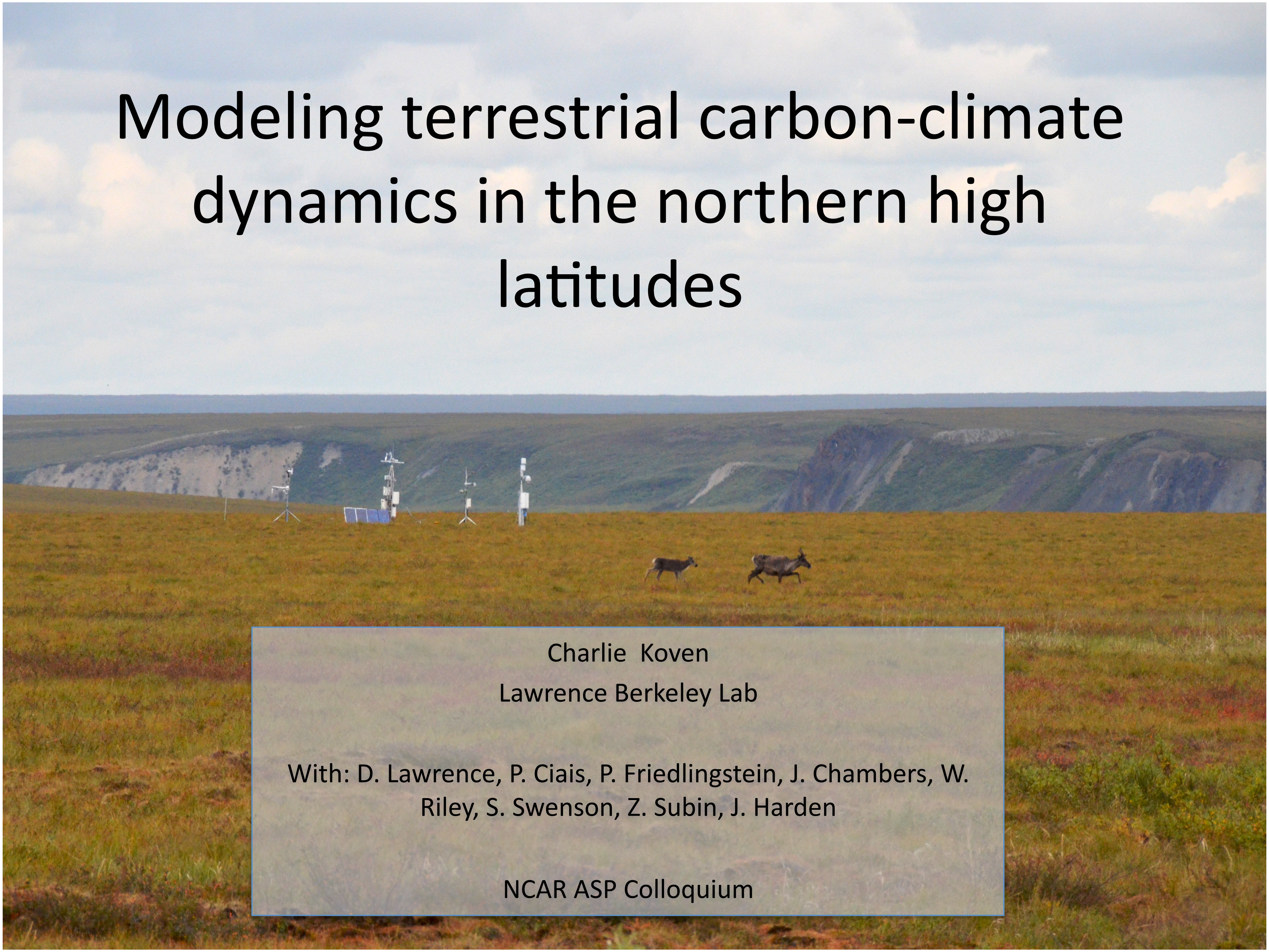


Modeling terrestrial carbon-climate dynamics in the northern high latitudes

Charlie Koven

Lawrence Berkeley Lab

With: D. Lawrence, P. Ciais, P. Friedlingstein, J. Chambers, W. Riley, S. Swenson, Z. Subin, J. Harden

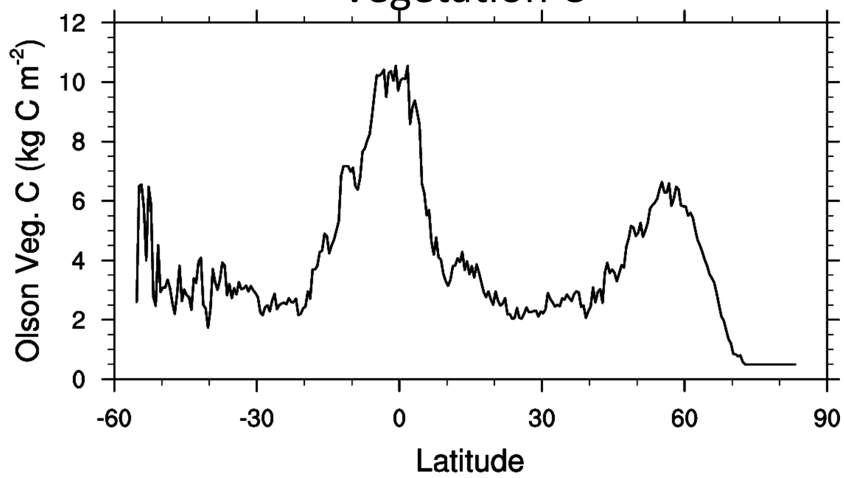
NCAR ASP Colloquium

Outline

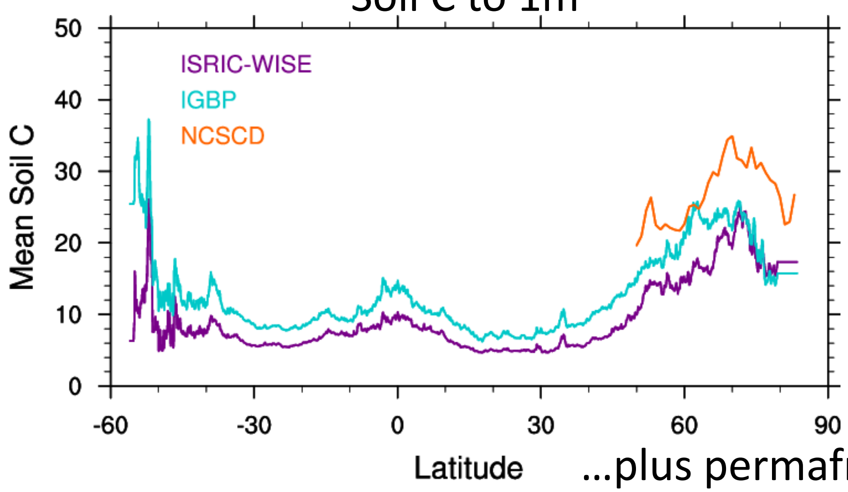
- Intro: how do high-latitude terrestrial ecosystems fit into the global carbon cycle?
- Boreal forest, tundra, and vegetation C dynamics
- Permafrost and soil C dynamics

High latitude C cycle: Large stocks, Small fluxes

Vegetation C

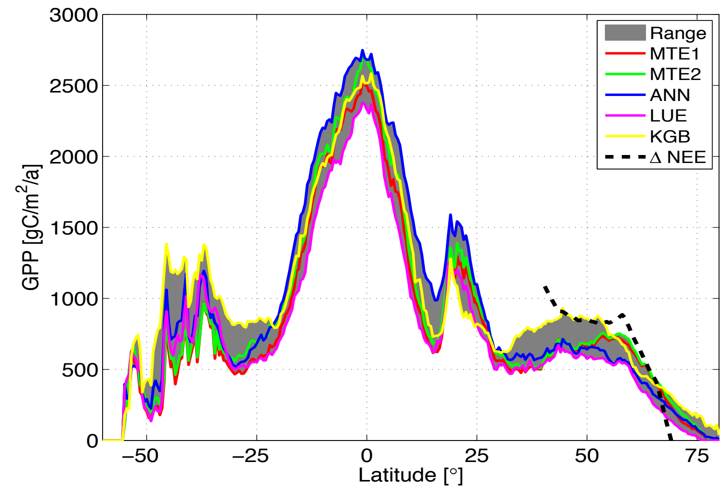


Soil C to 1m



...plus permafrost C below 1m

GPP



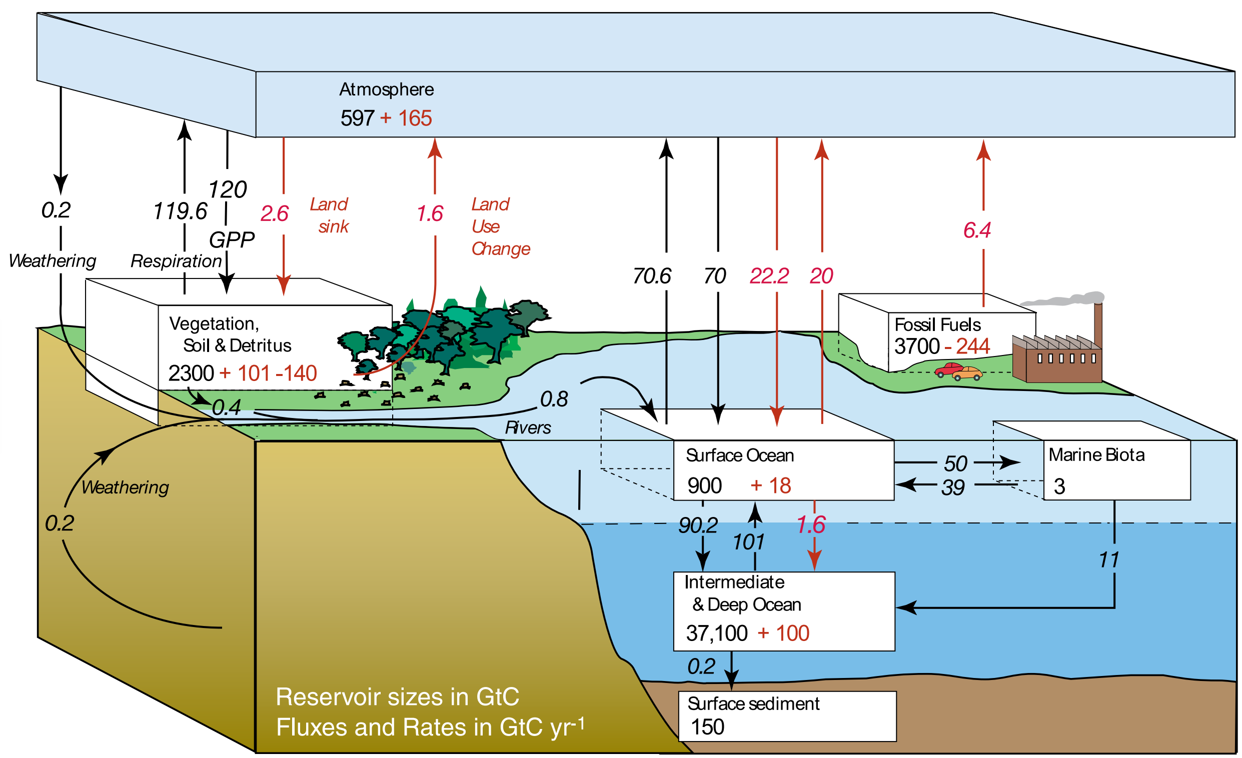
Beer et al., 2010

$$m = f\tau$$

Poleward trend in decomposition goes to zero faster than productivity

Problem: Huge amount of organic carbon in permafrost soils. How does this carbon interact with climate change?

Permafrost
1500



IPCC, 2007

Classic view of terrestrial carbon-climate feedback

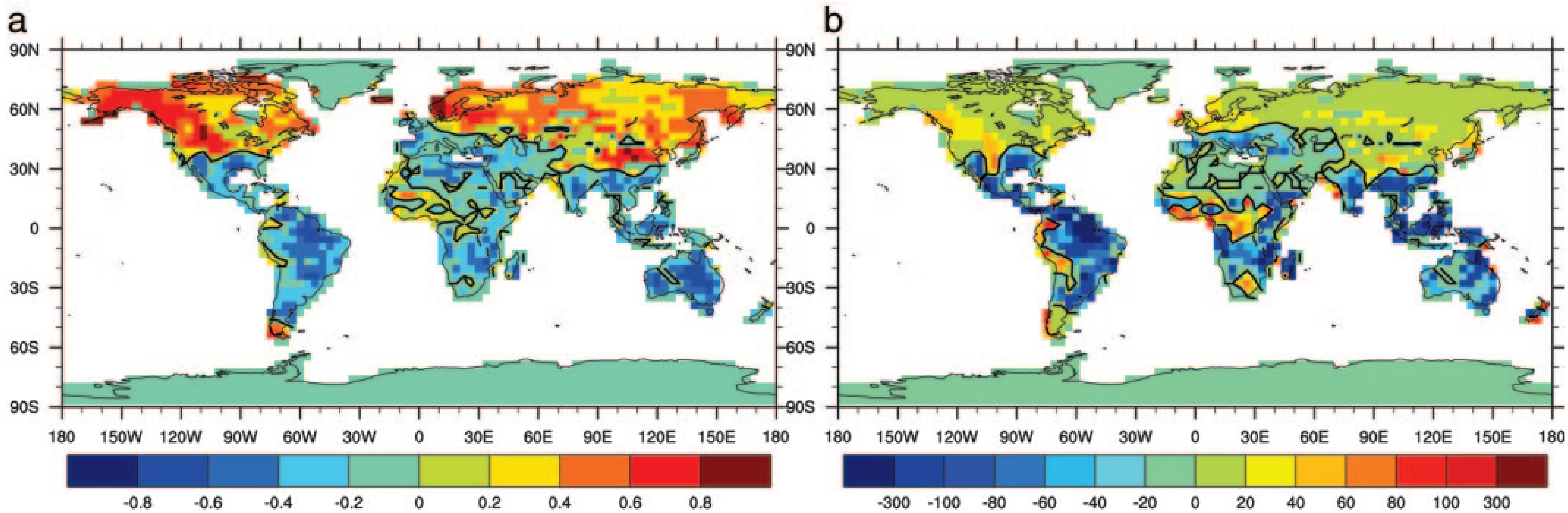
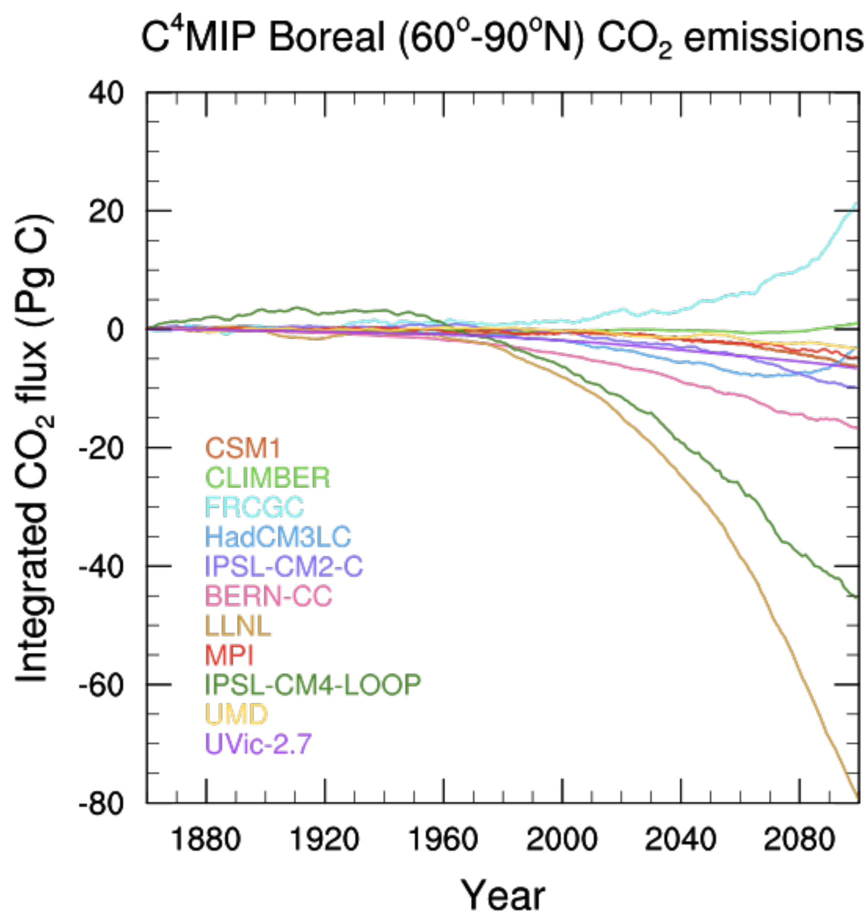


Fig. 3. Regional differences in the change in hydrologic regime and ecosystem productivity with global warming. (*a*) Correlation between annual mean δT_{air} and $\delta\beta_{iran}$ for the 21st century. β_{iran} is an index (between 0 and 1) of soil moisture saturation. (*b*) Regression (in kgC/m^2 per yr per K) of annual mean δNPP against annual mean δT_{air}. δ is defined as the difference between experiments A2_ROL and A2_OL for the 21st century.

Fung et al., 2005

C^{4}MIP (Friedlingstein et al., 2006) generation of global coupled carbon-climate models mostly show weak high-latitude terrestrial carbon sink due to warming.

How does response to warming change if we add more complex representations of these ecosystems?



Boreal forest, tundra, and vegetation C dynamics

Climate Analogs

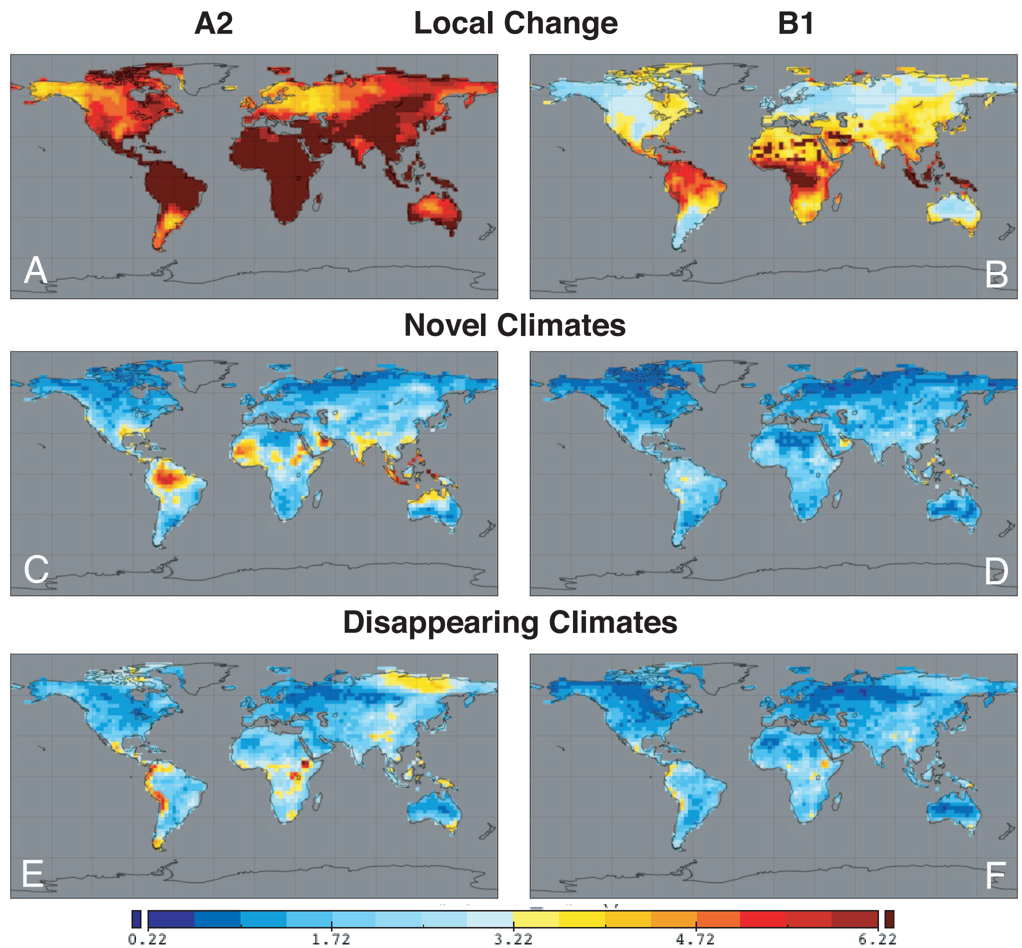
Compare across two time periods (*reference* and *modified*):

$$SED = \sqrt{\sum_i \frac{(\mu_{i,ref} - \mu_{i,mod})^2}{\sigma^2_{i,ref}}}$$

SED: Standard Euclidean Distance

$\mu_{i,ref}$ and $\mu_{i,mod}$: means of variable *I*

$\sigma_{i,ref}$: standard deviation variable *i*

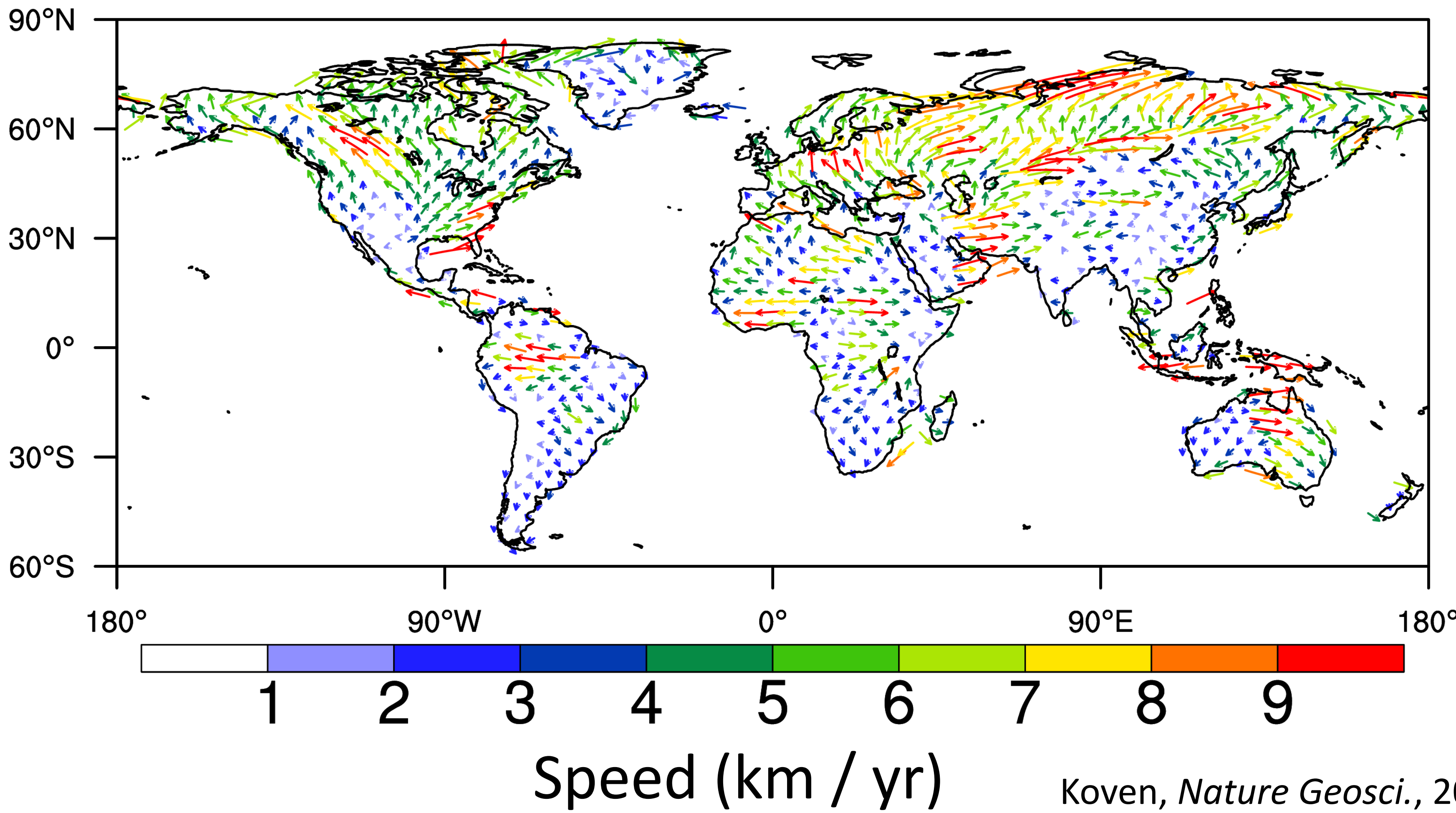


Williams et al., 2007

Climate Analog Velocity:

Mean change across 21 CMIP5 climate models:

(Hist: 1960-1989) -> (RCP4.5: 2040-2060)



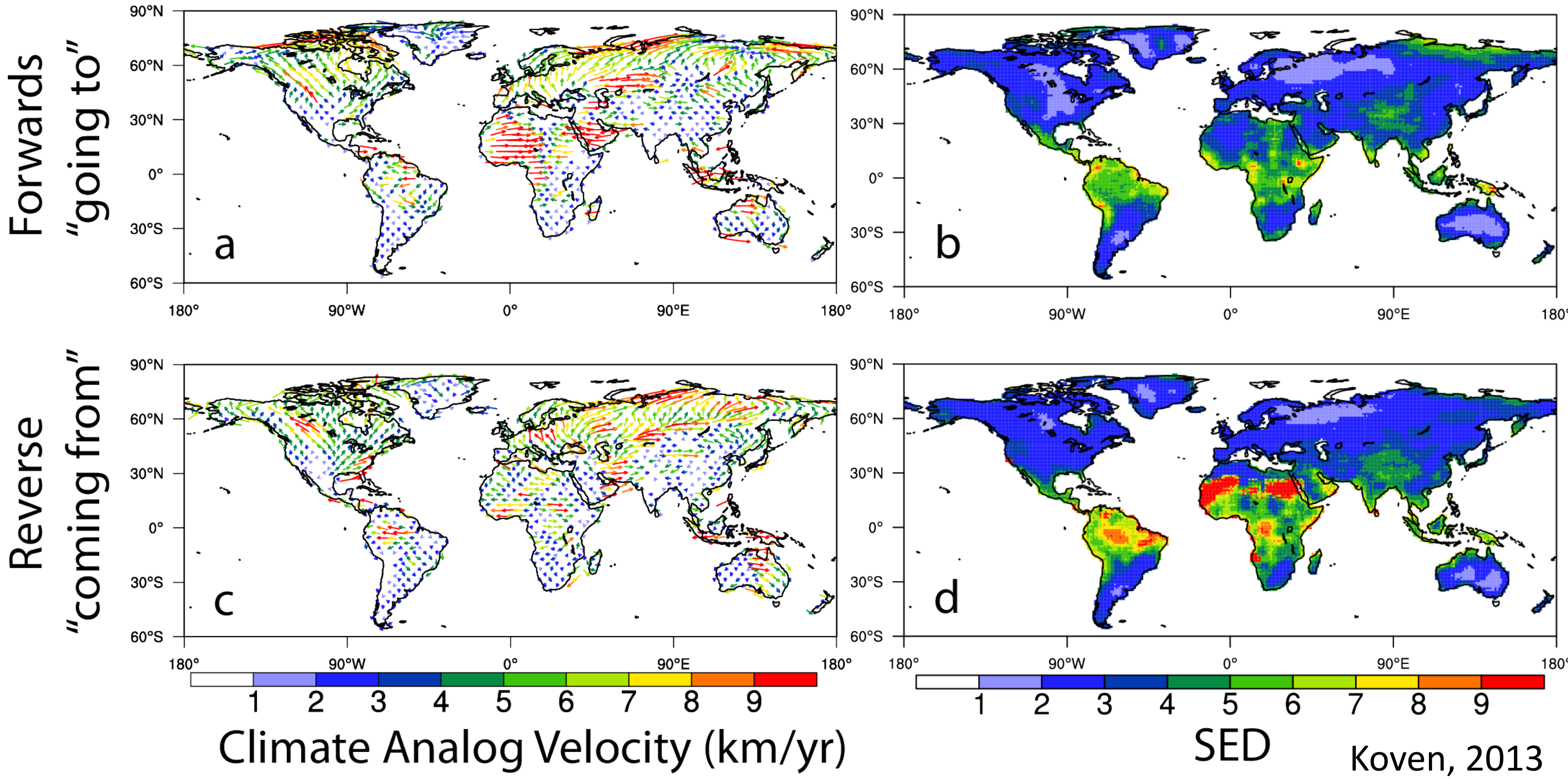
Koven, *Nature Geosci.*, 2013

Arrow length = distance travelled by best climate analog in between 2 periods

Two senses: where is climate going to and where is climate coming from?

Climate change vectors: 1975-2050

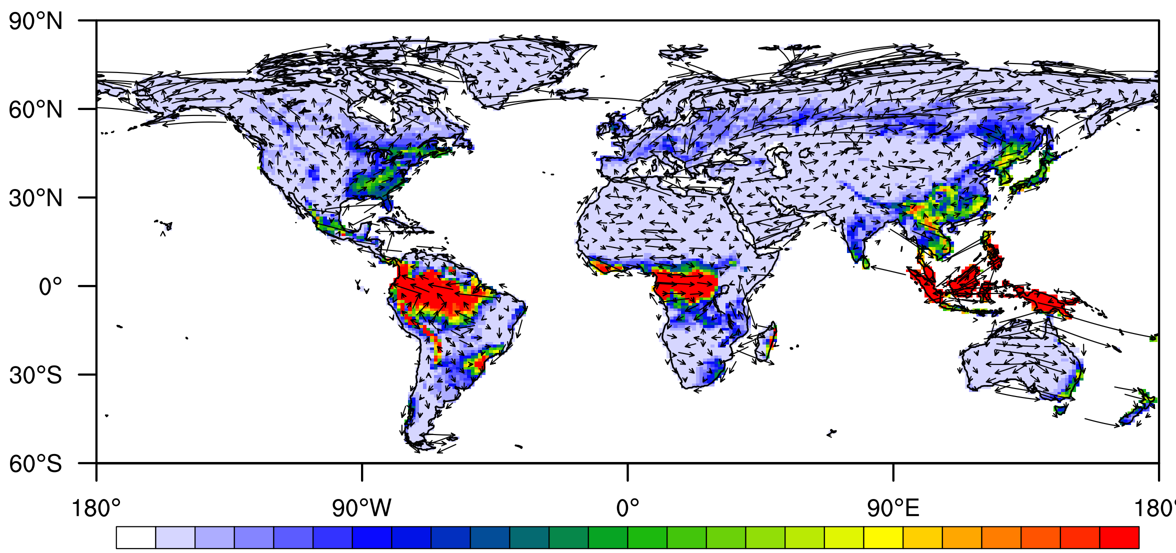
Relative difference of closest climate analog



Koven, 2013

Assume that equilibrium carbon stocks are best estimated by, and move with, their reference historical climate—carbon change then becomes analogous to a transport problem

$$\frac{\partial C}{\partial t} = -\left(u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y}\right)$$

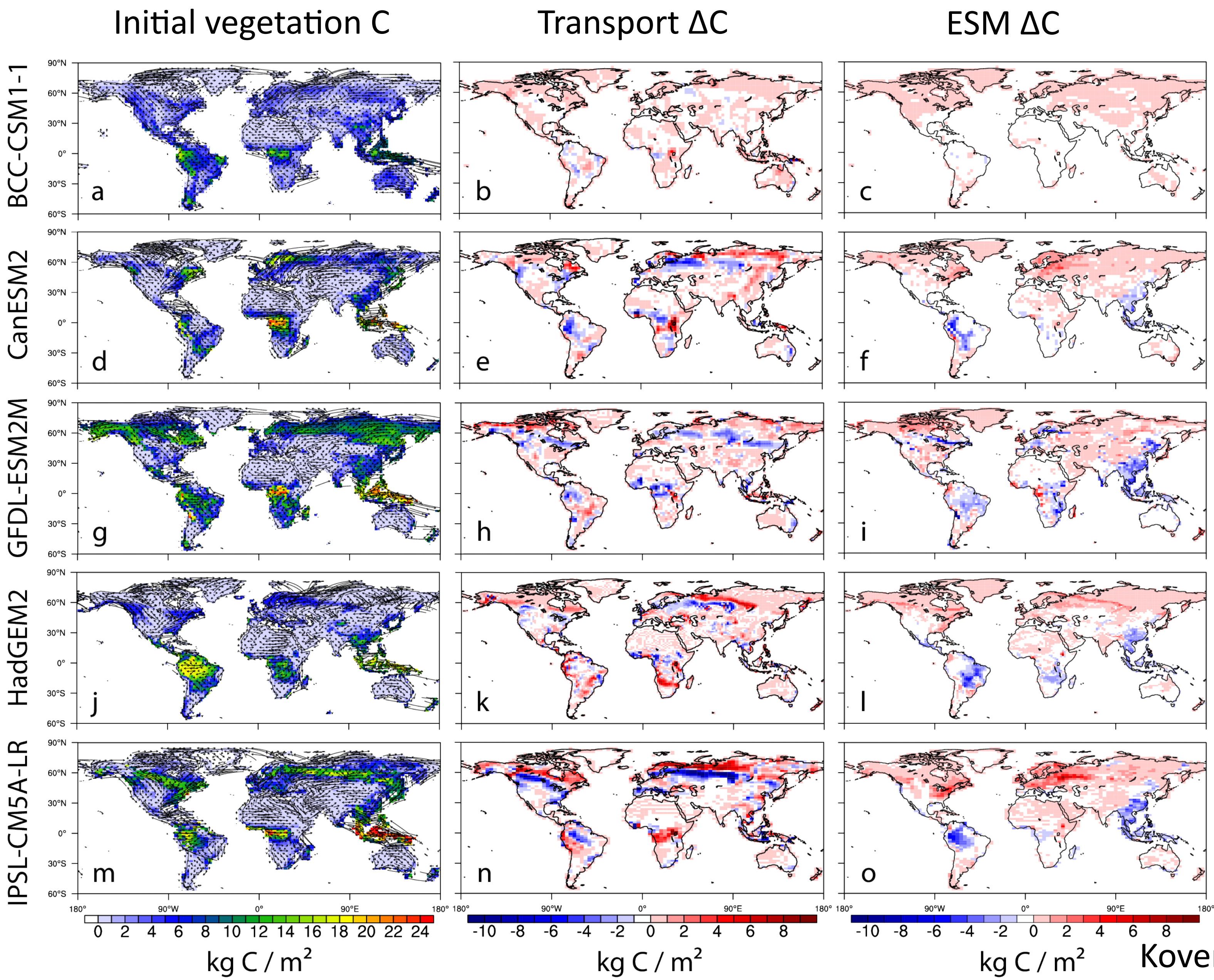


Initial C_{veg} with climate vectors (kg C m^{-2})

Koven, 2013

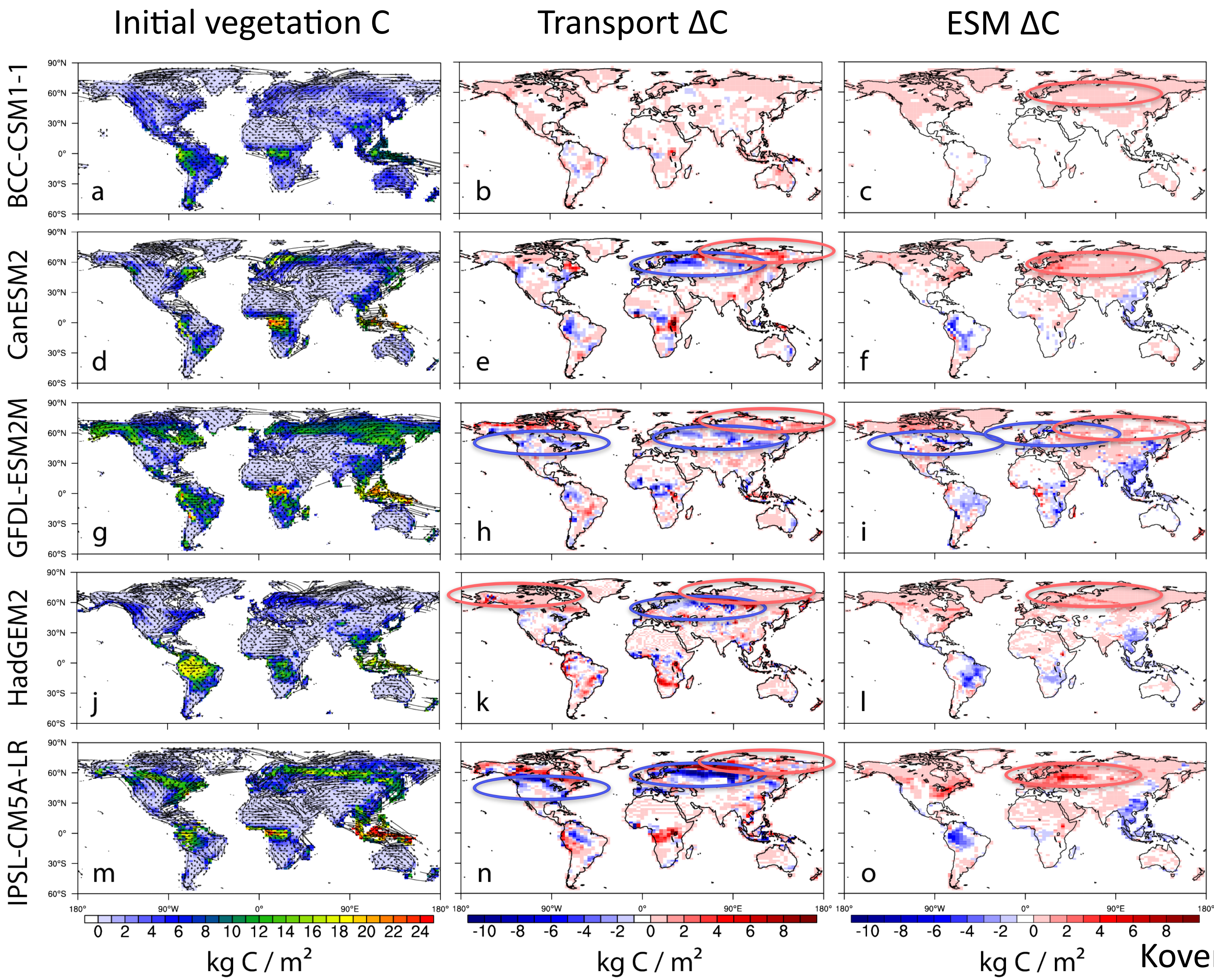
Compare this idea of carbon change to traditional fixed-grid perspective of ESMs. Do they agree?

CMIP5 "esmfdbk2" models



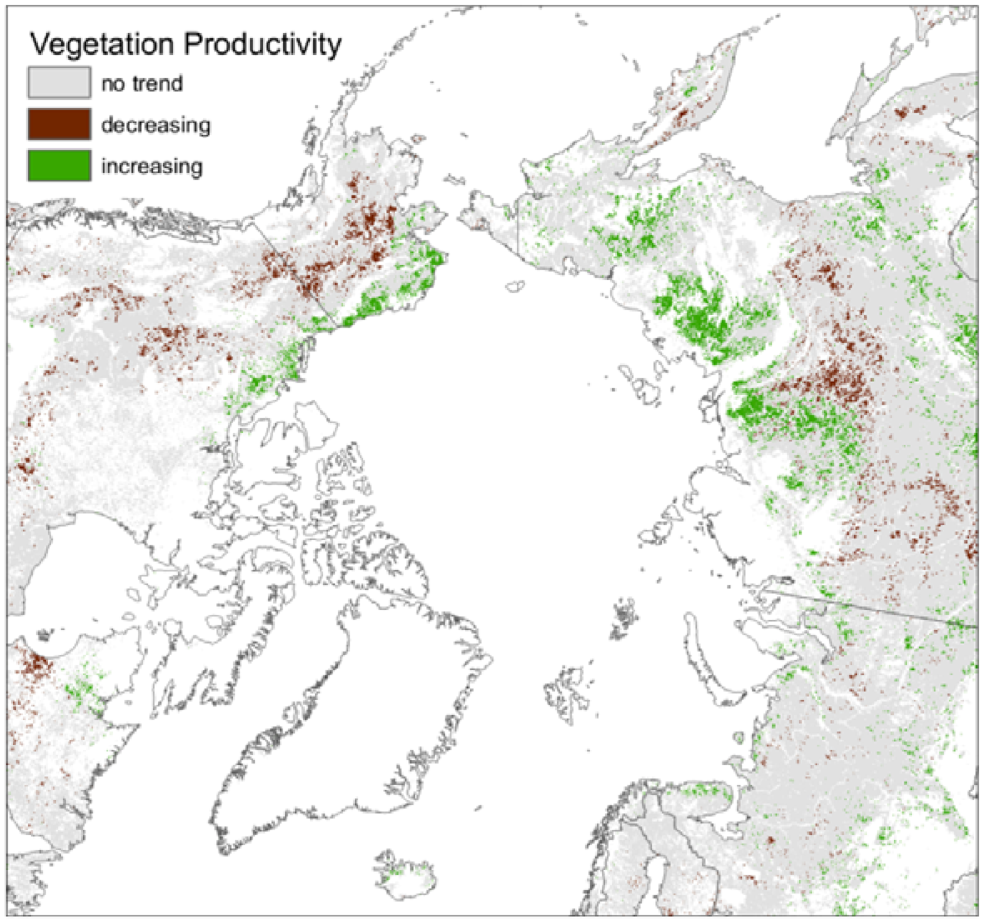
Koven, 2013

CMIP5 “esmfdbk2” models



Koven, 2013

Observations: greening/browning trends from remote sensing

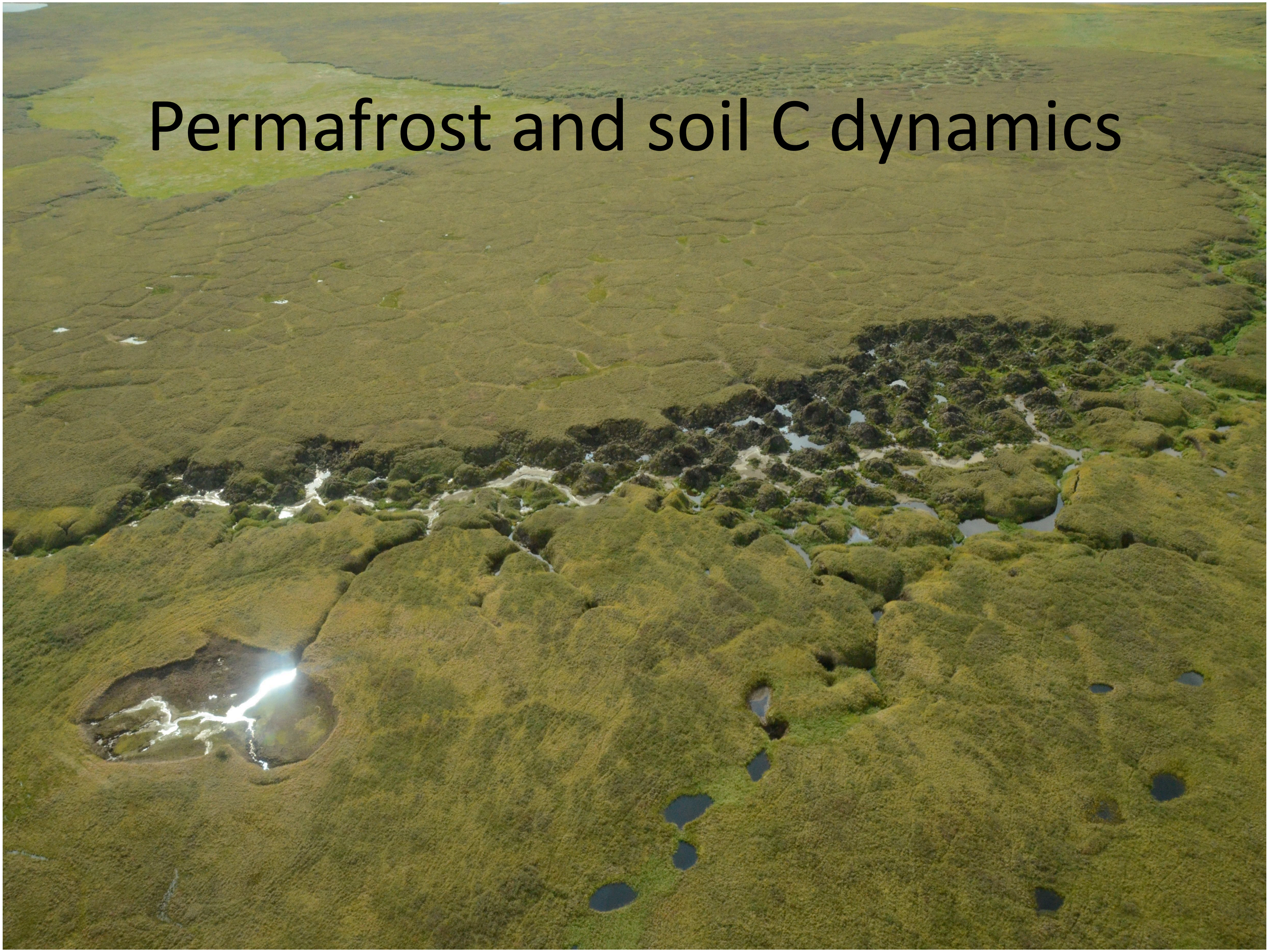


Beck and Goetz, 2011

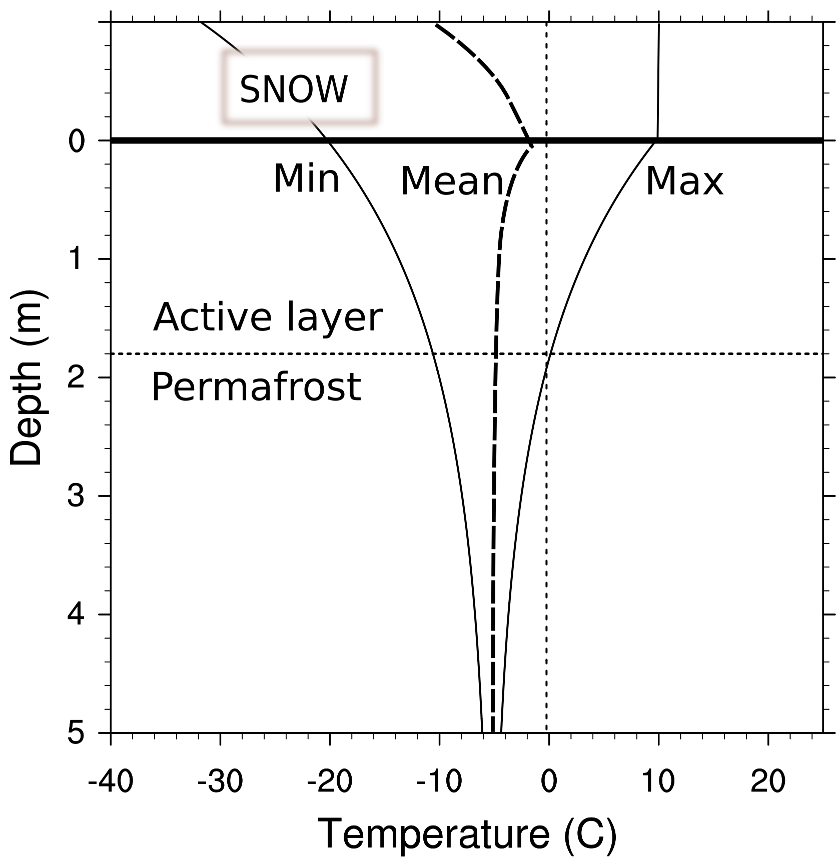
Conclusions—Part 1

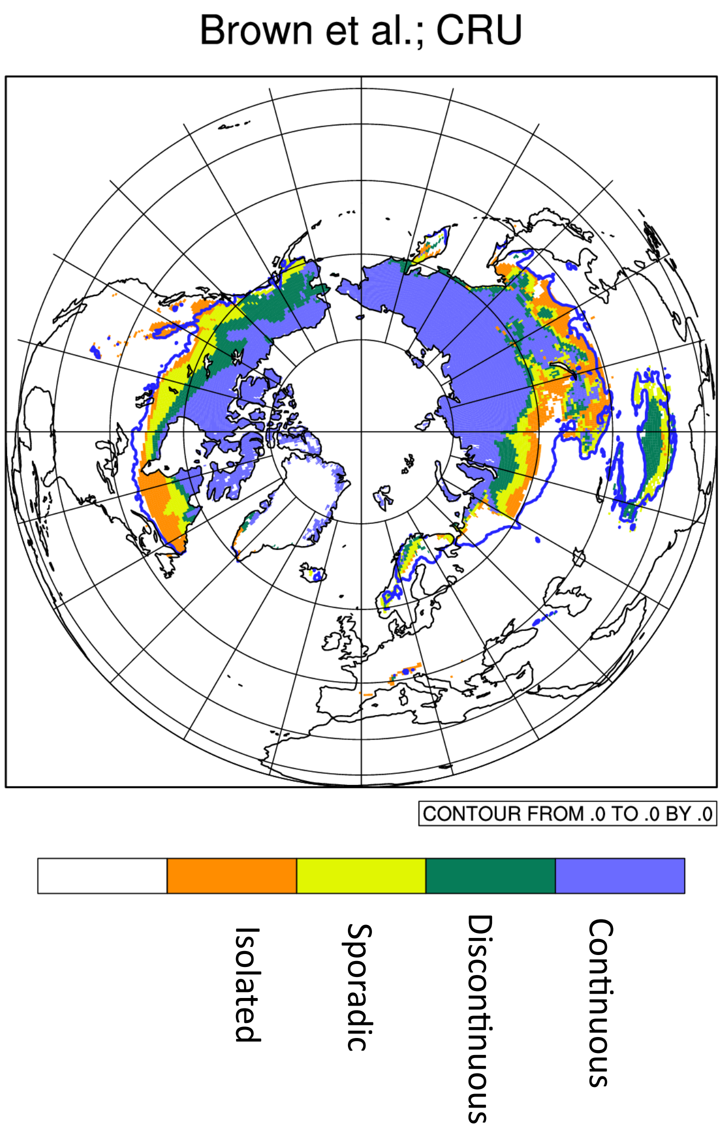
- Climate analog approach may be a useful qualitative constraint for comparing to process-based models:
  - Are the relevant processes included?
- Majority of CMIP5 models show broad vegetation C gains throughout boreal region as forest expands northward
- Climate-analog view suggests that this will be a poleward shift rather than an expansion, with C gains at northern edge offset by losses at Southern boundary
- Models need to increase mechanistic representation of the forest disturbance and mortality processes that would lead to this shift to better estimate the likelihood, magnitude and timescale of these losses

Permafrost and soil C dynamics

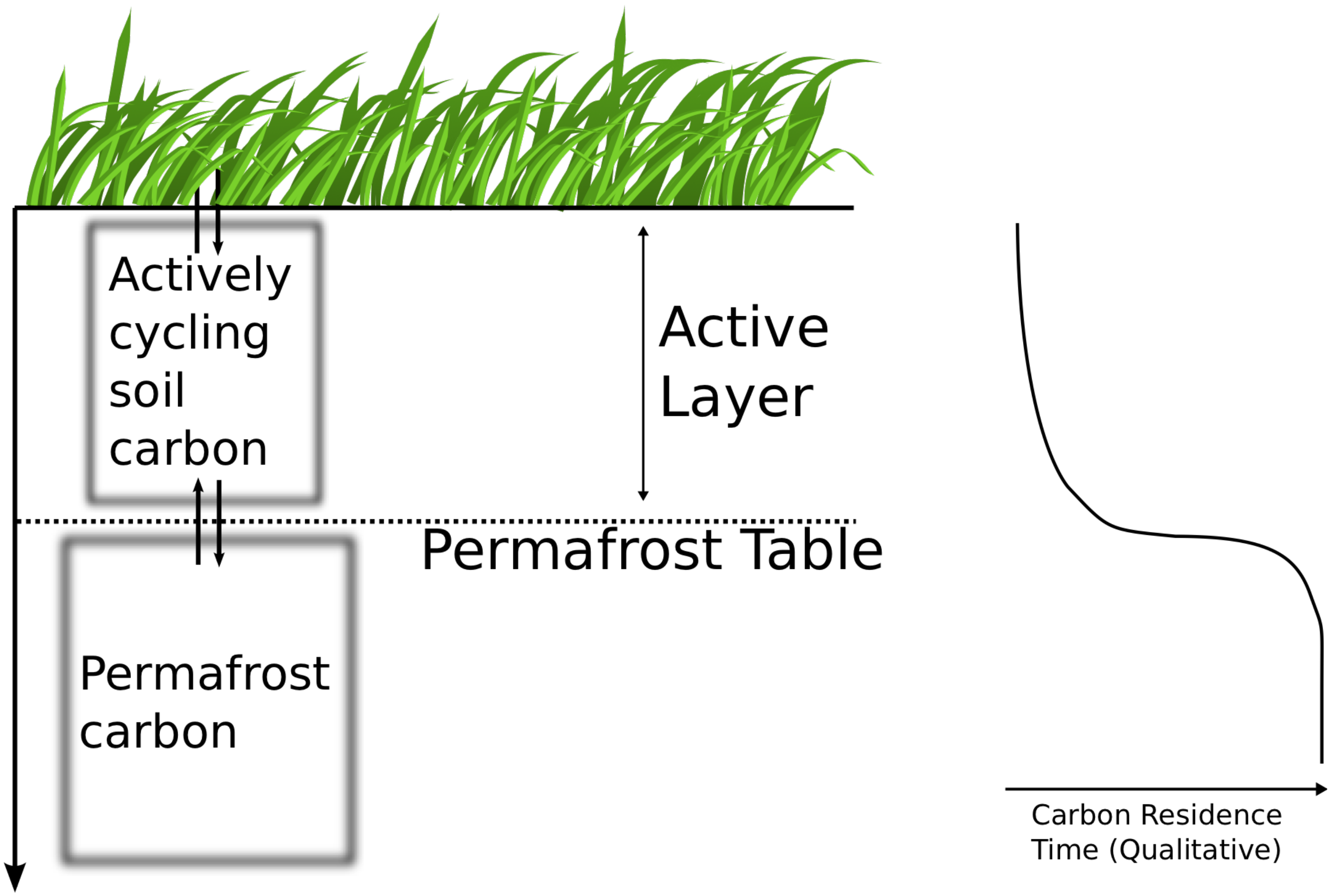


What is Permafrost?

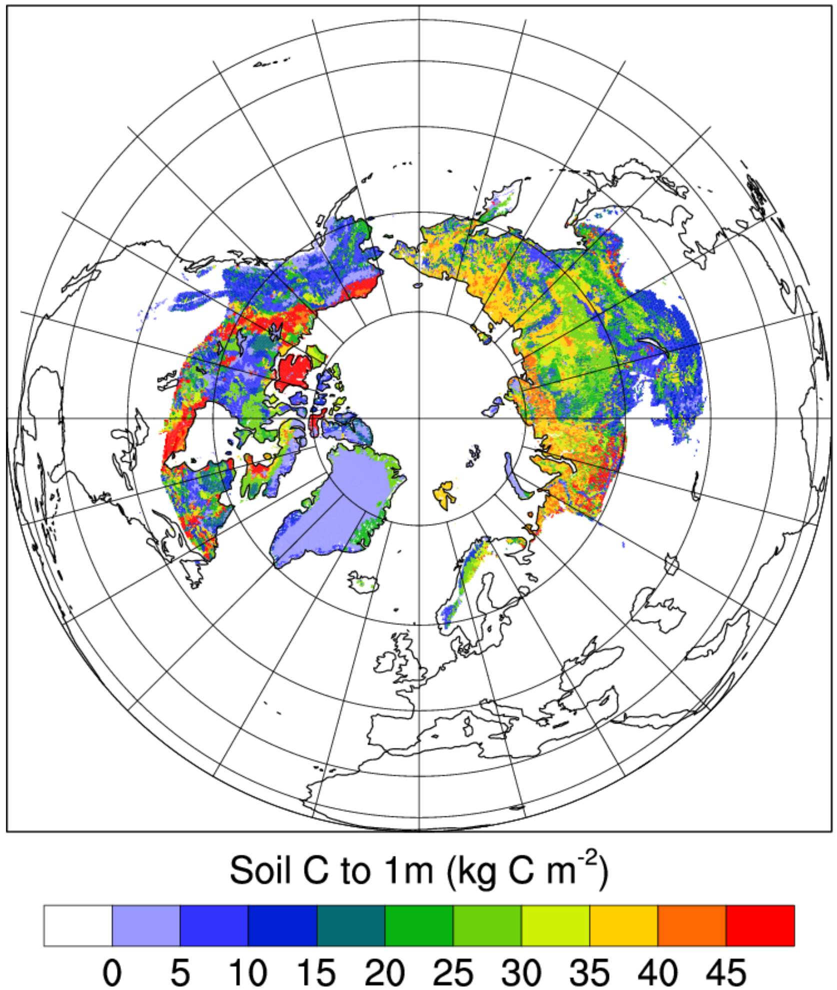




Why so much C in permafrost soils?

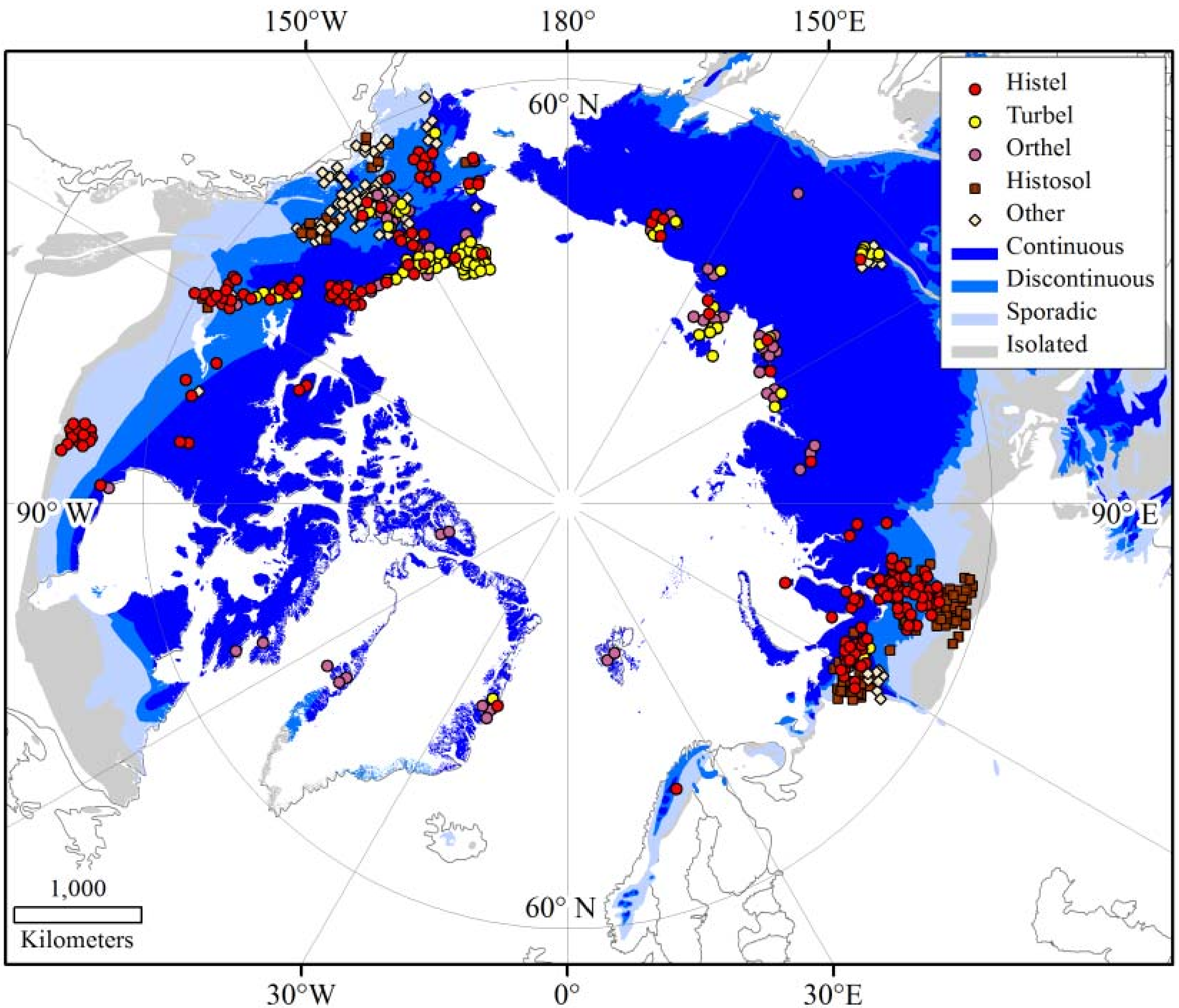


High concentrations of C in permafrost soils, in both surface and deeper soil layers



Data from NCSCD: Tarnocai et al. (2007), Hugelius et al. (2012)

… but there are vast areas, particularly in Siberia, where we have no pedon observations



Hugelius et al., *ESSDD,* 2013

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
- Responsible for formation of much of the frozen C pools in permafrost soils

Photo: *Soil Atlas of the Northern Circumpolar Region*

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

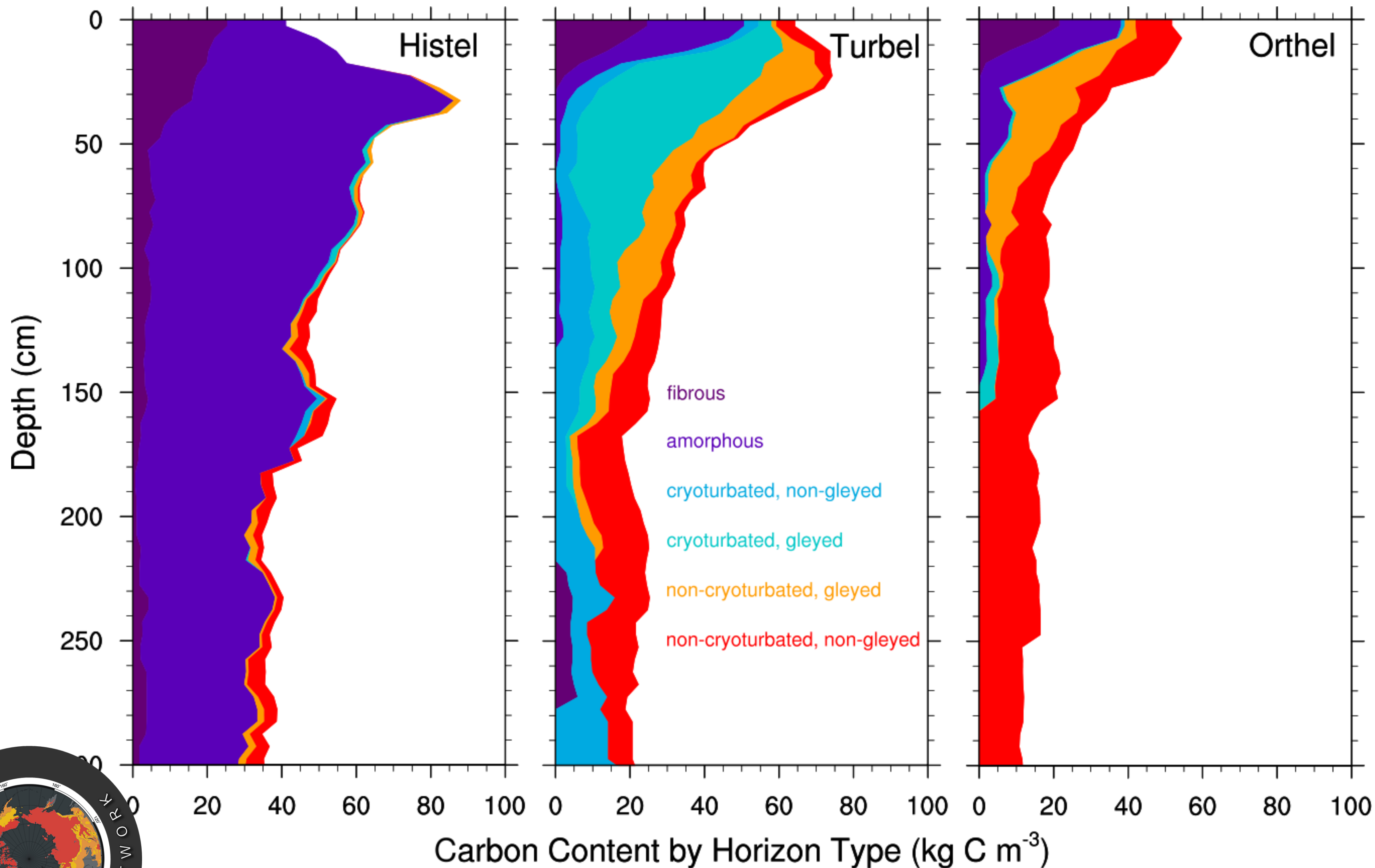
Photo: *Soil Atlas of the Northern Circumpolar Region*

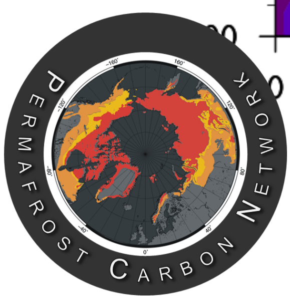
Yedoma: Deep, C-rich and ice-rich Pleistocene permafrost sediments

- 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.

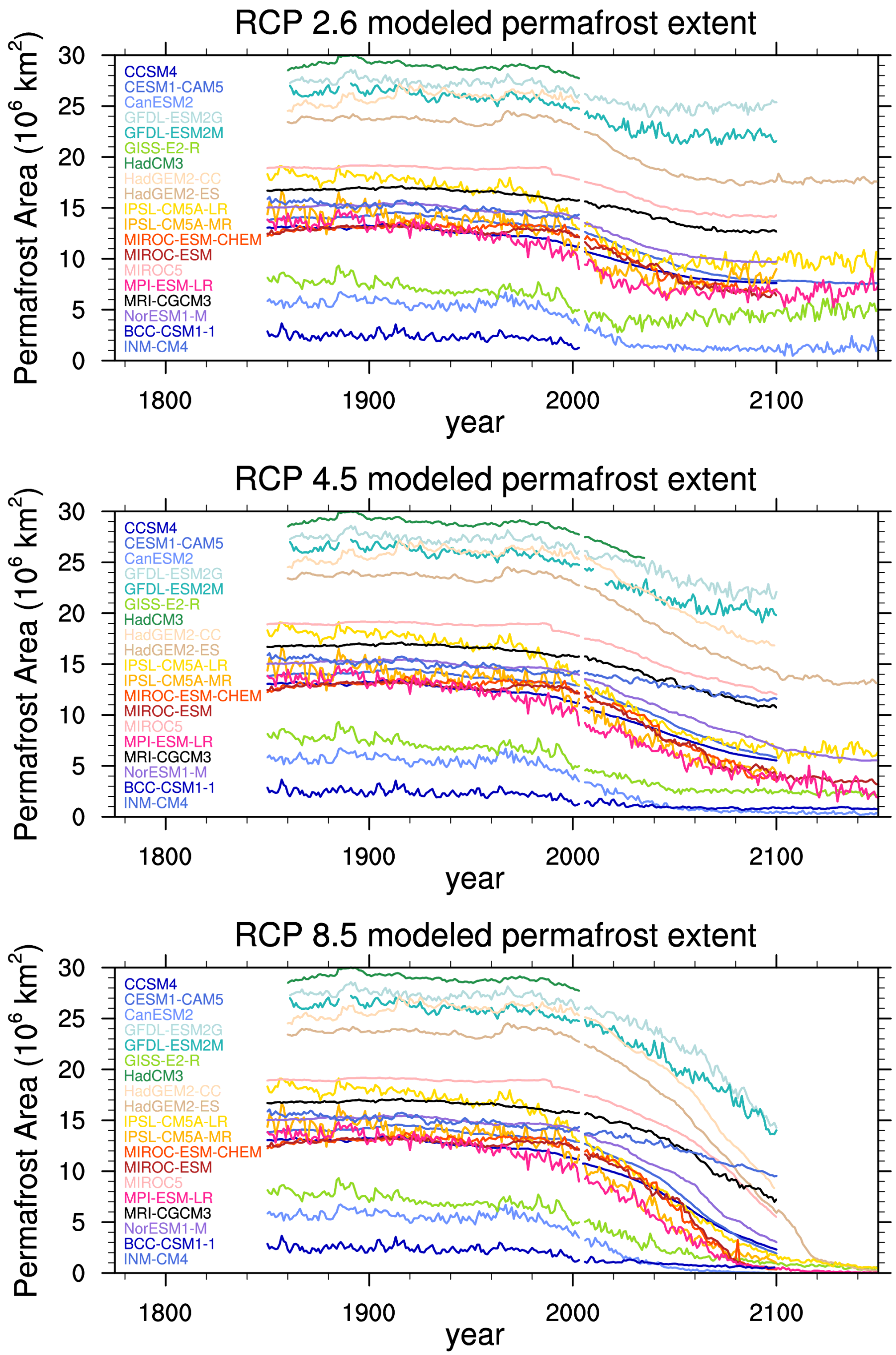




Harden, Koven, et al., *GRL,* 2012

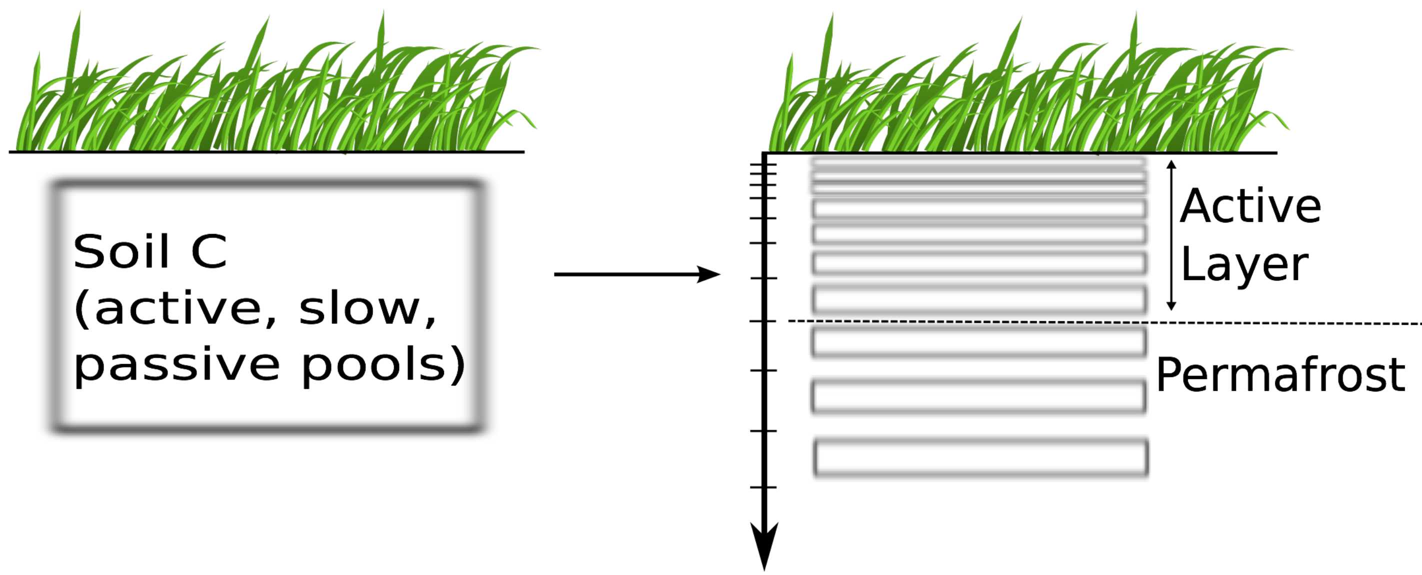
CMIP5 projections of permafrost extent

- Agreement among models that permafrost will thaw with warming
- Large disagreement in initial permafrost areas indicative of shortcomings in soil and snow physics
- None of the models include permafrost C



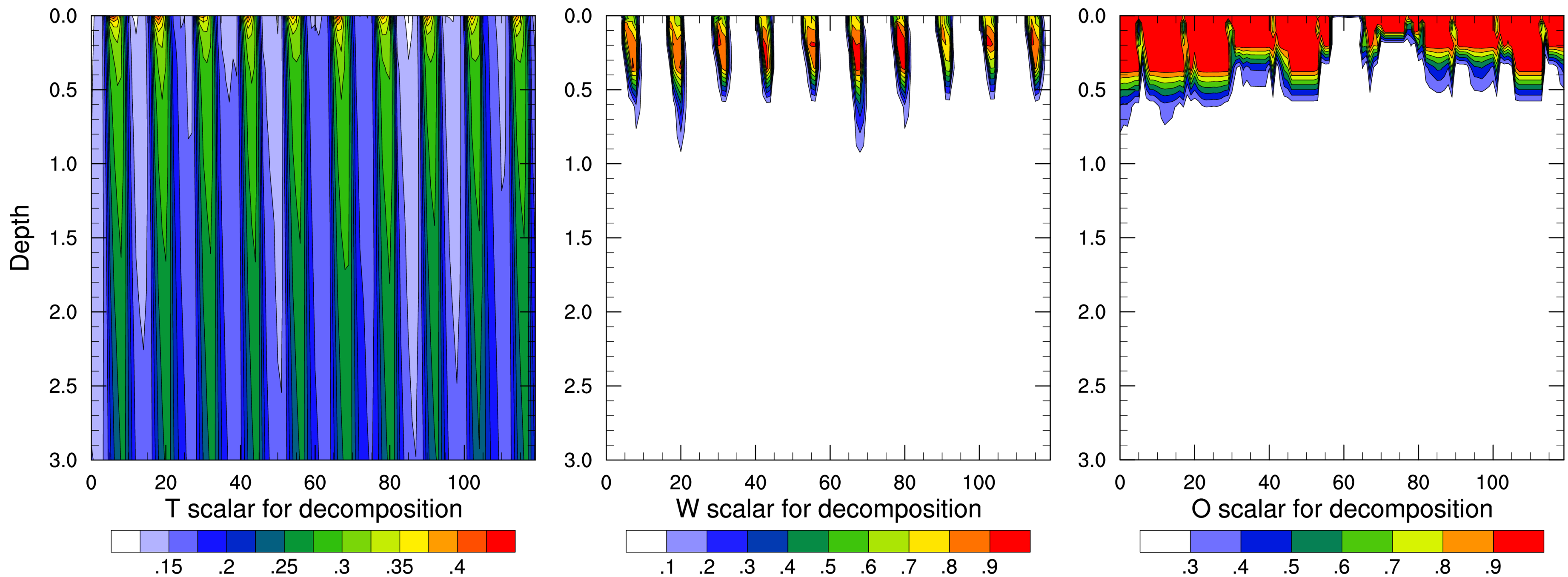
Koven et al., *J. Clim.*, 2012

Need to have model that can track carbon dynamics for both surface and deep soils; here we modify land model to explicitly represent vertical profile of soil carbon and its temperature-, moisture-, and oxygen-dependent residence time



Effect is to make soil carbon cycling depth-dependant with greatly reduced decomposition in permafrost

Example: 10 years at Barrow, Alaska (x-axes below are time in months):
what are the depth-resolved environmental controls on C turnover?

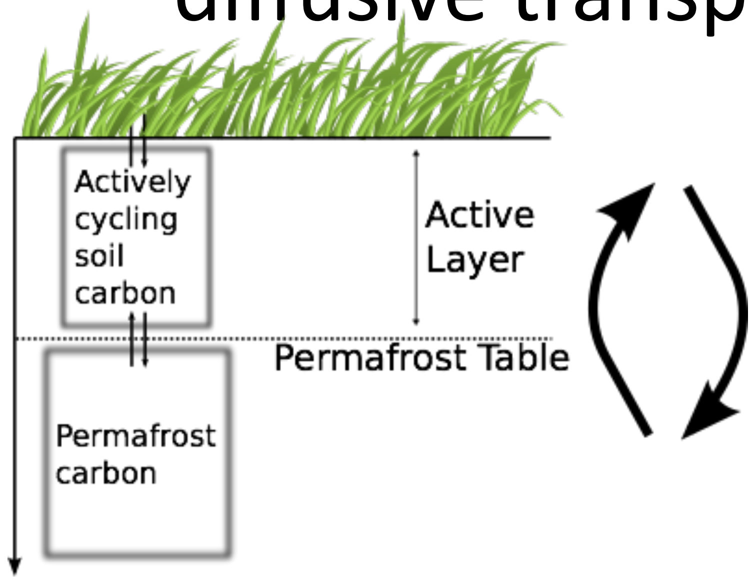


Temperature: Q_{10}=2

Moisture: function of soil (liquid) water tension

Oxygen: supply must meet stoichiometric demand

Vertical mixing by cryoturbation modeled as diffusive transport



$$\frac{\partial C_i(z)}{\partial t} = S(z) - kC_i(z) + \frac{\partial}{\partial z}\left(D(z)\frac{\partial C_i}{\partial z}\right)$$

- Carbon input S, based on rooting profile, only in the active layer
- k, decomposition rate constant, is function of temperature, moisture, oxygen, depth
- Mixing below active layer allows carbon to be subducted into upper permafrost

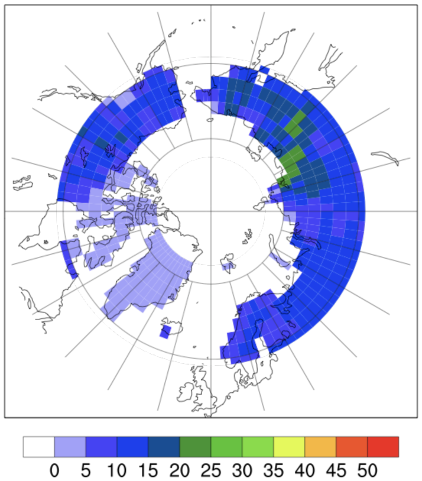
Experiments using ORCHIDEE land model

Experiment Name	**Processes included**	**Parameter values tested**
Control	Standard ORCHIDEE + vertical discretization of soil carbon; improved snow insulation and ice latent heat	
Freeze	Control + Inhibition of soil C decomposition when frozen	frozen resp func: Exponential, Q_{10}=100,1000 Linear, T_0 = -1,-3
Permafrost	Freeze + Insulation by soil organic matter, vertical mixing of soil carbon, and Yedoma	Diffusion constant D= $1m^2/100yr$, $1m^2/1000yr$
Heating	Permafrost + exothermic heat release with decomposition	Heat release term = 20, 40 MJ/kg C for active pool C

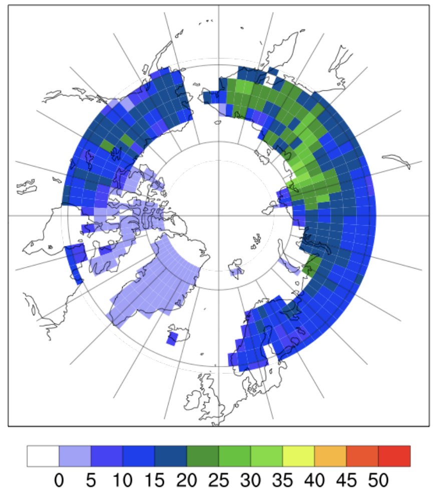
Koven, et al., *PNAS,* 2011

Initial steady-state carbon stocks (kg C m^{-2}) to 1m

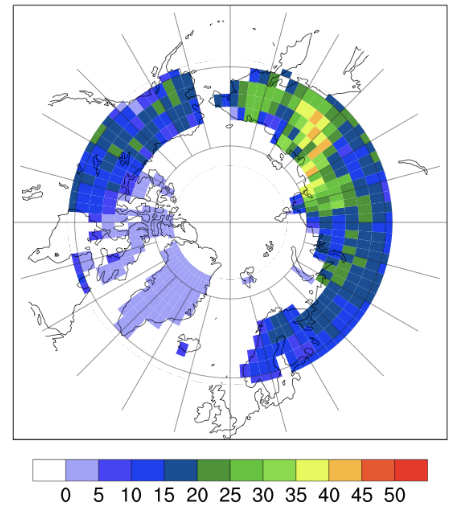
Control



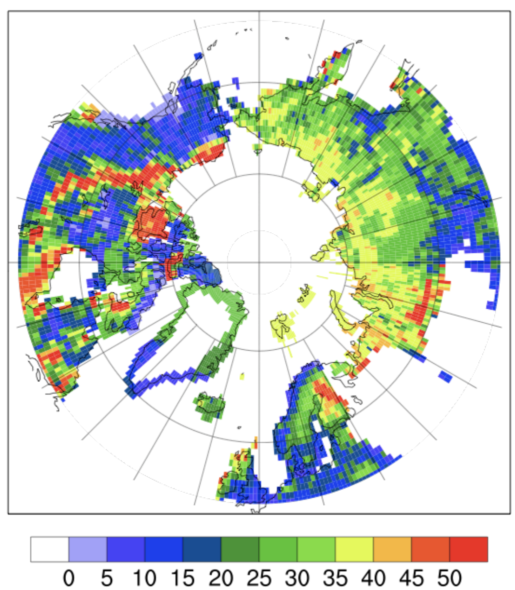
Freeze



Permafrost



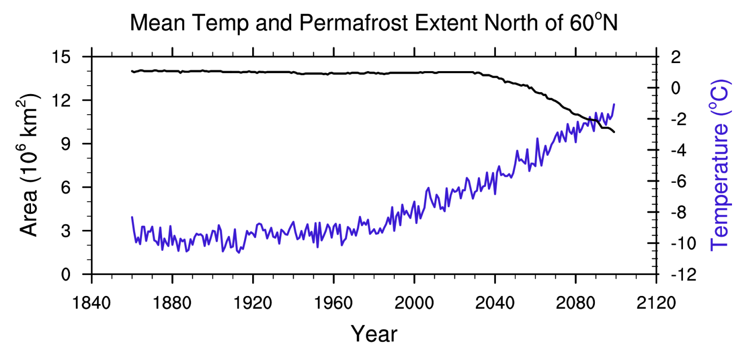
Initial carbon stocks increase from 200 Pg to 500 Pg for polar region to 3m depth; however still underestimate because peatlands and organic soils not included

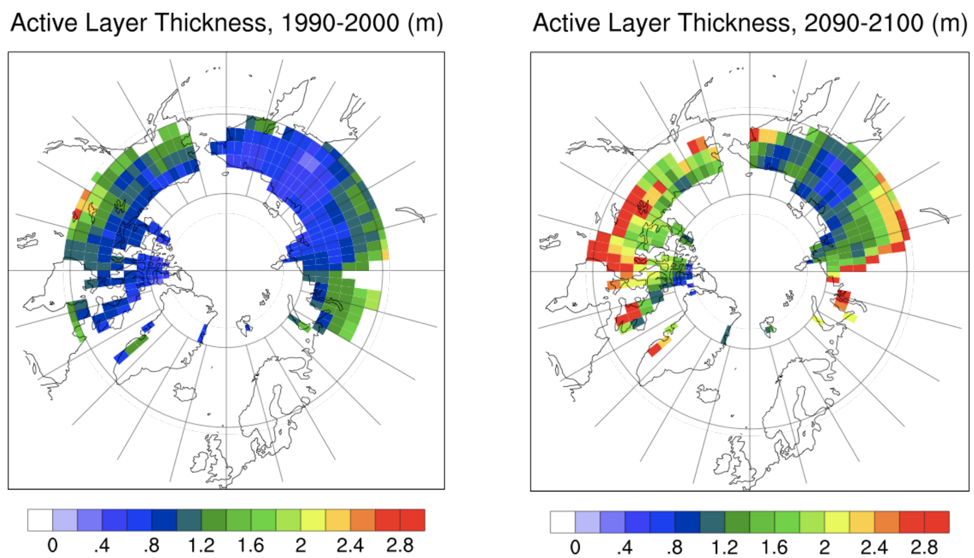


Observations (Tarnocai et al., 2007)

Koven, et al., 2011

Future climate change scenario: ORCHIDEE run offline, forced by IPSL CM4 model anomalies (relative to CRU) under transient (SRES A2) warming from 1860 - 2100





Large Warming at High Latitudes

30% reduction in permafrost extent by 2100

Significant thickening of active layer in remaining permafrost areas

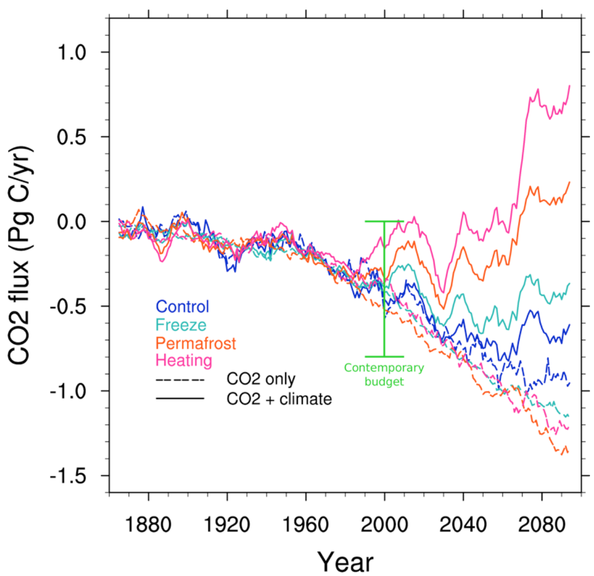
Koven, et al., 2011

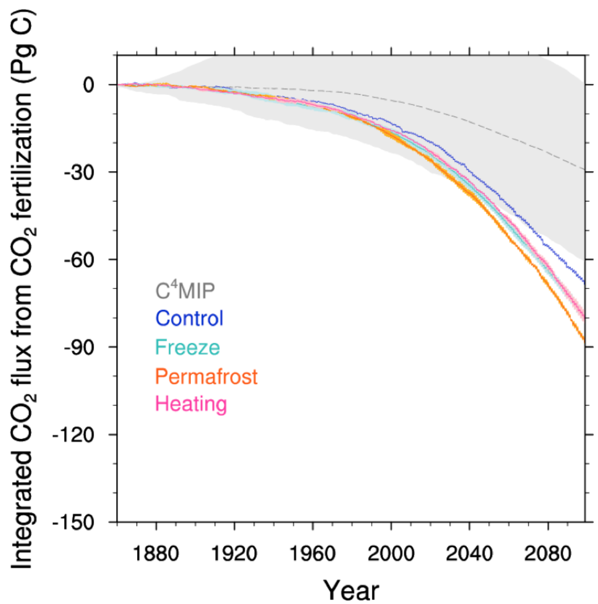
21st century integrated CO_2 balance of high latitudes

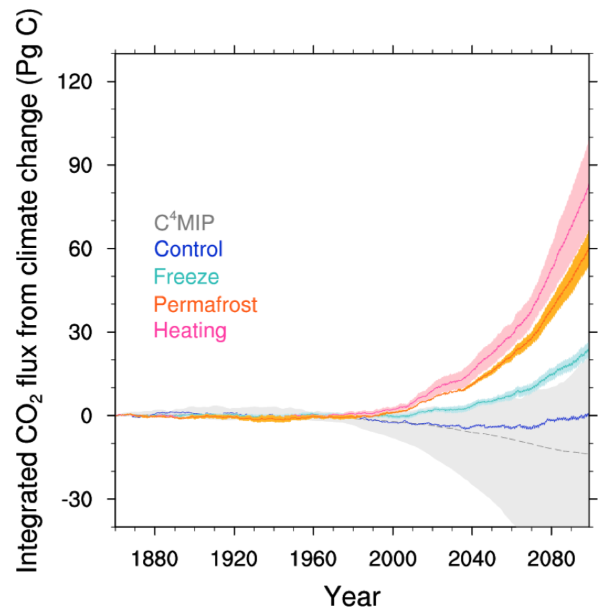
CO2 balance

Integrated change due to CO2 fertilization

Integrated change due to warming







In Permafrost experiment, high latitudes shift from C sink to source by 2100

Koven, et al., 2011

Literature estimates of carbon loss (PgC)

62 ± 6 ORCHIDEE (Koven et al., 2011)

100 ± 40 SibCASA (Schaefer et al. 2011)

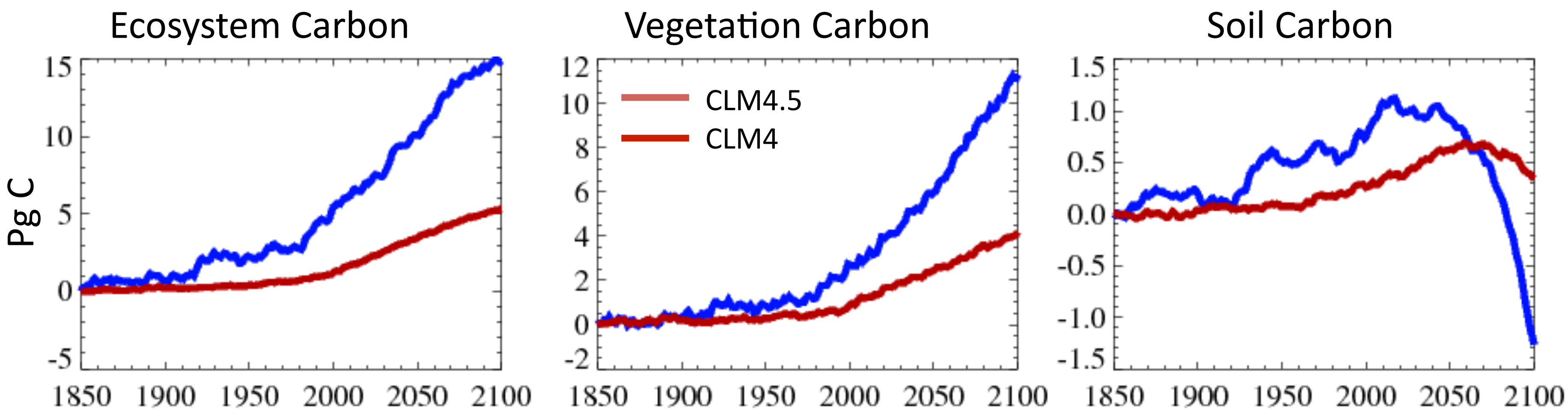
72 ± 40 MAGICC (Deimling et al., 2011)

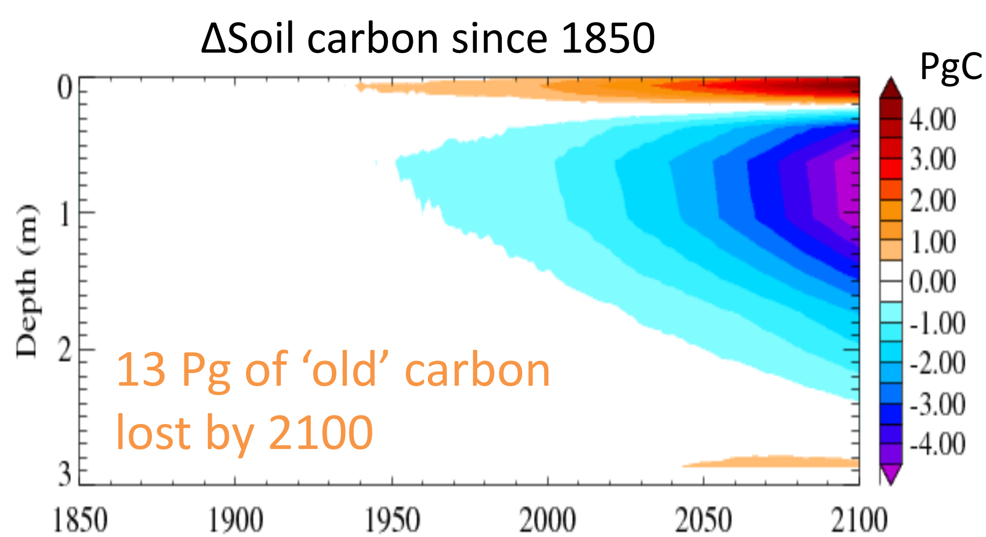
12 ± 6 TEM (Zhuang et al. 2006)

Current research: CLM4.5

- Included layered soil BGC into CLM4.5
- More complex coupling between hydrology and soil C
- C-N feedbacks: to what extent can increased mineralization stimulate productivity and offset C losses?
- Future scenario experiments still ongoing…

Carbon stock trends in permafrost zone

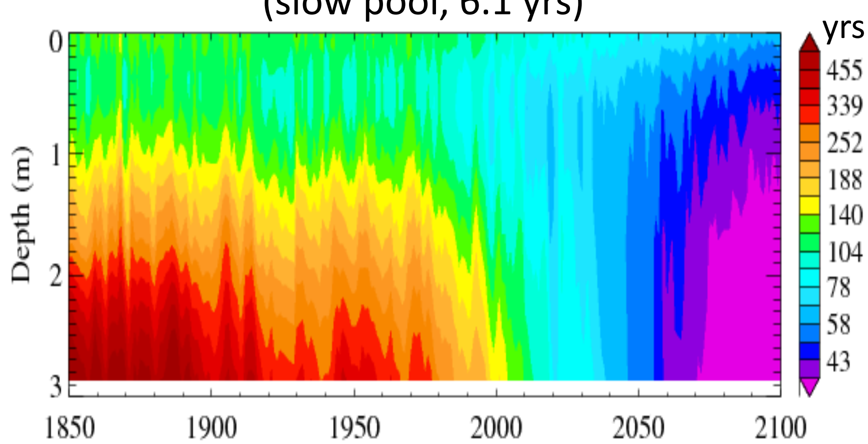




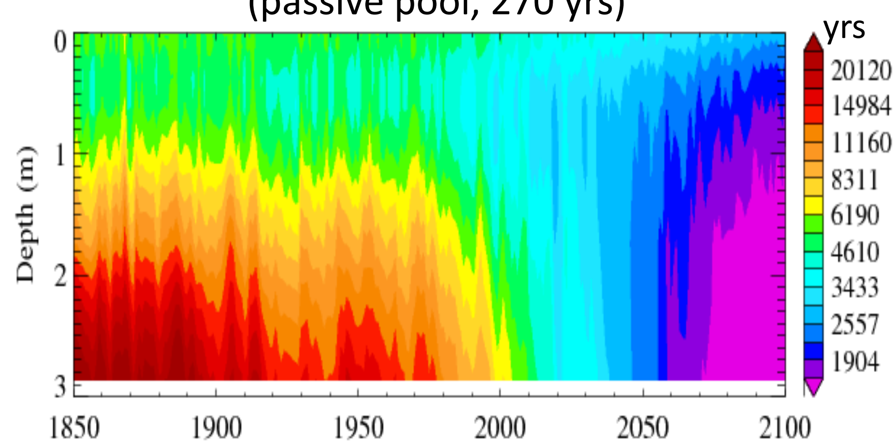
Figures: D. Lawrence

Long term permafrost carbon vulnerability

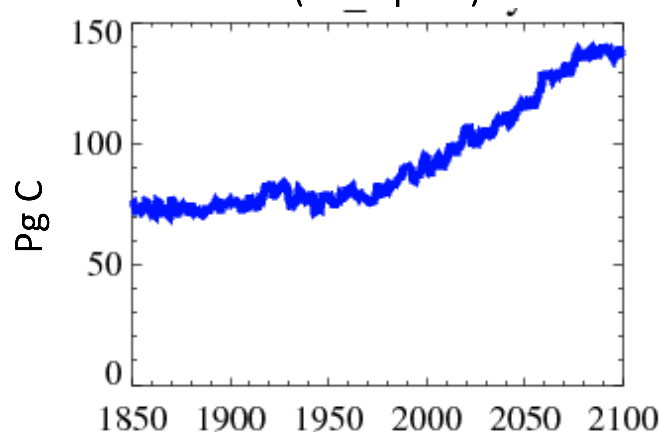
Soil carbon turnover timescale
(slow pool, 6.1 yrs)



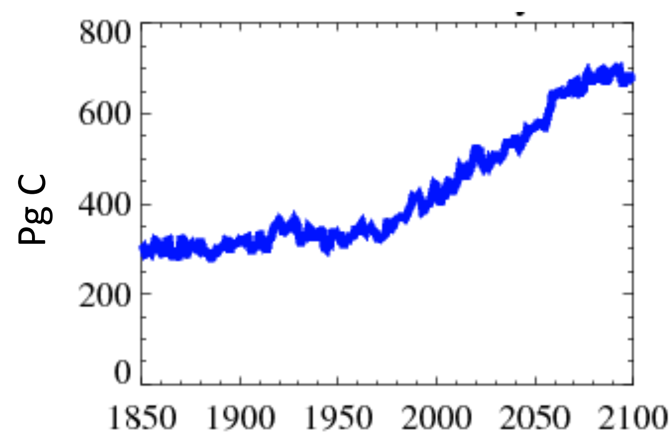
Soil carbon turnover timescale
(passive pool, 270 yrs)



Soil carbon in active layer
(slow pool)



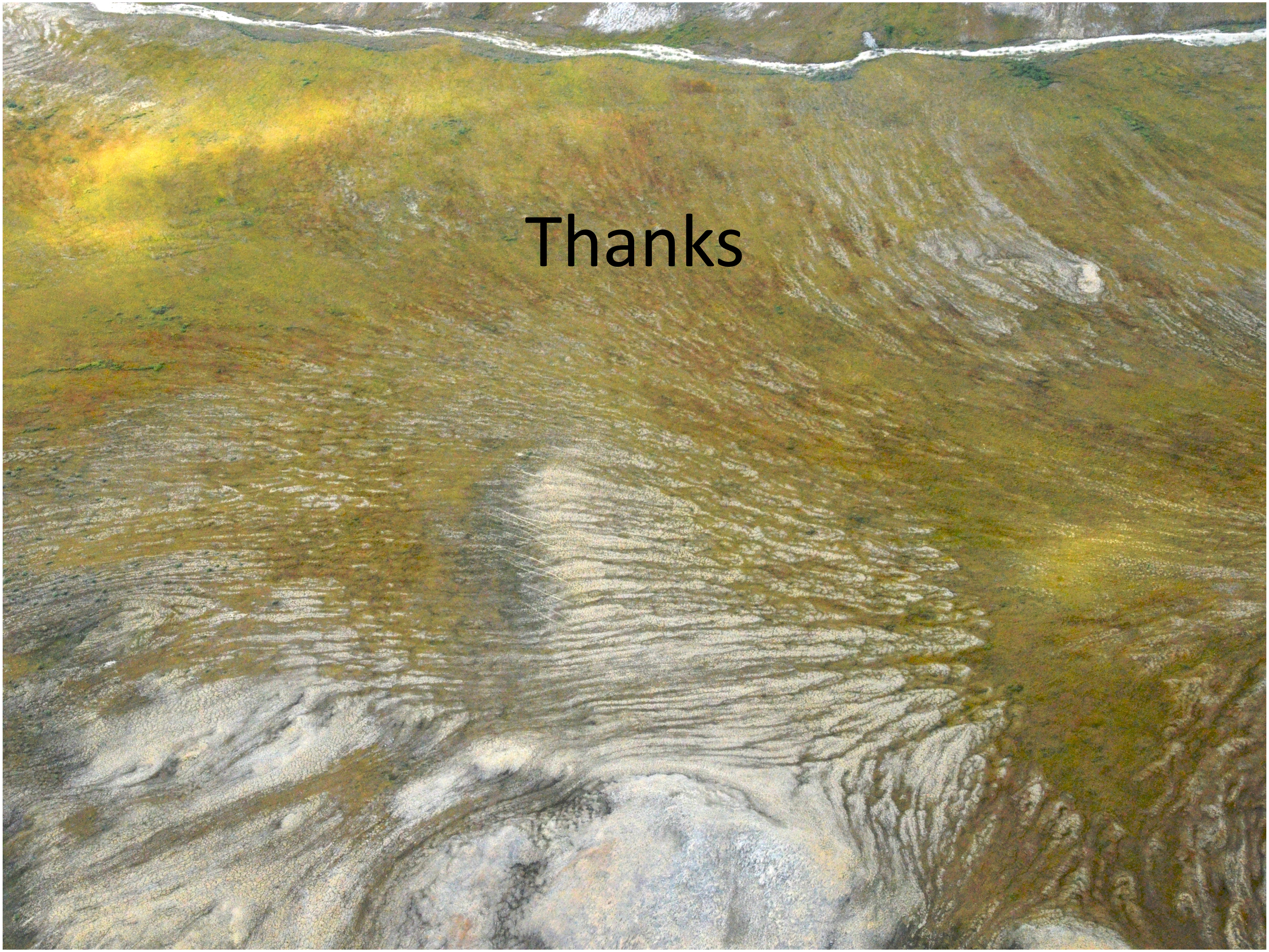
Soil carbon in active layer
(passive pool)



Figures: D. Lawrence

Conclusions—Part 2

- Permafrost C can be represented in ESMs by considering the vertical profiles of C turnover processes and the detailed linkages between soil biogeophysics and soil biogeochemistry
- Including these processes allows a C-only model to shift from negative C-climate feedback to a positive C-climate feedback over the 21st century
- Including N feedbacks may partially offset and/or delay this shift; uncertainty is large…


Thanks