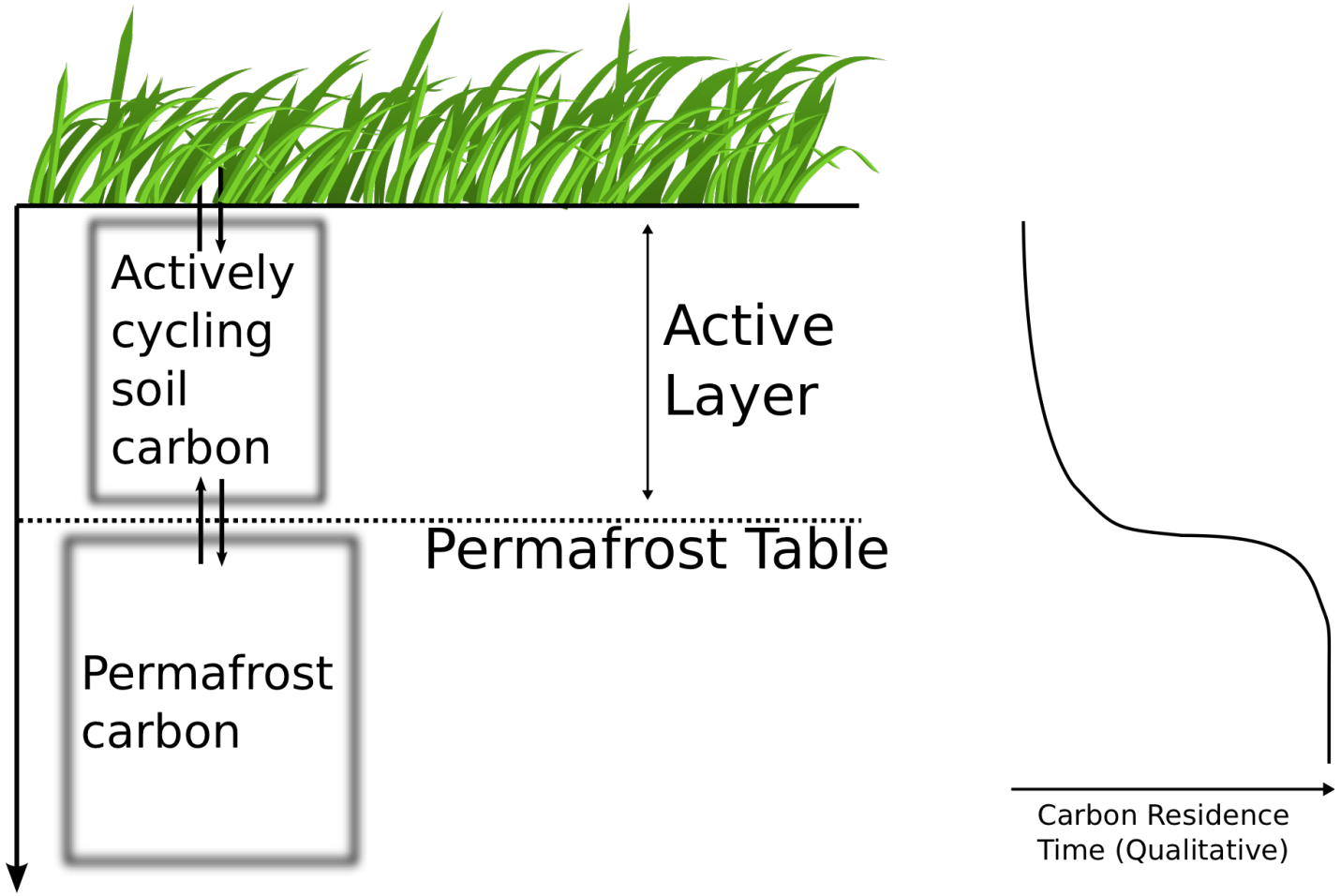
# Strawman model hierarchy:

(3) Simplest permafrost model; same $Q_{10}$ function, with zero decomposition when Tsoil < 0°C, but now evaluate this function over soil column through 0-1m depth interval and take average.

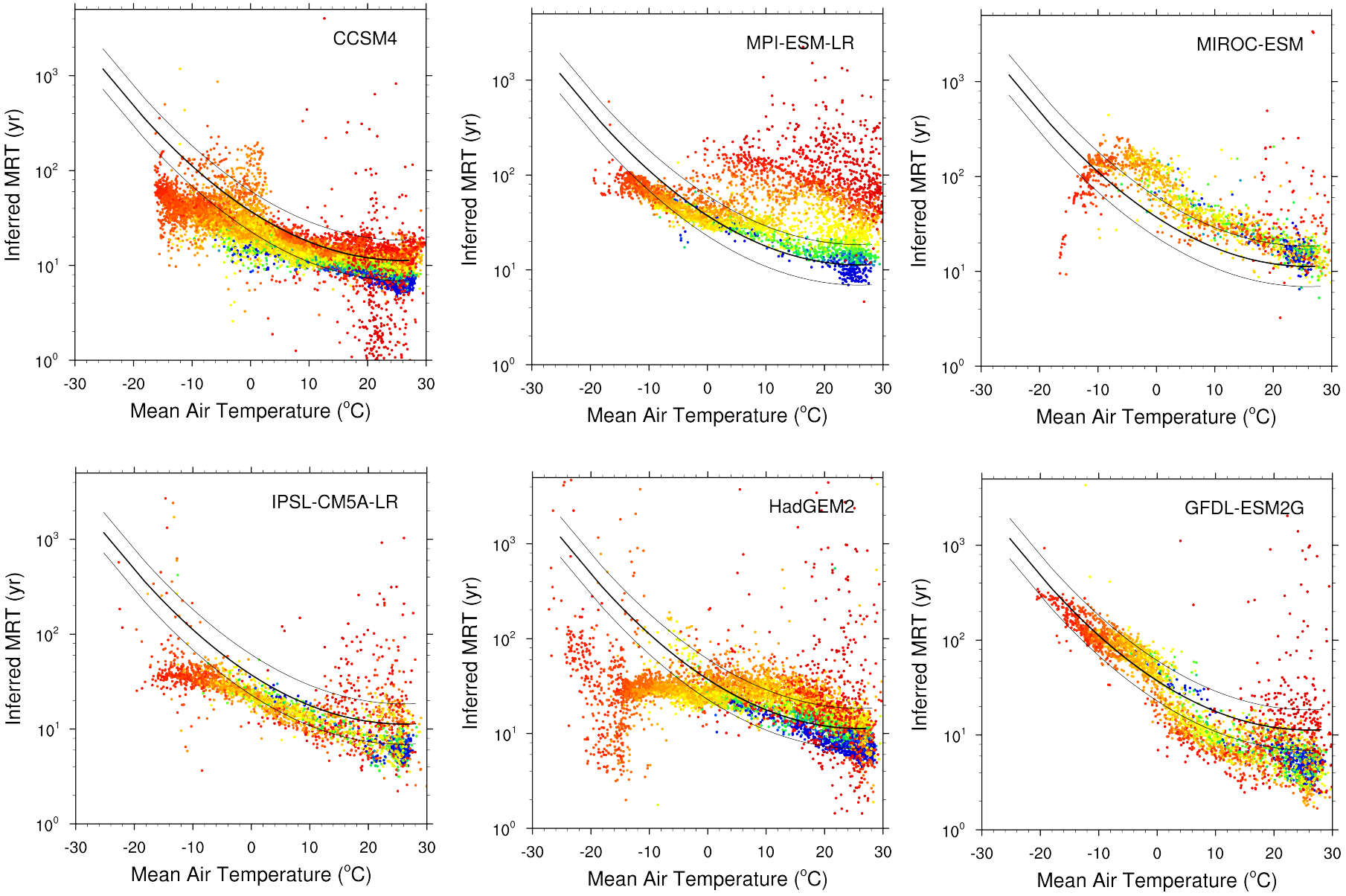



Koven et al., *in prep*

# Why so much C in permafrost soils? Because active layer thins with decreasing temperatures, allowing trapped carbon to remain in permafrost

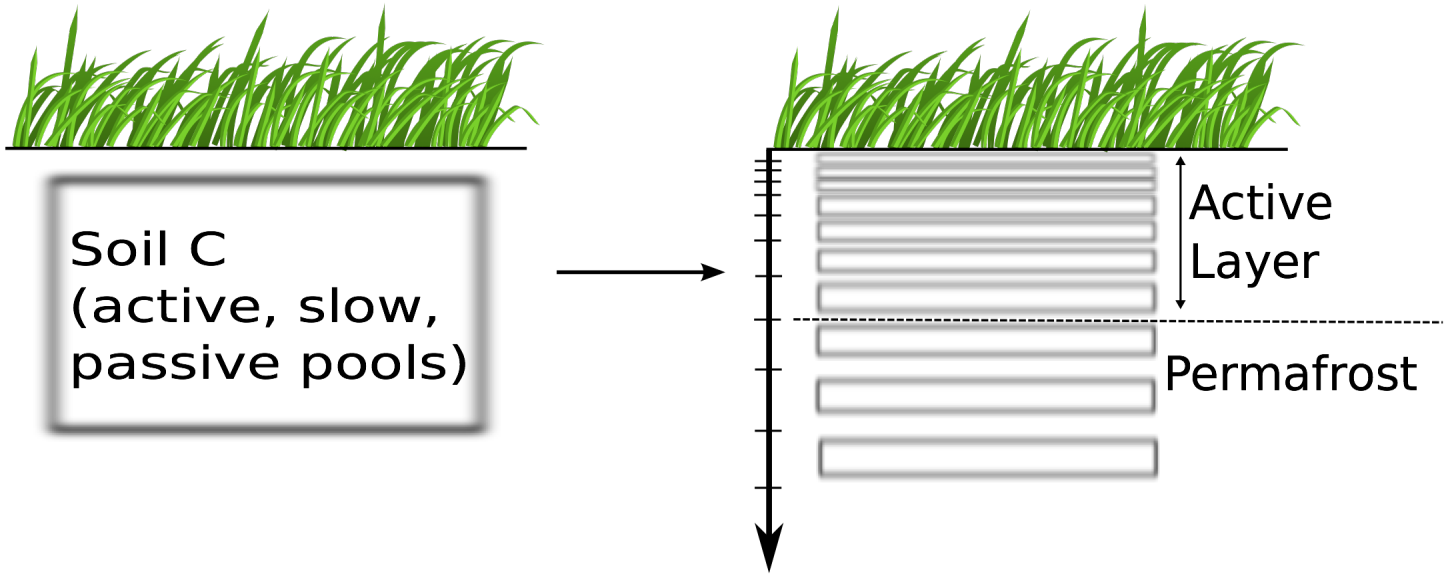


# How do CMIP5 ESMs rate as compared to this metric?



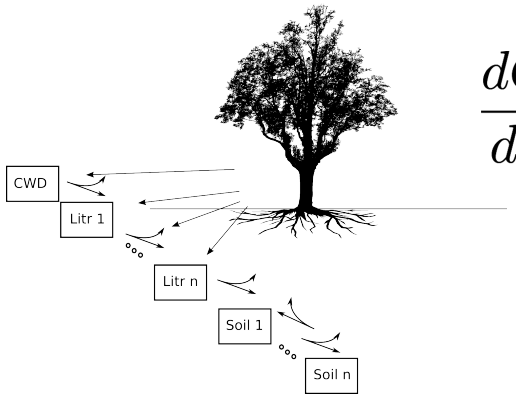

Koven et al., *in prep*

To estimate permafrost feedback strength in an ESM: allow land models to explicitly represent vertical profile of soil organic matter and its temperature-, moisture-, and oxygen-dependent residence time



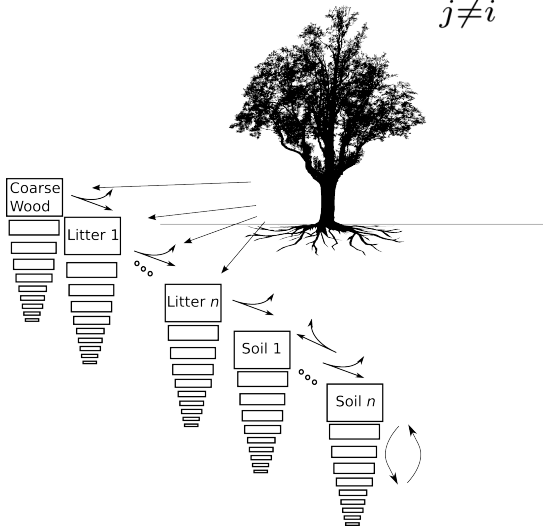

Koven, et al., 2011

# Vertical Soil Carbon Model in CLM and ACME: ODEs to PDEs




$$\frac{dC_i}{dT} = R_i + \sum_{j \neq i} (1 - r_j) T_{ji} k_j C_j - k_i C_i$$

$$\frac{\partial C_i(z)}{\partial t} = R_i(z) + \sum_{j \neq i} (1 - r_j) T_{ji} k_j(z) C_j(z) - k_i(z) C_i(z) + \frac{\partial}{\partial z}\left( D(z) \frac{\partial C_i}{\partial z} \right) + A(z) \frac{\partial C_i}{\partial z}$$




**4 new terms needed:**

- Root, leaf, and stem input profiles R(z)
- Decomposition rate profiles k(z)
- Advective transport rate A(z)
- Diffusive transport rate D(z)

**Also makes the whole land model 2x more expensive…**

# Controls on Soil Turnover in CLM4.5BGC:

## base rate, temperature, moisture, oxygen, and depth modifiers

$$k_i = k_{0,i} r_T r_W r_O r_z$$

$$r_z = \exp\left(-\frac{z}{z_\tau}\right)$$

$Q_{10}$ (of 1.5)

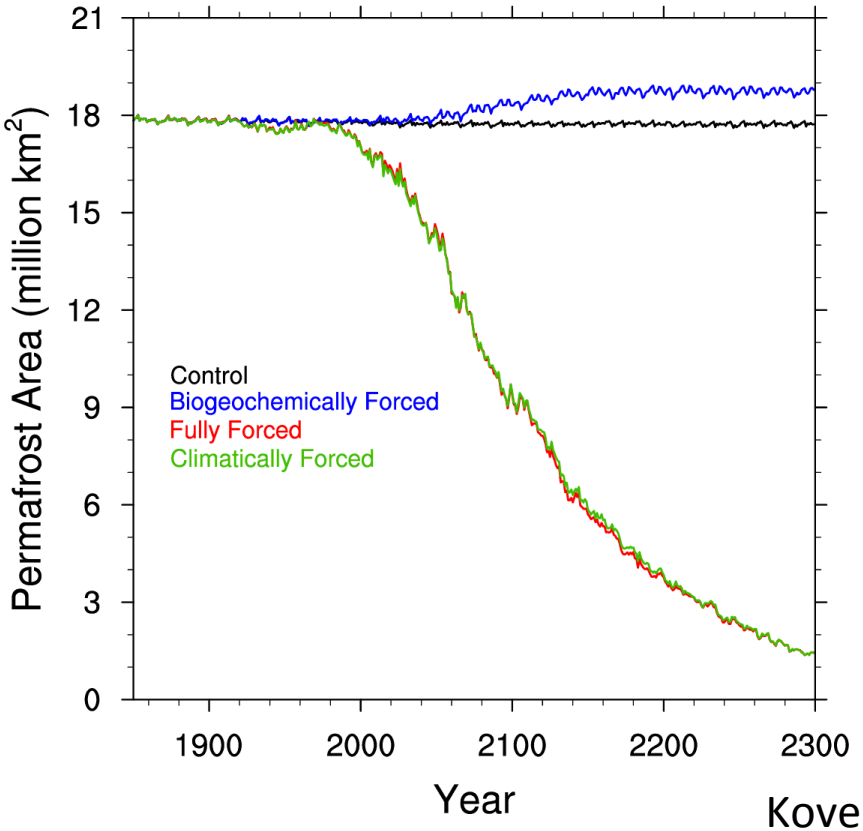
Matric potential of (unfrozen) water

Stoichiometric oxygen supply vs. demand

Experimental Design: Use $Z_\tau$ to assess the sensitivity of response to the decomposability of deep SOM

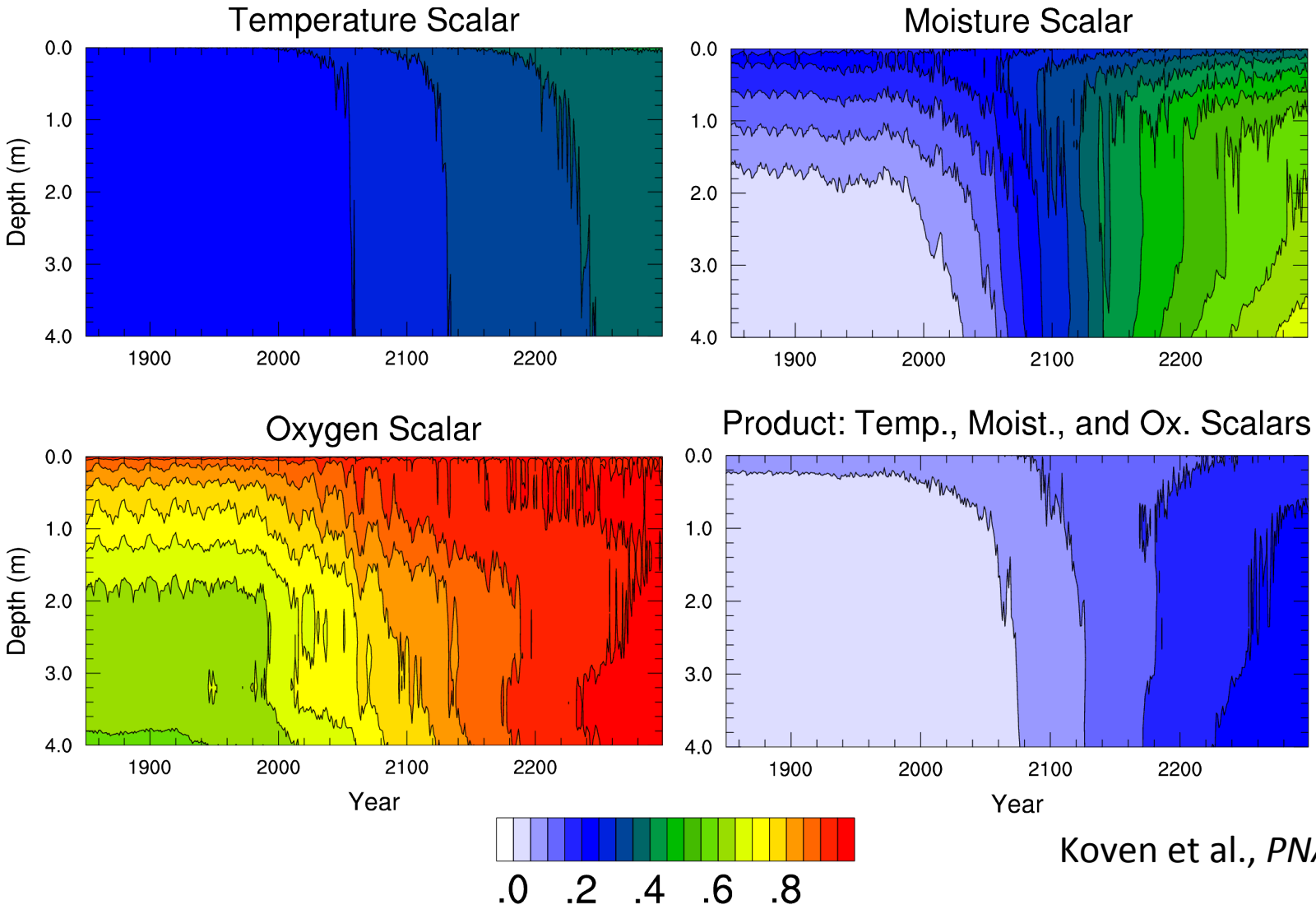
Full experimental setup in CLM4.5 :

1. Forced by offline transient historical+RCP8.5 warming and/or $CO_2$ scenarios to calculate physical and biogeochemical responses to climate change, $CO_2$ fertilization, and interactions
2. CLM4.5BGC including N feedbacks vs. C-only version of CM4.5BGC to assess role of N feedbacks
3. Vary $Z_\tau$ to assess role of deep SOM



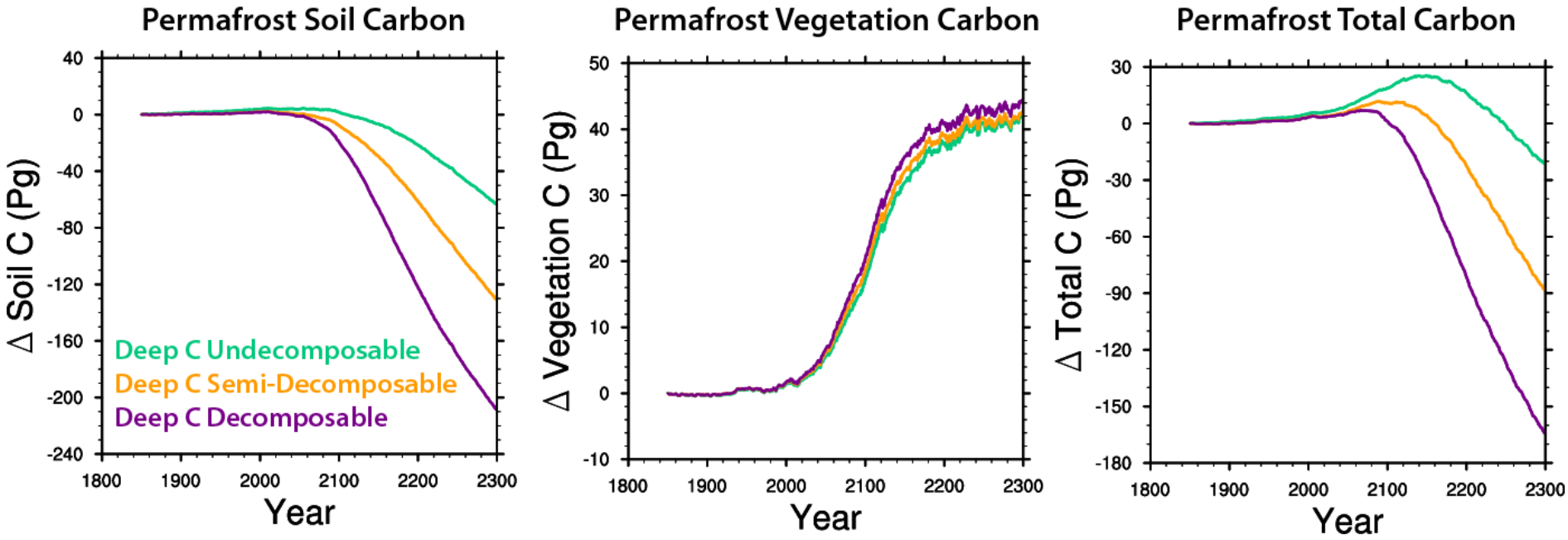

Koven et al., *PNAS* 2015

# Reversal of vertical profile in environmental decomposition limitation as permafrost changes to seasonally frozen ground. Note that strongest control is via the (liquid) moisture scalar.




Koven et al., *PNAS* 2015

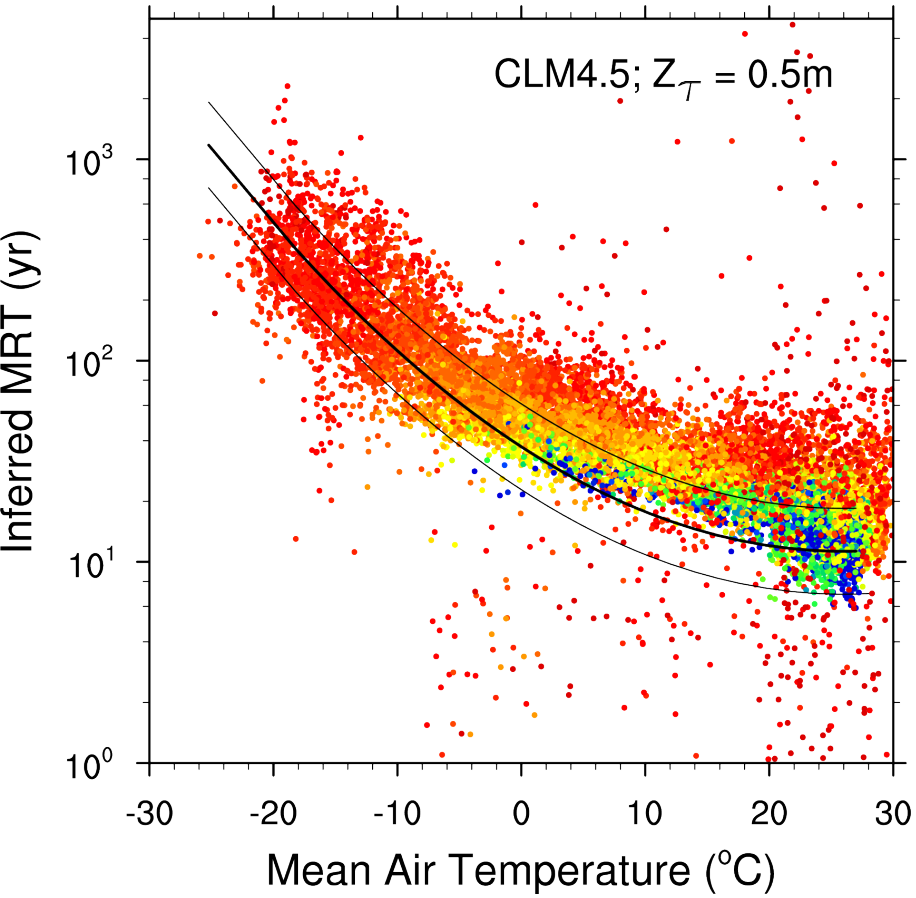
# Ecosystem models suggest total magnitude of carbon loss is a sensitive function of deep soil decomposability

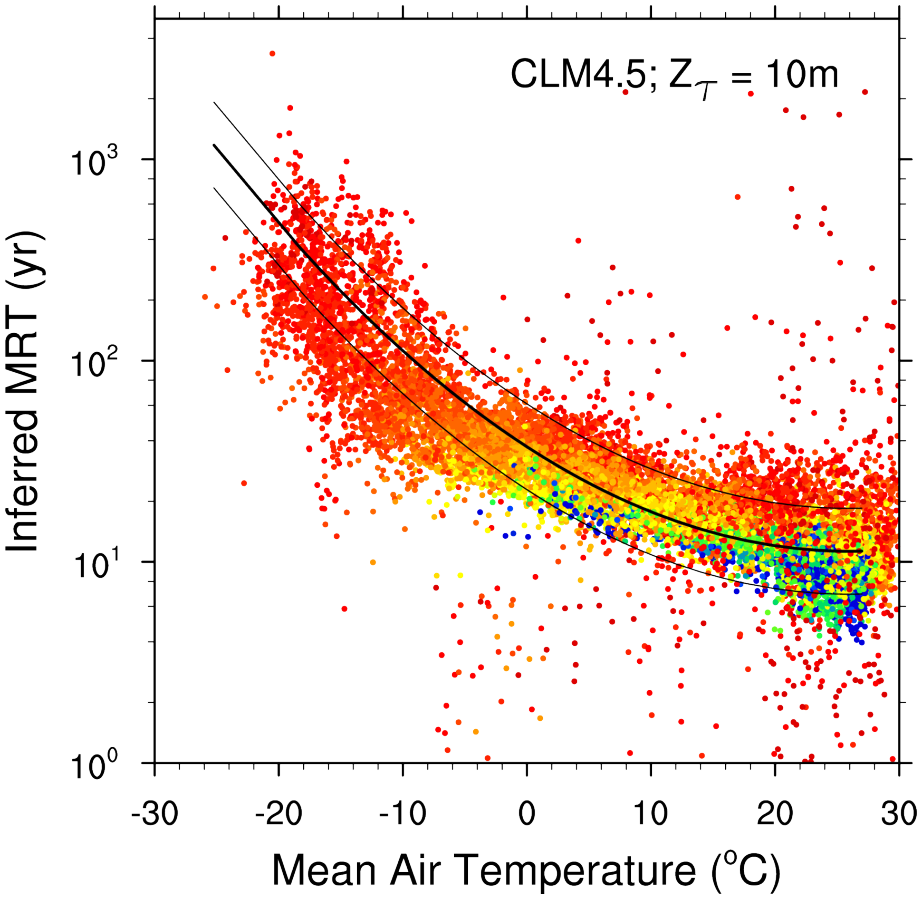



Koven et al., *PNAS*, 2015

- With decomposable deep soil organic matter, soil C losses dominate and lead to a large positive feedback from the permafrost region
- Inclusion of nitrogen cycle suggests that plants may not effectively use extra nitrogen released by decomposing deep soils to mitigate C losses

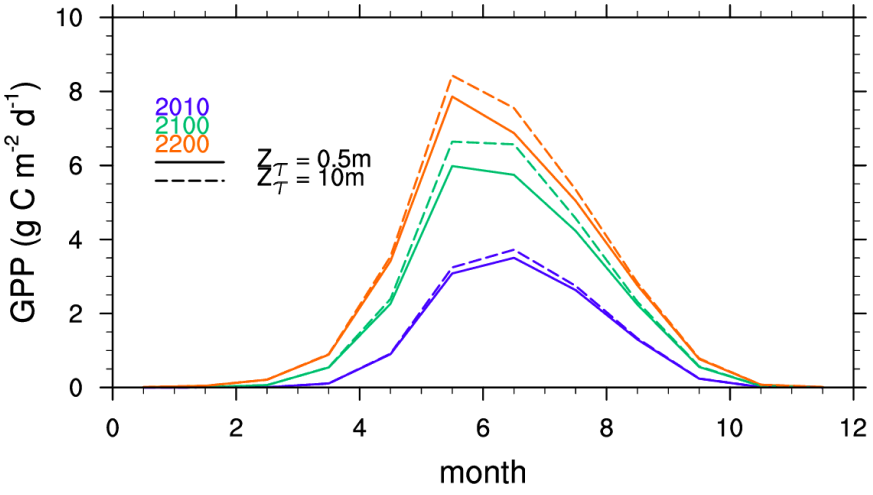
# Climatological control on soil turnover diagnostic suggests more sensitive model is also more accurate

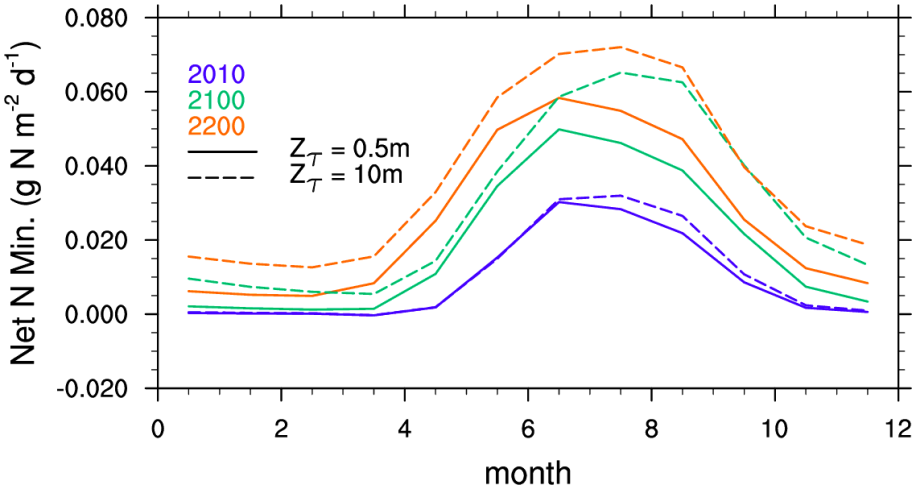



Koven et al., *in prep*

# Why small response of vegetation to additional N from mineralizing deep N?

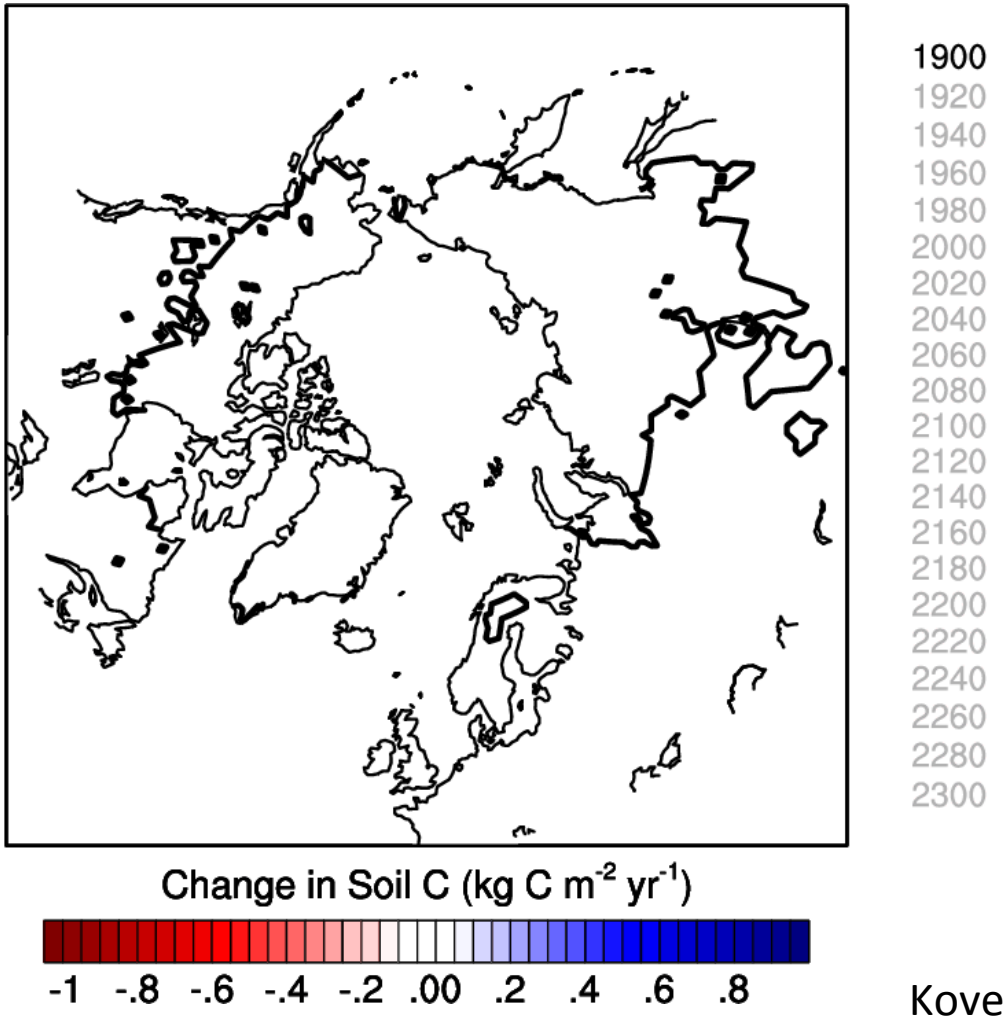



Koven et al., *PNAS*, 2015

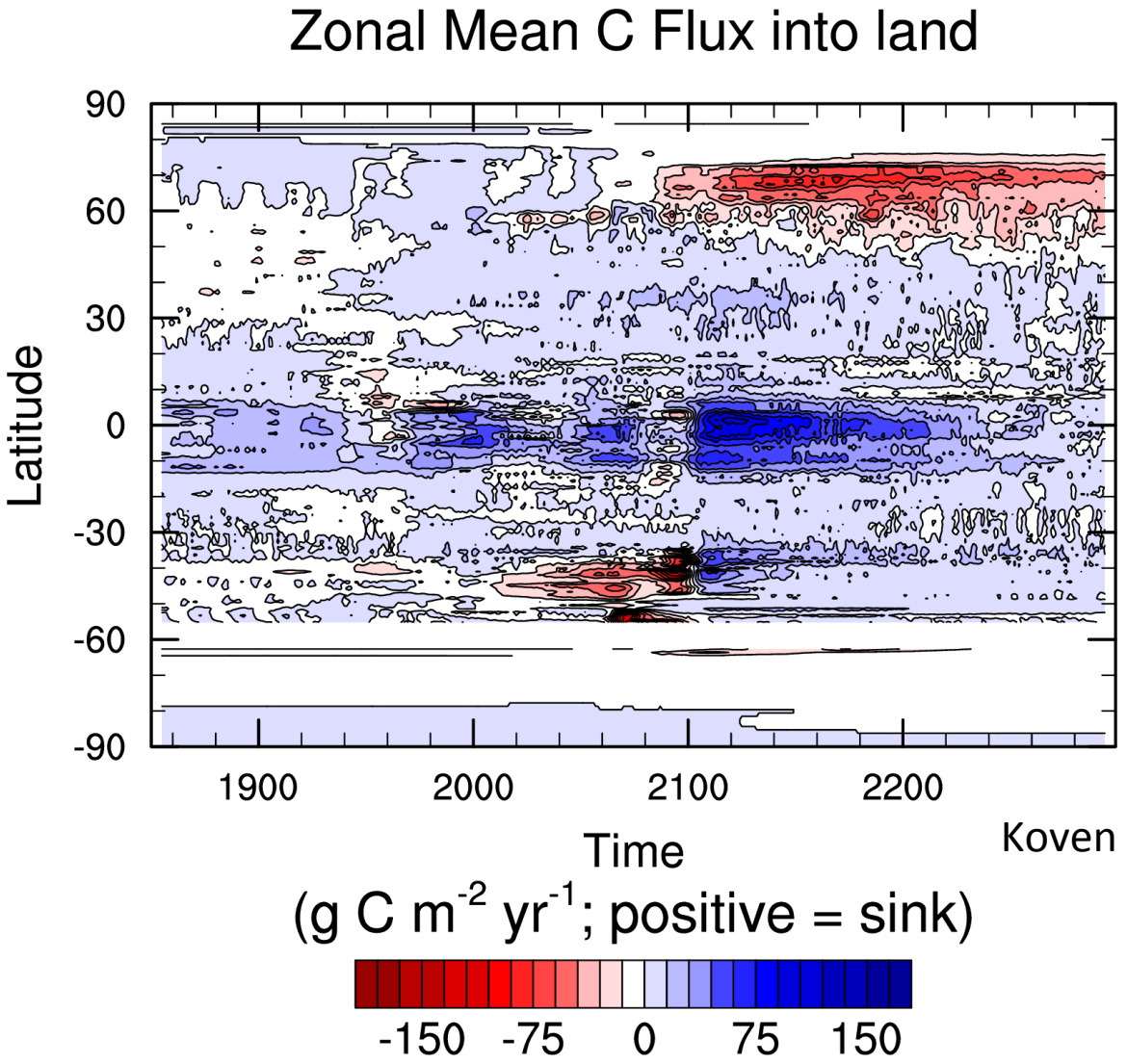
Seasonal asynchrony between N demands and extra N supply means that deep SOM not as available for plant uptake;
Also, plants already getting extra N from shallow soils

# Projected soil C emissions follow the retreating permafrost boundary and persist long after permafrost has thawed




Koven et al., *PNAS*, 2015

# Carbon losses from permafrost may be large; similar magnitude to, but slower than, carbon responses of tropical forests




Koven et al., *PNAS*, 2015

# Conclusions

- Climate controls on permafrost carbon storage are strong due to freeze/thaw state change and long-term storage in permafrost layers, with additional control by anoxia
- Must consider vertical profiles of soil biogeochemistry to model these processes. Relatively straightforward change that allows model to natively capture carbon dynamics in permafrost regions
- When including key permafrost processes, sign of carbon response to warming at high latitudes shifts from sink to source, and likely a very large source.
- Nitrogen fertilization from decomposing deep soils unlikely to offset carbon losses
- Total estimated permafrost feedback strength of around 20-30 Pg Carbon / $^{o}$C.
- Permafrost represents an important low frequency carbon cycle mode in the Earth system that acts to amplify climate change