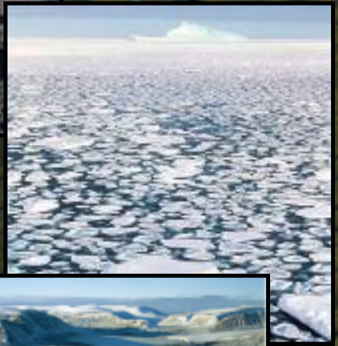
Permafrost-climate feedbacks in CESM/CLM



David Lawrence

Andrew Slater[2], Sean Swenson[1], Charlie Koven[3], Bill Riley[3], Zack Subin[3], Hanna Lee[1] and the CESM LMWG

[1]NCAR Earth System Lab, Boulder, CO

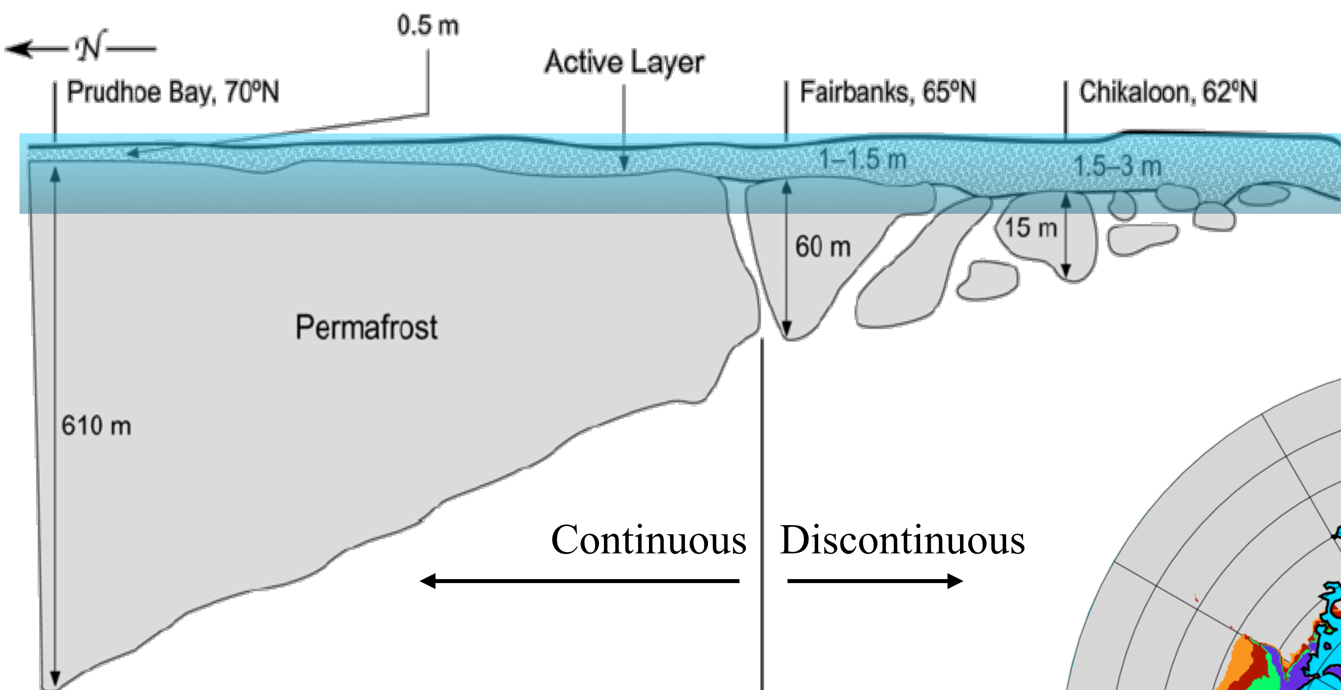
[2]NSIDC, Boulder, CO

[3]LBNL, Berkeley, CA

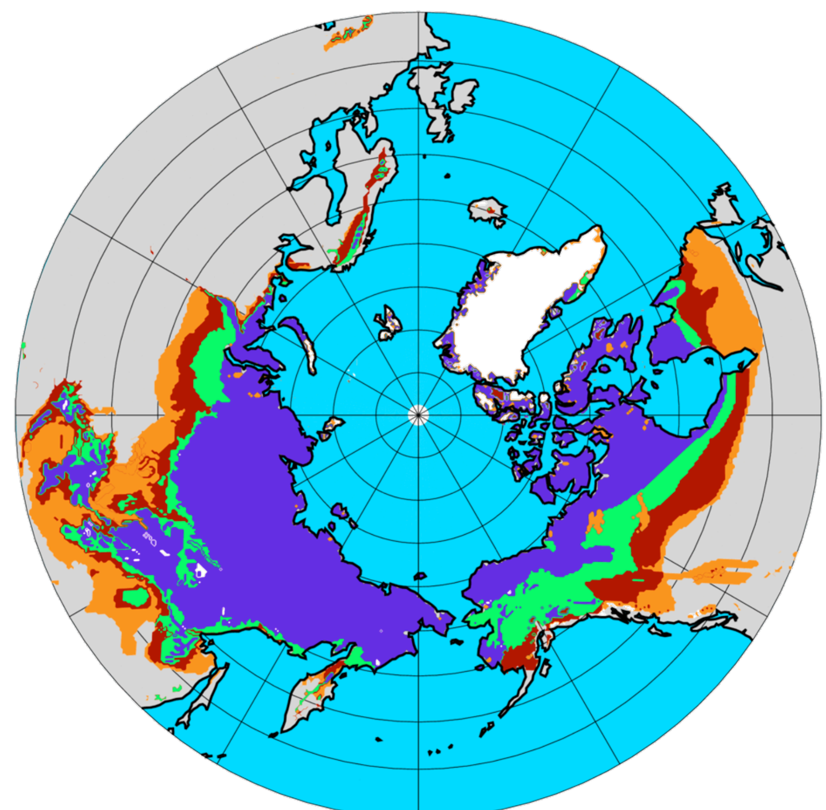
NCAR is sponsored by the National Science Foundation


What is permafrost?
Definition: Soil or rock that remains below 0°C for two or more consecutive years

Global Permafrost Distribution



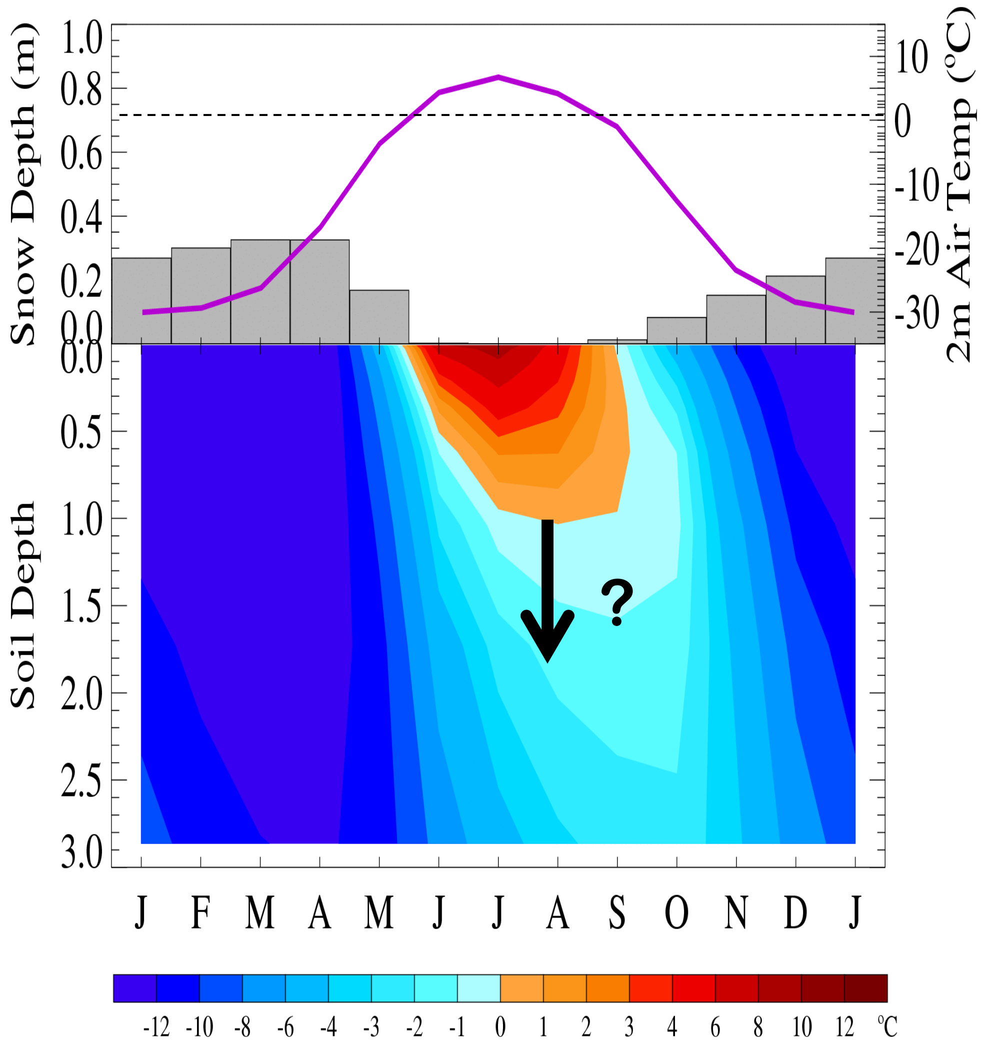
IPA Permafrost Distribution Map



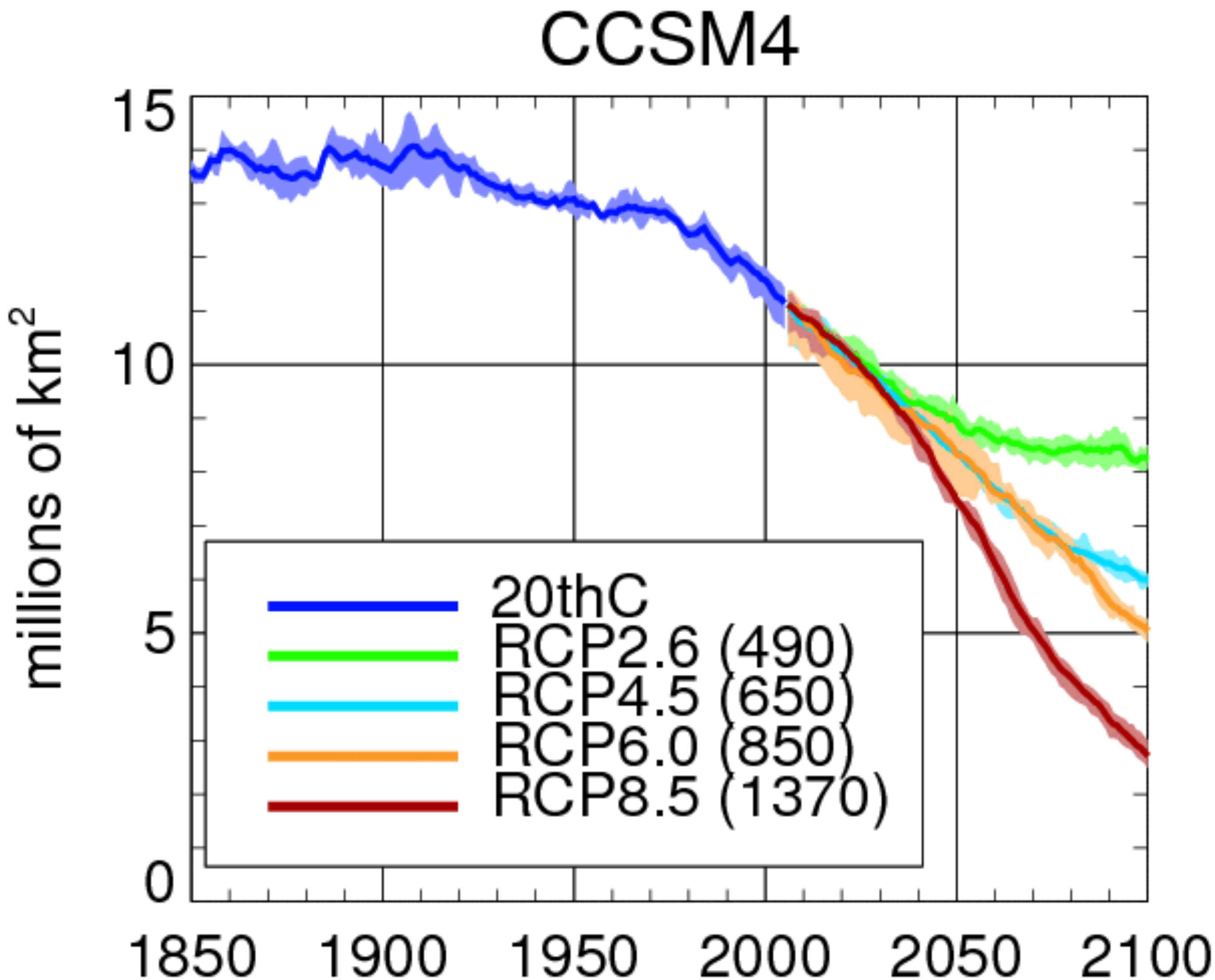
- Continuous (90 – 100% coverage)
- Discontinuous (50 – 90%)
- Sporadic (10 – 50%)
- Isolated (0 – 10%)

Brown et al. 1998

Active Layer Thickness (ALT)

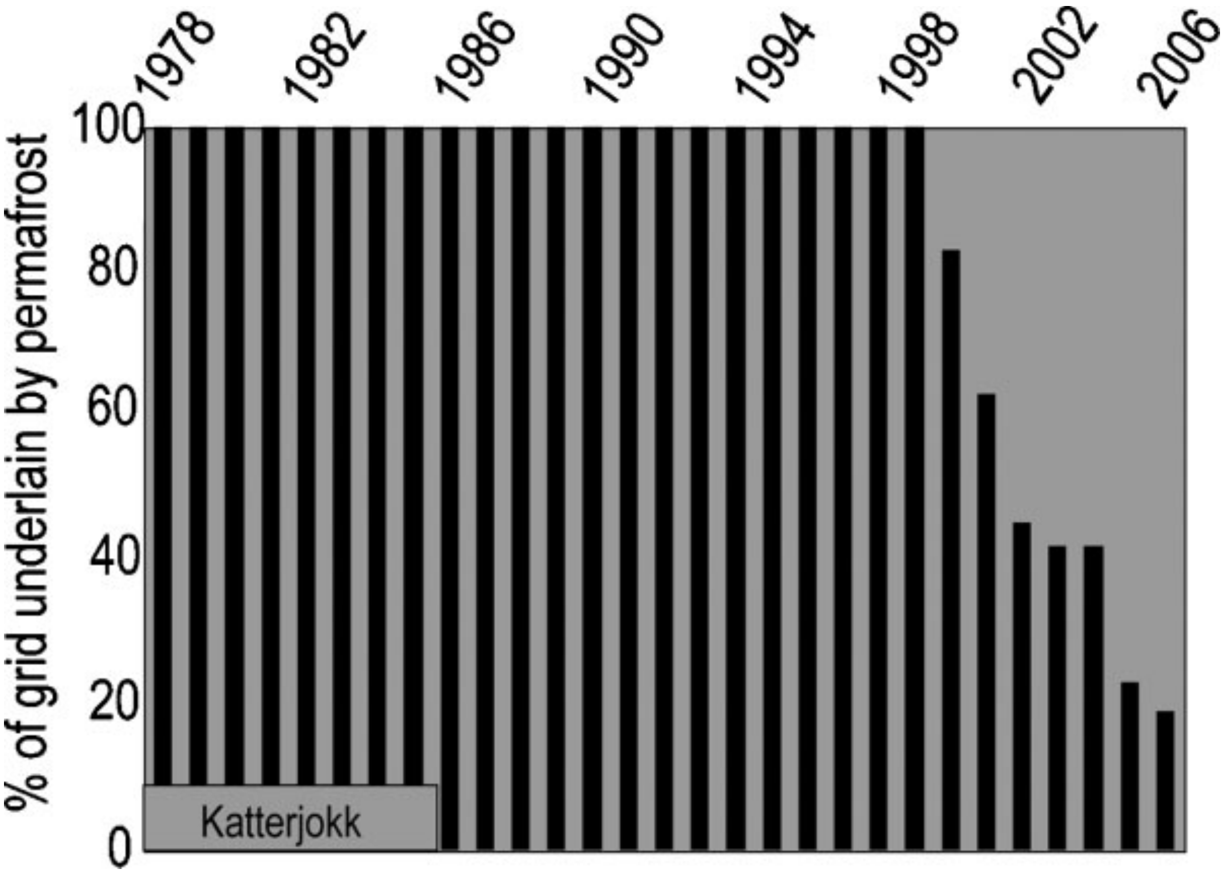


Projections of near-surface permafrost thaw



Lawrence and Slater, 2005; Lawrence et al., J.Clim, 2012

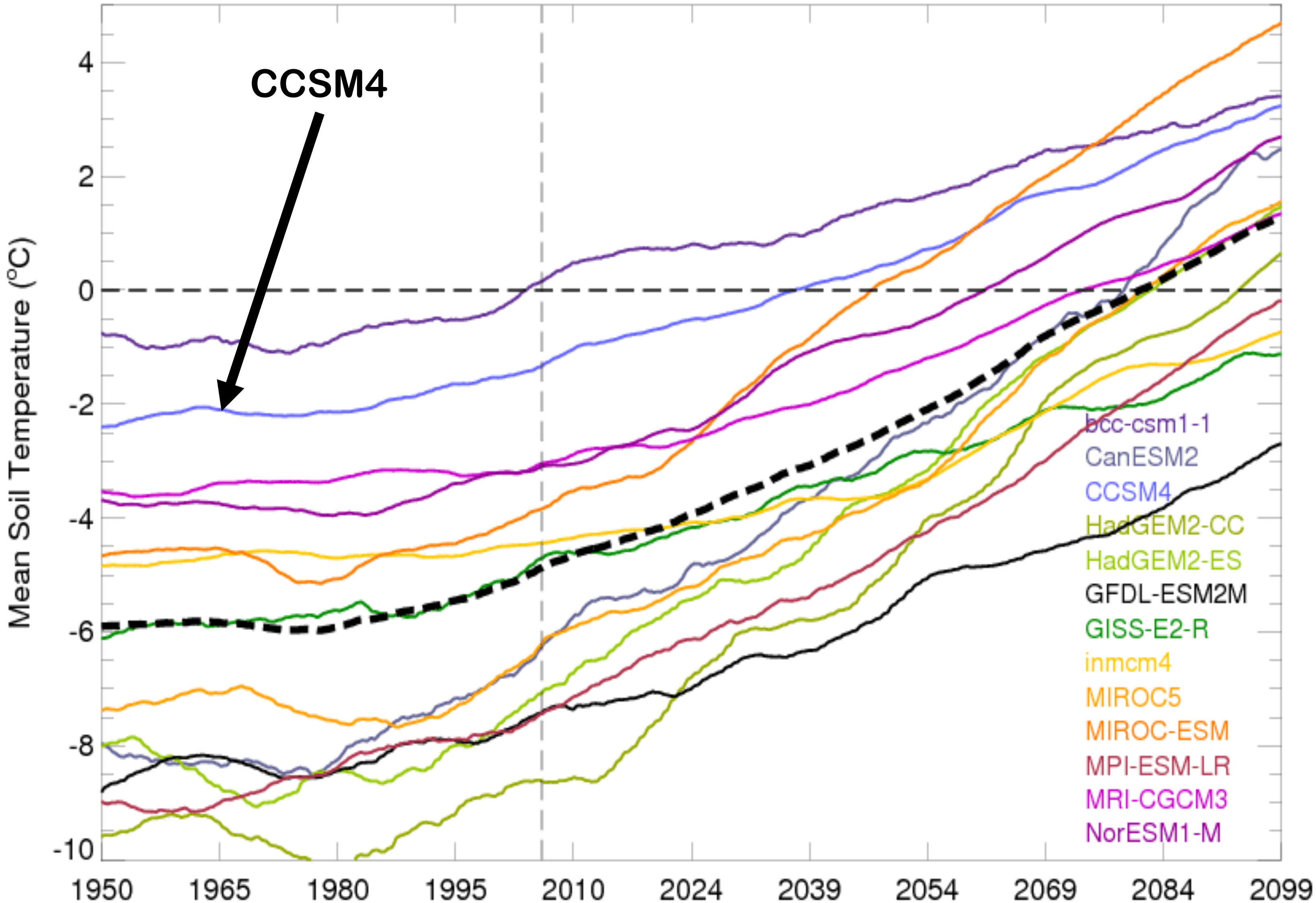
Observed rapid permafrost degradation



IPY synthesis: Widespread warming and thawing
(Romanovsky et al. 2010)

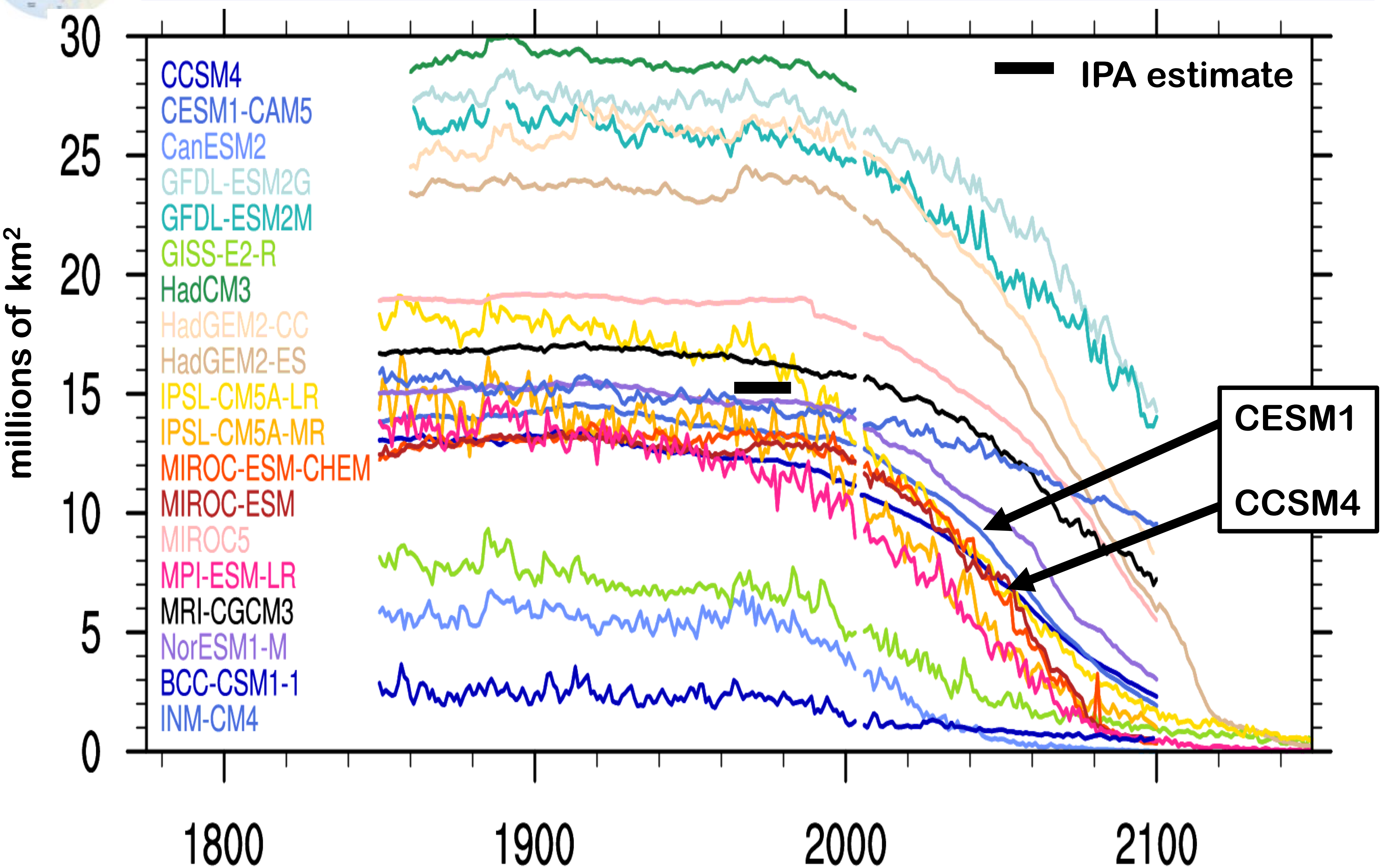
Akerman and Johansson, 2008

CMIP5 Models: Mean Soil Temperature across permafrost domain @ 3.3m (RCP 8.5)



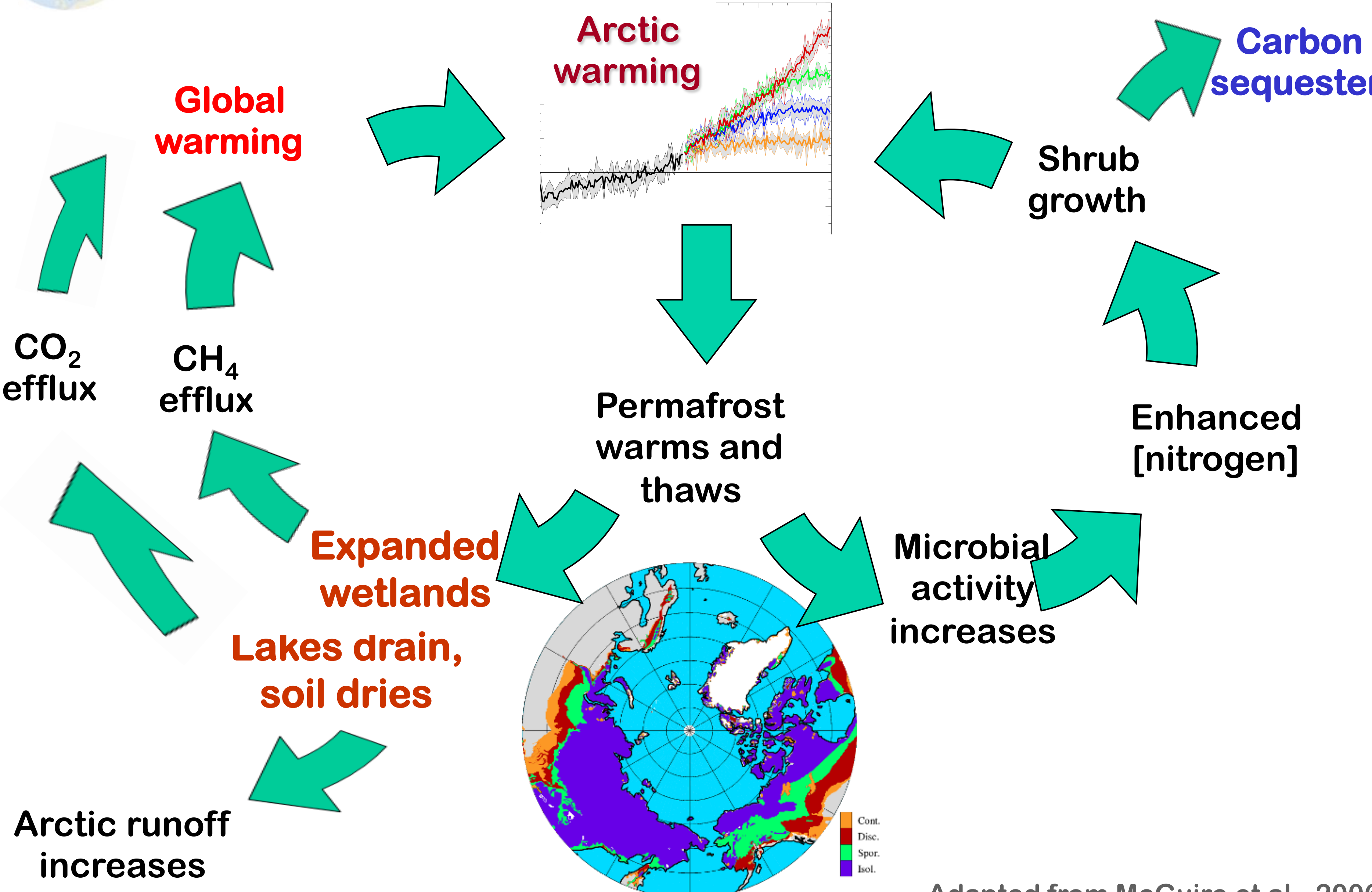
Slater and Lawrence, J.Clim, 2013

CMIP5 Models: Near-surface permafrost extent (RCP 8.5)



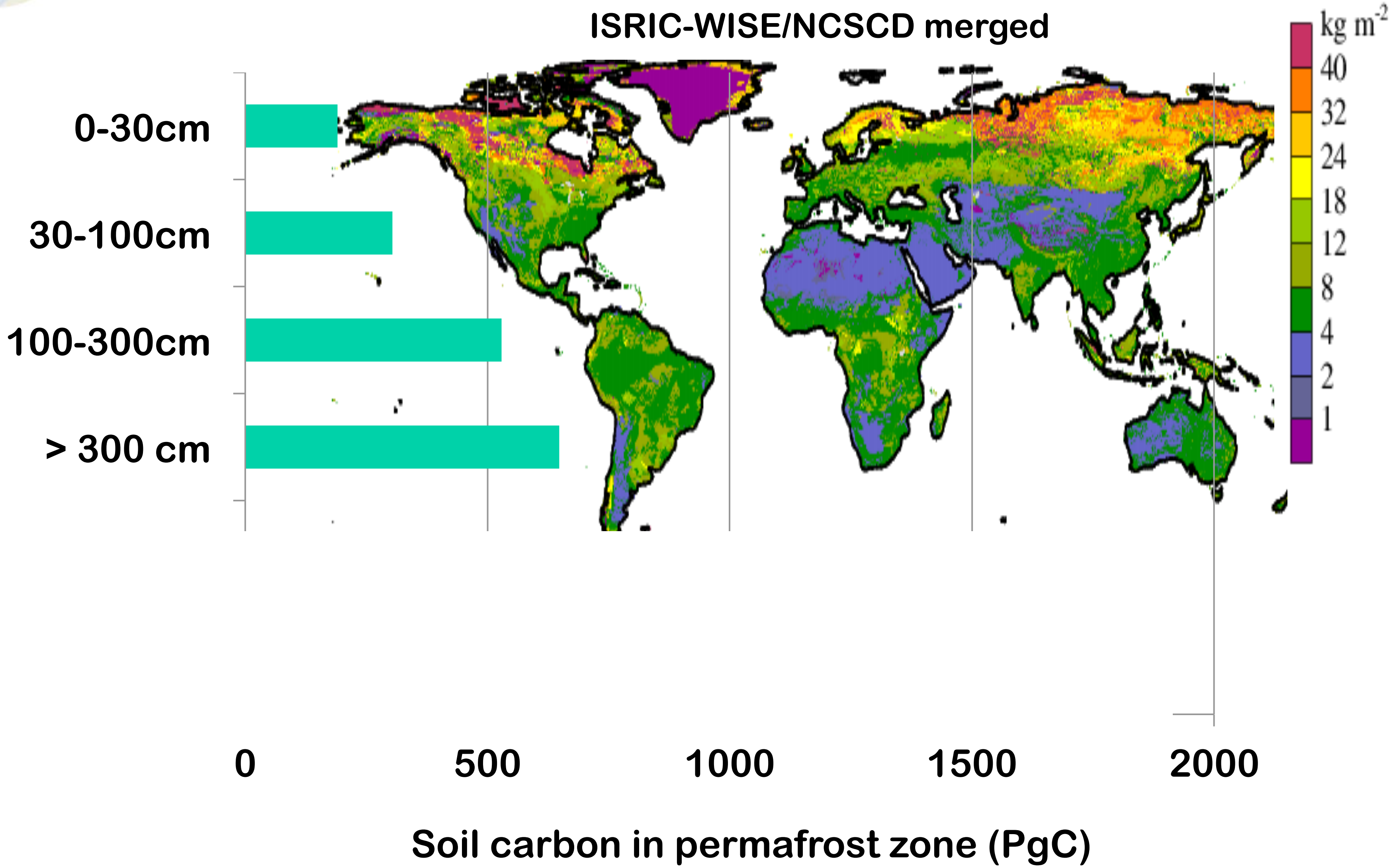
Koven et al., J.Clim, 2013; Slater and Lawrence, 2013

Potential Arctic terrestrial climate-change feedbacks



Adapted from McGuire et al., 2006

Soil carbon in permafrost zone

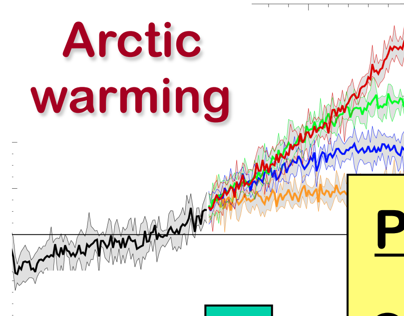


Tarnocai et al. 2009

Potential Arctic terrestrial climate-change feedbacks

Global warming

Arctic warming



Carbon sequester

Permafrost-Carbon feedback

Carbon stocks in permafrost-affected soil

~ 1700 PgC (Tarnocai et al., 2009)

Atmos carbon content

~ 750 PgC + ~9 PgC yr^{-1}

CH_4 or CO_2?: CH_4 is ~25x stronger GHG than CO_2

Permafrost warms and thaws

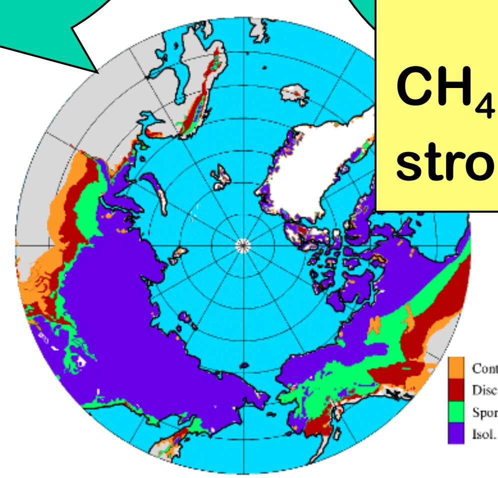
Expanded wetlands

Lakes drain, soil dries

Arctic runoff increases

CO_2 efflux

CH_4 efflux



Adapted from McGuire et al., 2006

What happens to soil carbon as soil warms and permafrost thaws?

dry, well-drained soil

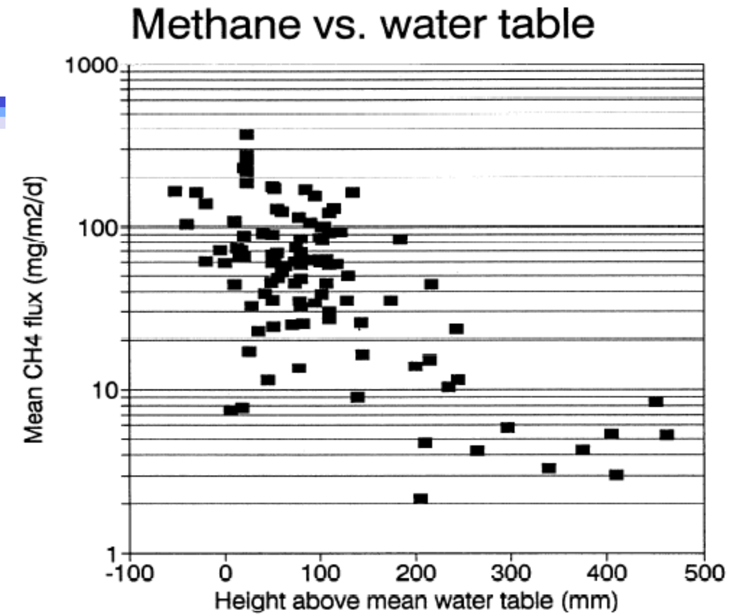
aerobic decomposition

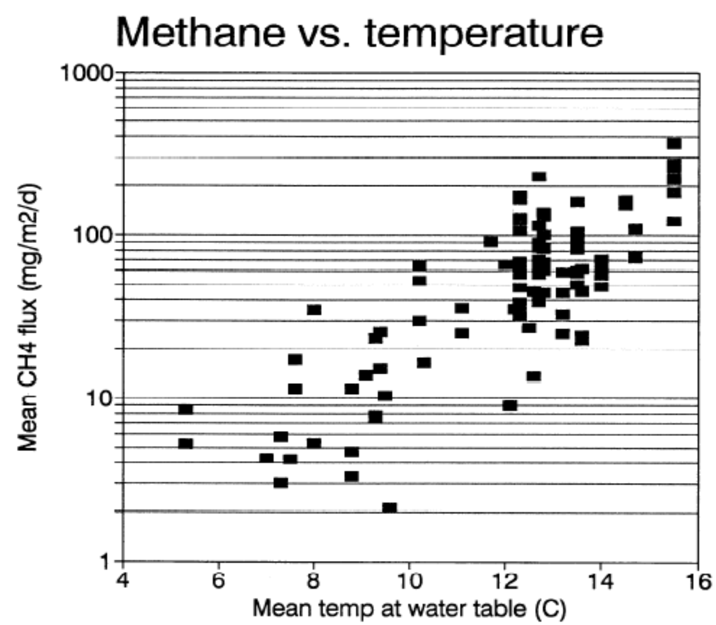
→ CO_2 emissions

increased wetlands and warmer soil

anaerobic decomposition

→ CH_4 production (25x GWP)

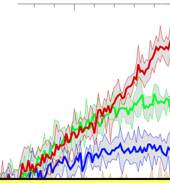




Bubier et al. 1995

Potential Arctic terrestrial climate-change feedbacks

Arctic warming



Global

Carbon sequester

What is the integrated effect of Arctic land feedbacks?

Is it + or — ?

The hydrology and permafrost-carbon feedbacks are not represented in CMIP3 or CMIP5 era Earth System models

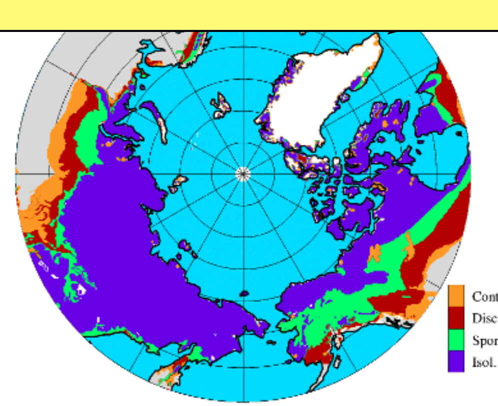
Limits our capacity to provide quantitative analysis on a key vulnerability in Earth system

CO_2 efflux

Lakes drain, soil dries

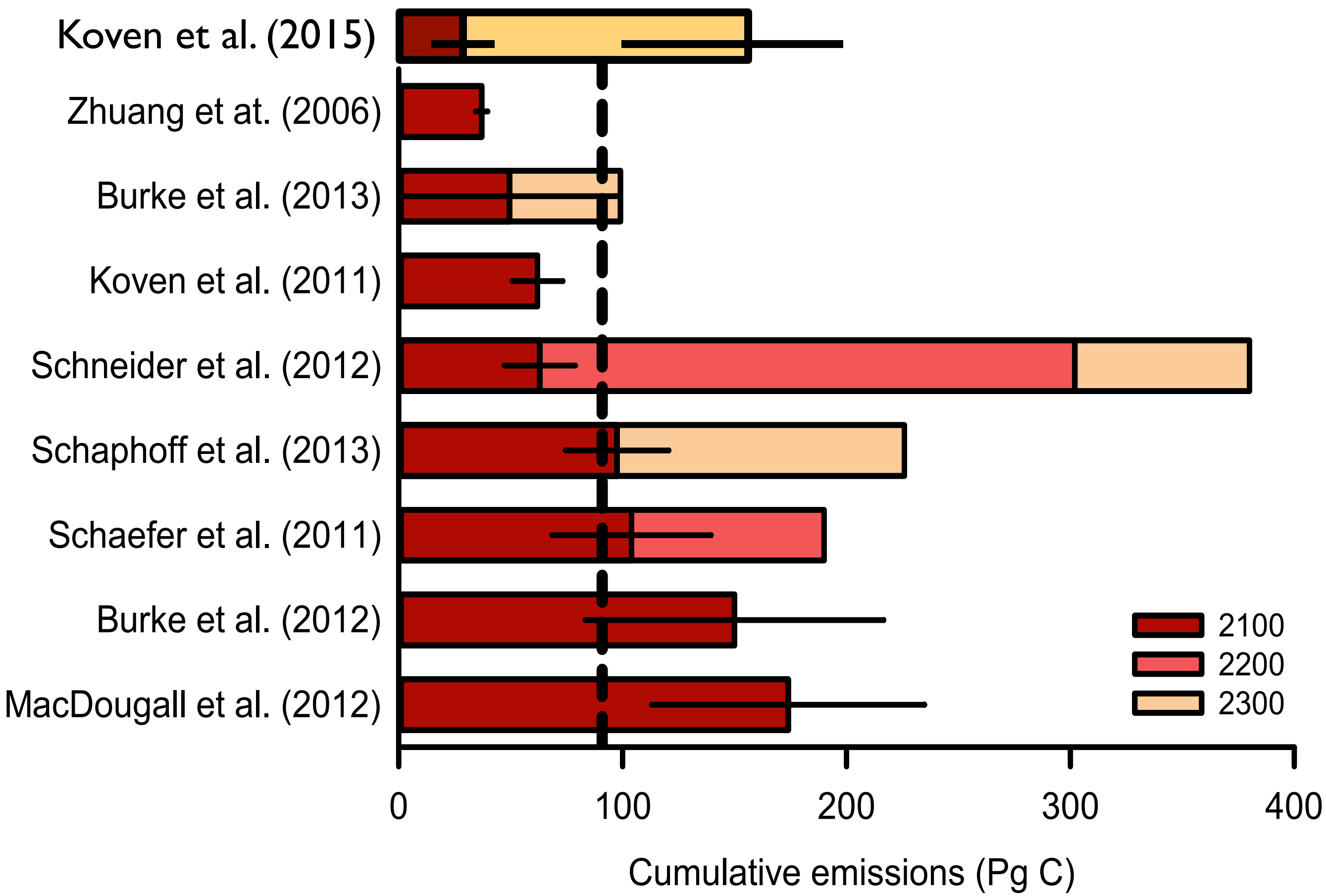
increases

Arctic runoff increases



Adapted from McGuire et al., 2006

Model projections of permafrost carbon emissions



By 2100 (RCP8.5)
Ensemble Mean
92±17 Pg C
5-15% of initial pool

Timescale
60% of permafrost carbon emissions after 2100

Context
Similar magnitude to land use change

Schaefer et al. 2014 Environmental Research Letters

LMWG Progress towards goal of representing permafrost feedbacks in CLM4.5

Soil biogeochemistry: vertically resolved soil carbon model; accounts for limitations on decomposition in cold/saturated conditions

CLM-CNDV (dynamic vegetation): added shrub PFT

CH_4 emission model:

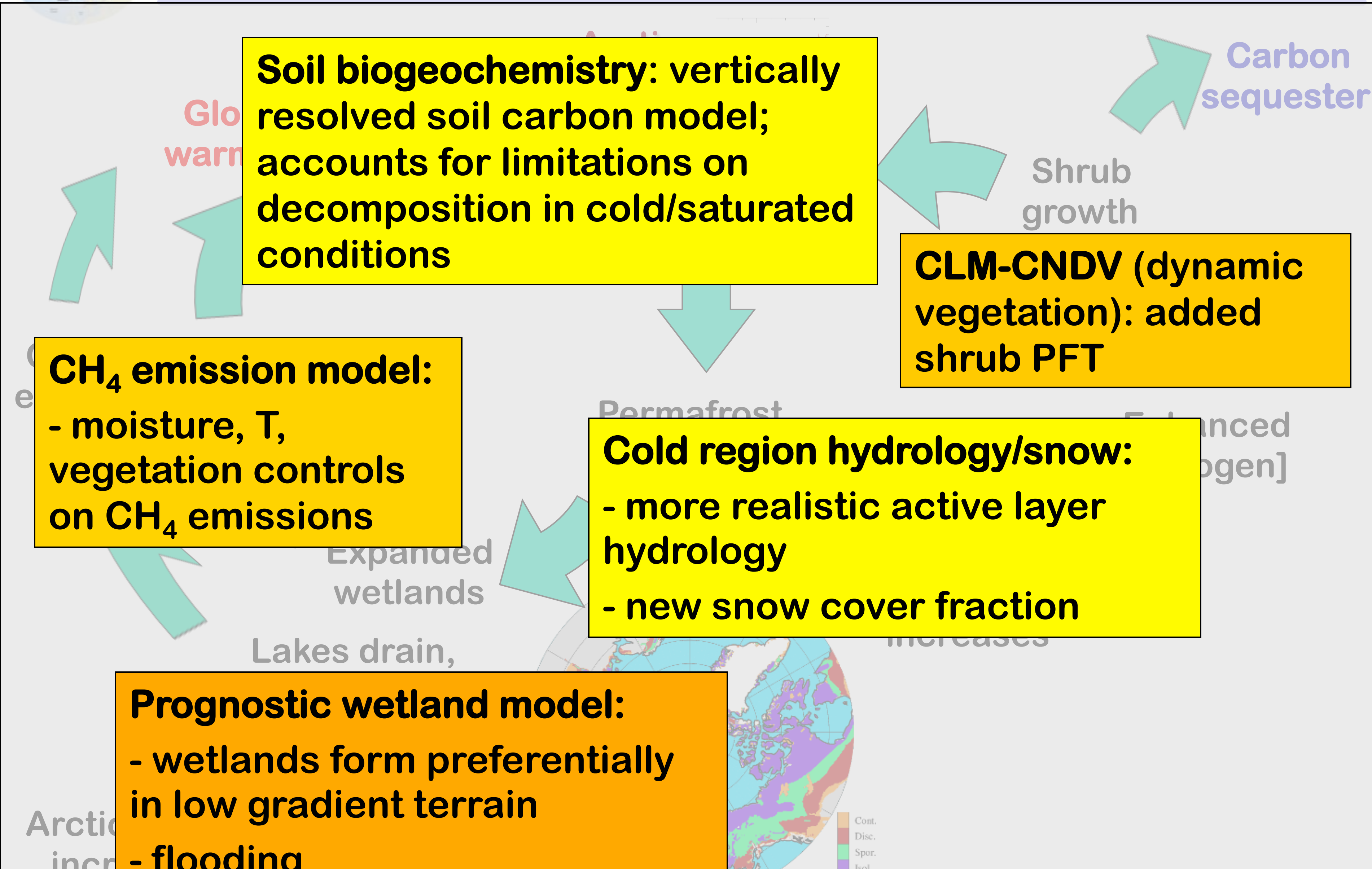
- moisture, T, vegetation controls on CH_4 emissions

Cold region hydrology/snow:

- more realistic active layer hydrology
- new snow cover fraction

Prognostic wetland model:

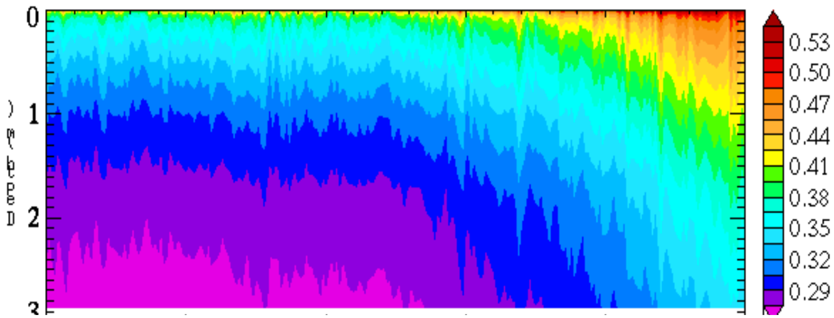
- wetlands form preferentially in low gradient terrain
- flooding



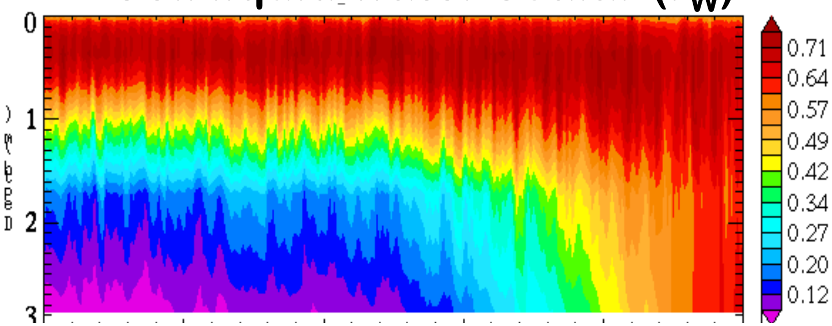
Adapted from McGuire et al., 2006

Soil carbon decomposition in CLM4.5
Permafrost zone

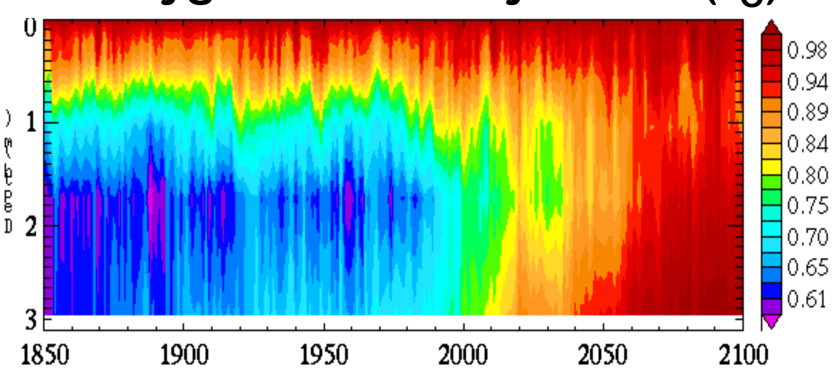
Temperature scalar (r_T)



Soil liquid water scalar (r_W)

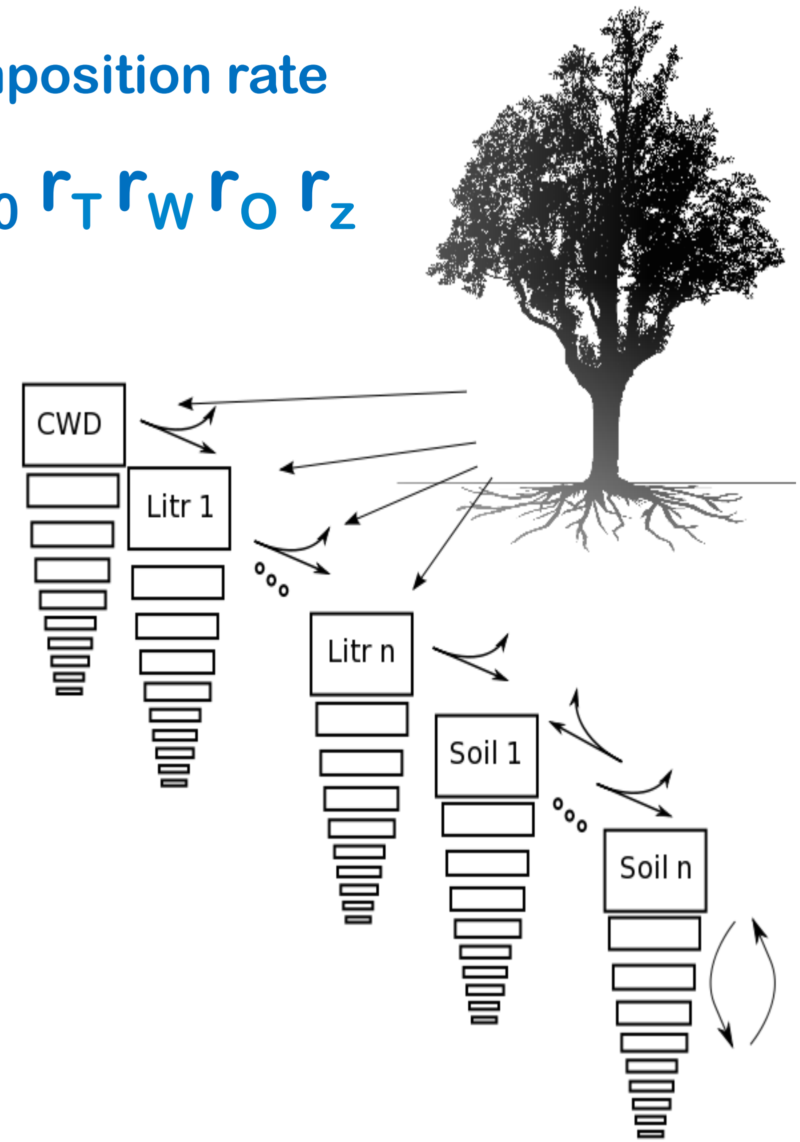


Oxygen availability scalar (r_O)

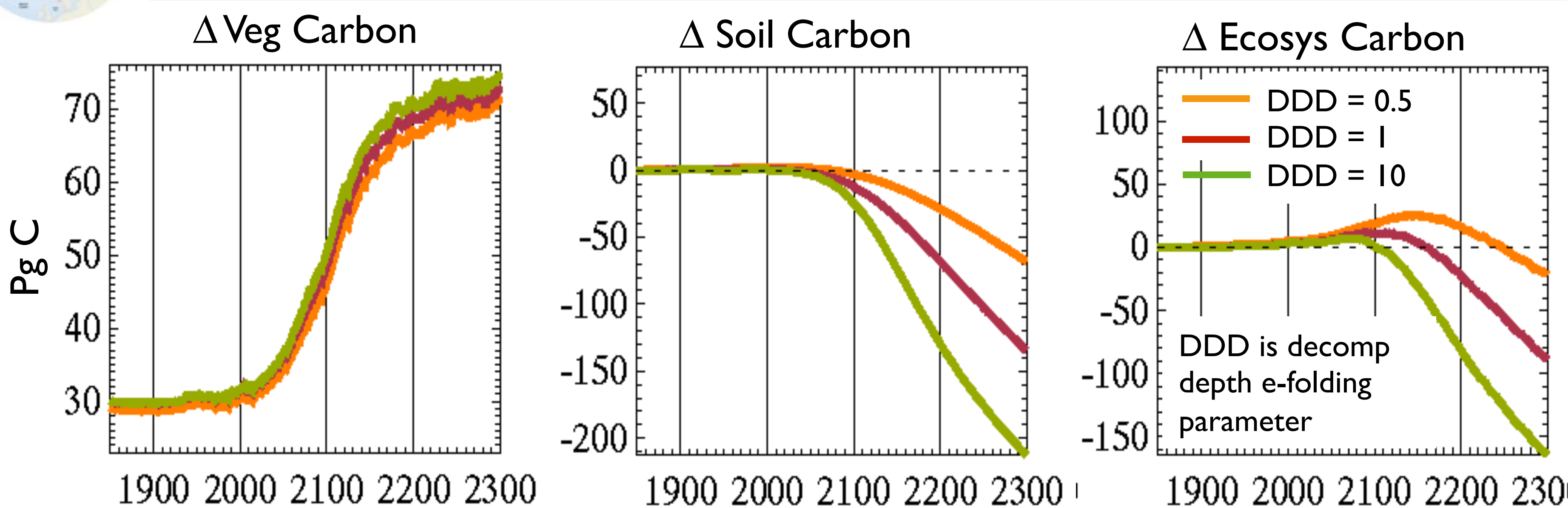


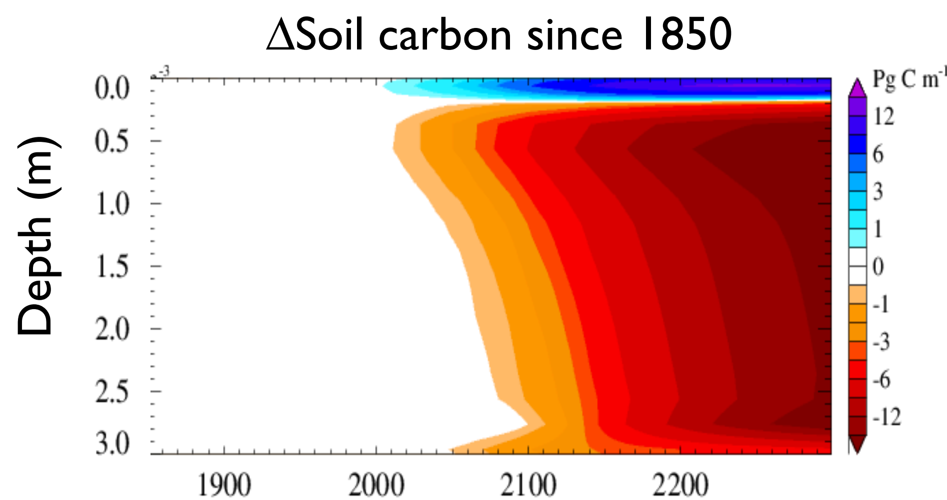
Decomposition rate

$$k = k_0 \, r_T \, r_W \, r_O \, r_z$$



Permafrost Carbon Feedback (CLM4.5BGC)



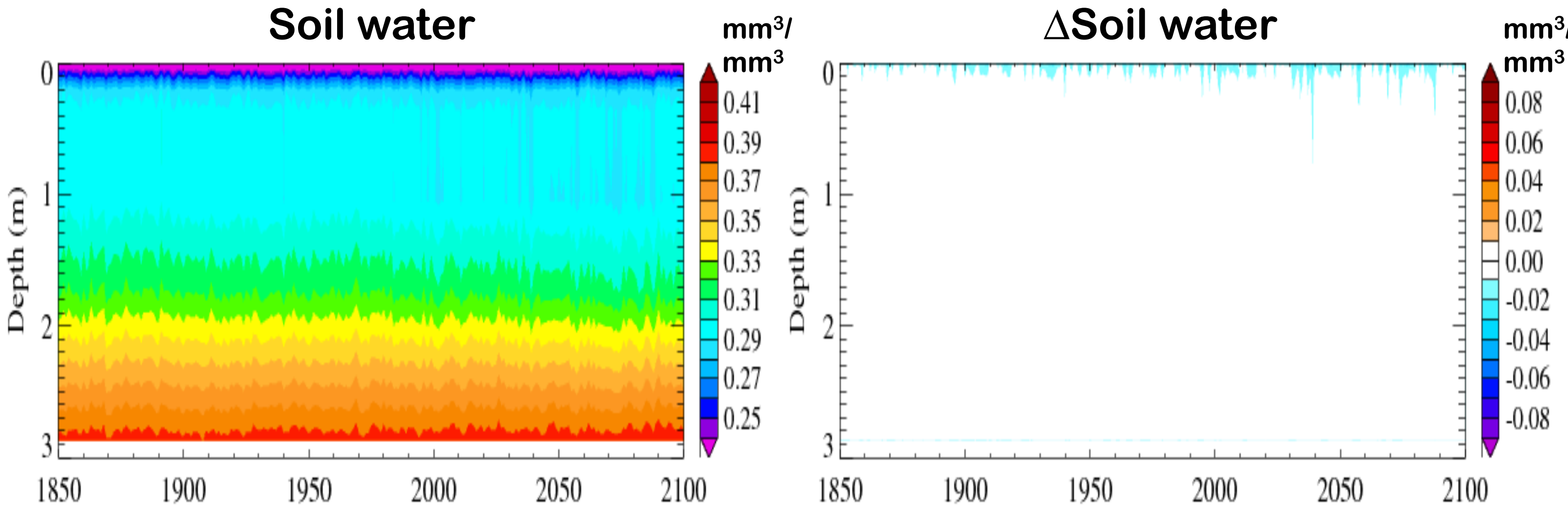


17 – 42 Pg of 'deep' carbon lost by 2100
103 – 252 Pg by 2300

Koven, Lawrence, and Riley, 2015

Soil hydrologic response to permafrost thaw (RCP8.5)

CLM4



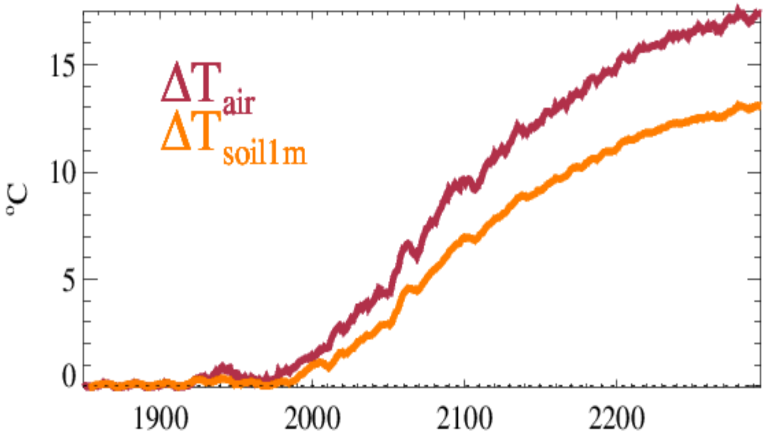
<u>**Problems with CLM4 active layer hydrology**</u>

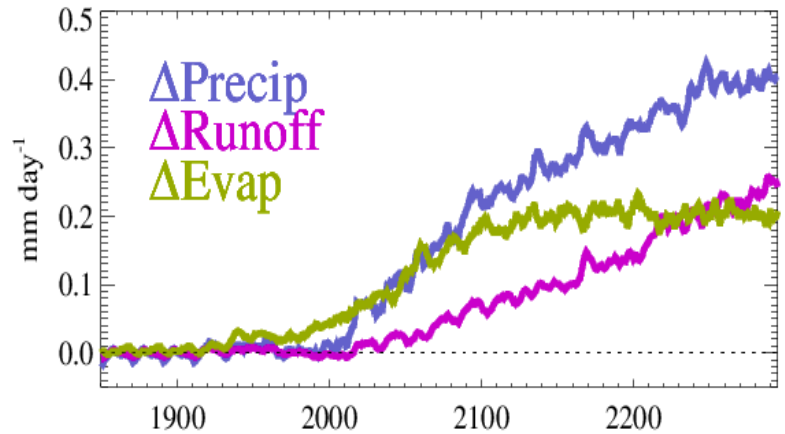
Surface soils are very dry

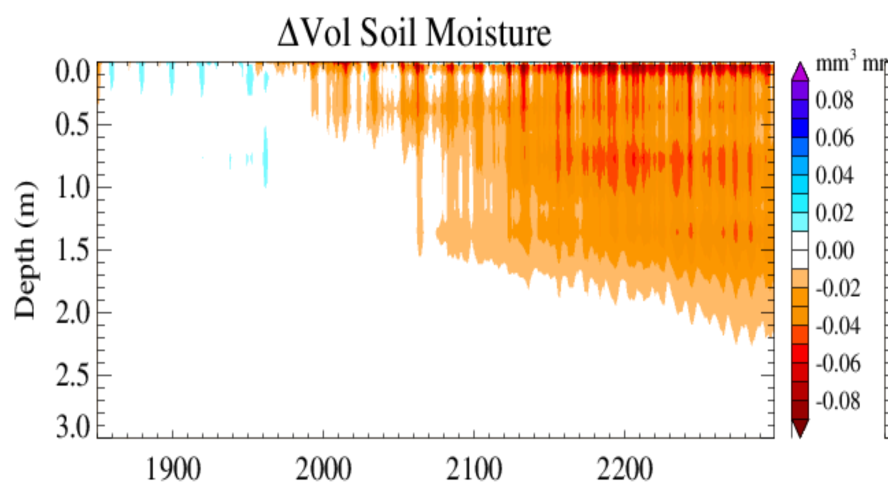
(some locations are too dry to support vegetation)

No soil moisture response to climate change or permafrost thaw

CESM Projections of temperature and water balance for permafrost domain (RCP8.5)

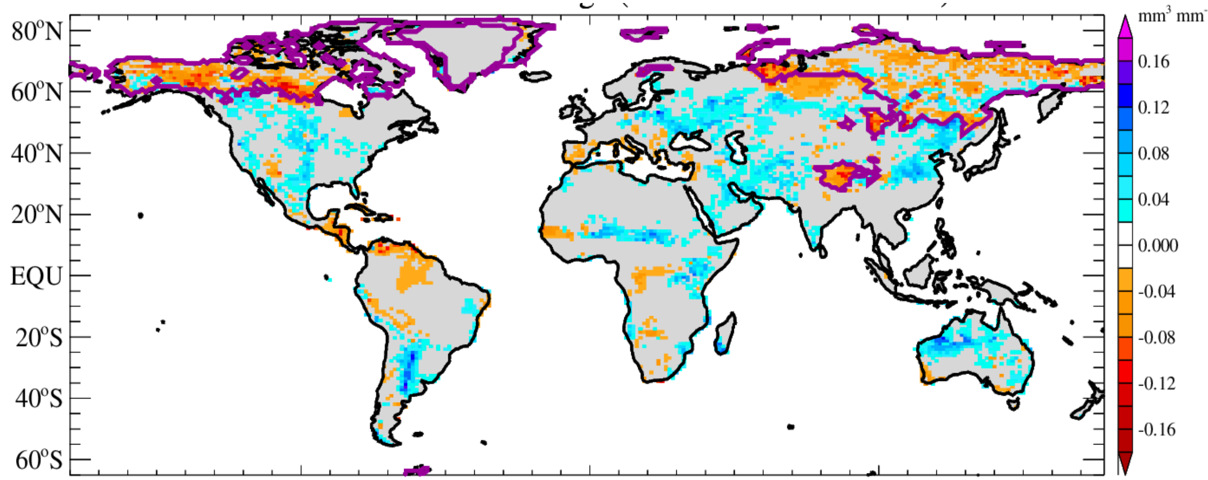




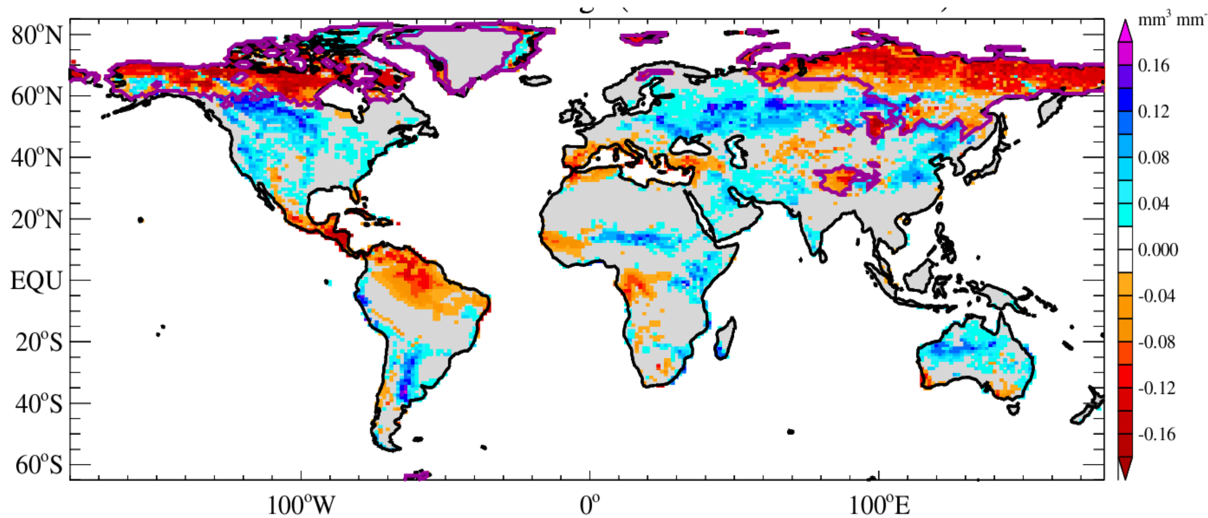


Projected soil moisture change (RCP8.5)
CLM4.5

Column soil moisture change by 2100

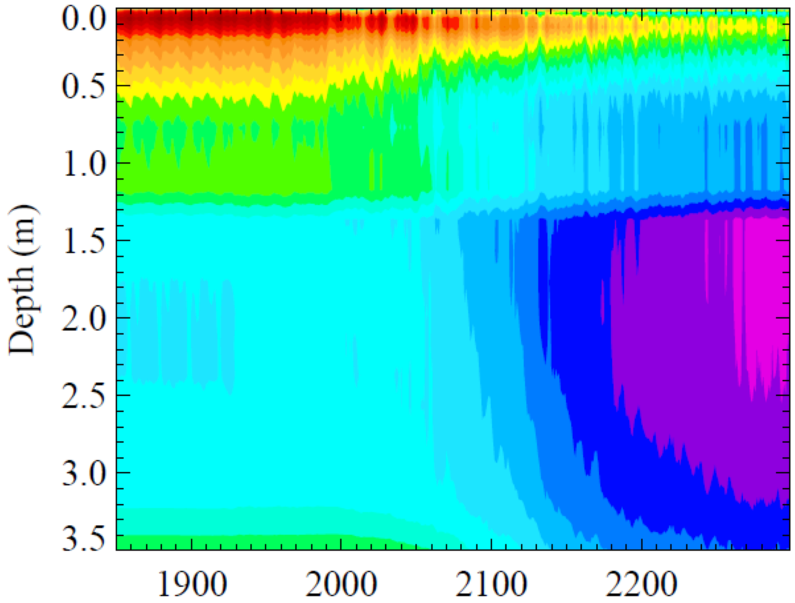


Column soil moisture change by 2300

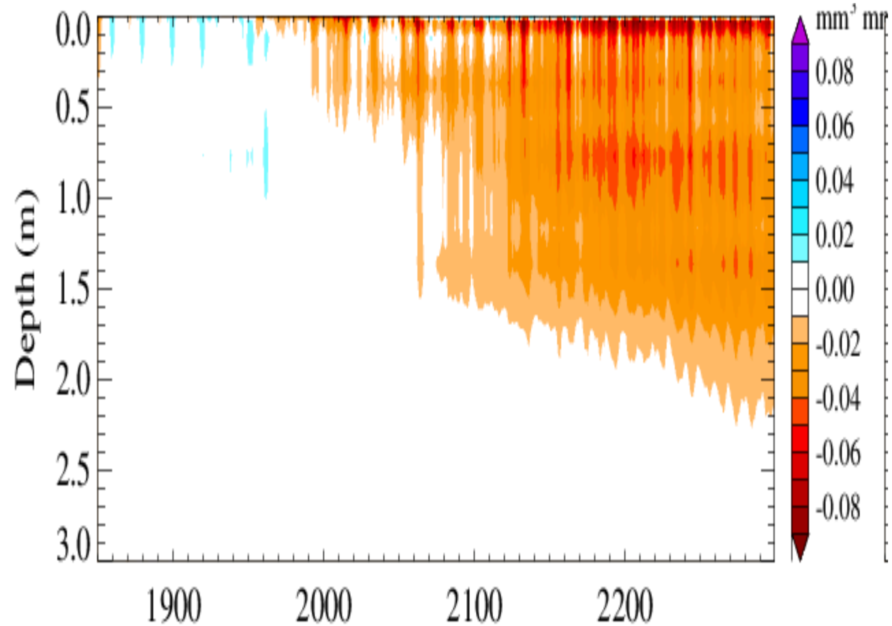


DRYSOIL

Soil Moisture

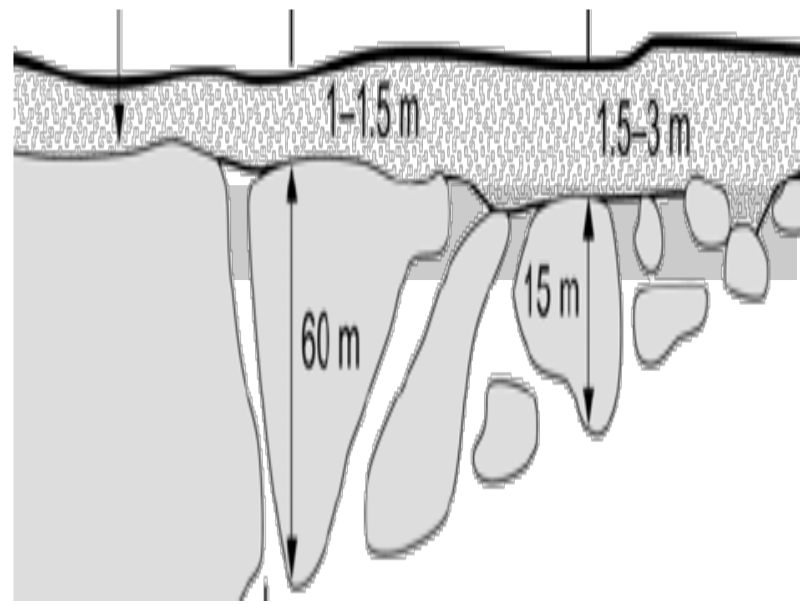


Δ Soil Moisture

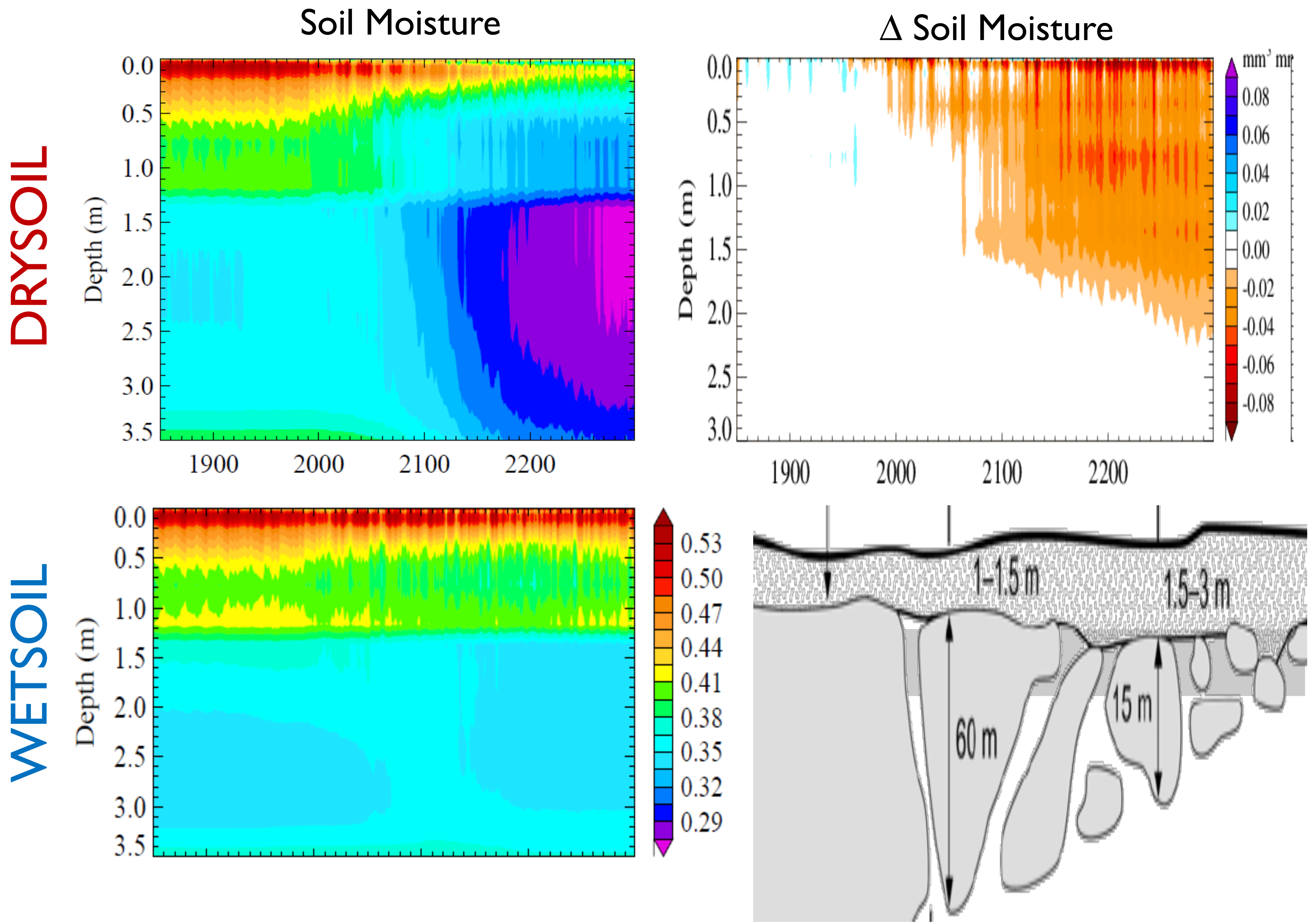


“WETSOIL” experiment

‘Maintain’ initial soil moisture conditions by maintaining the vertical profile of impedance to liquid water drainage



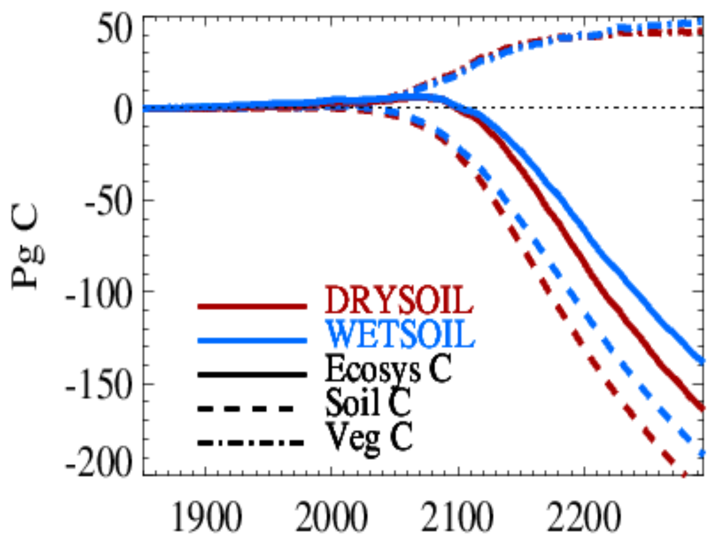
Lawrence et al., ERL, 2015



Lawrence et al., ERL, 2015

Global Warming Potential for DRYSOIL and WETSOIL expts

Δ Carbon Stock

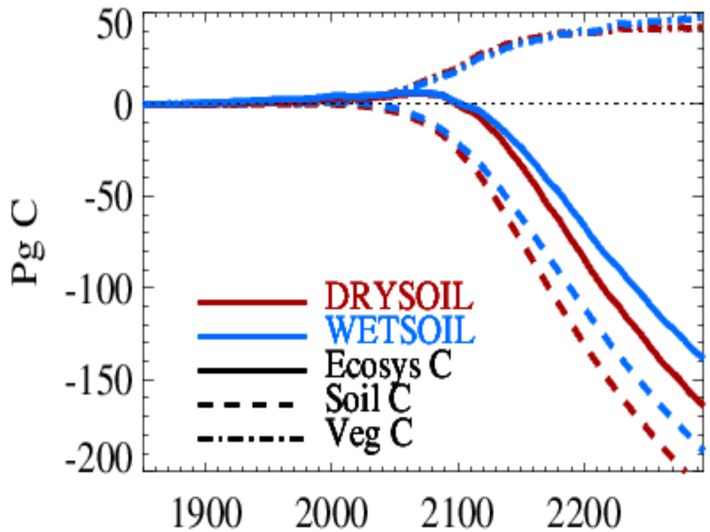


18% more permafrost soil carbon lost in DRYSOIL case

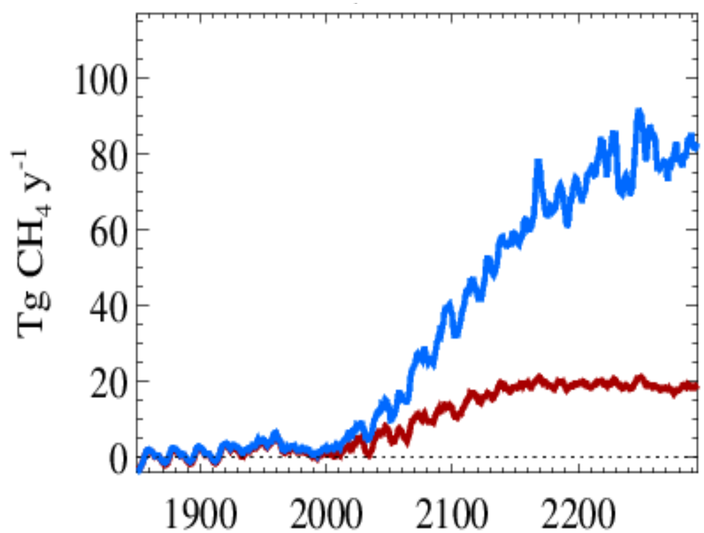
Lawrence et al., ERL, 2015

Global Warming Potential for DRYSOIL and WETSOIL expts

Δ Carbon Stock



Δ CH_4 emissions



DRYSOIL

CO_2 = 0.75

CH_4 = 0.19

0.94 Pg CO_2e-C y^{-1}

WETSOIL

CO_2 = 0.67

CH_4 = 0.82

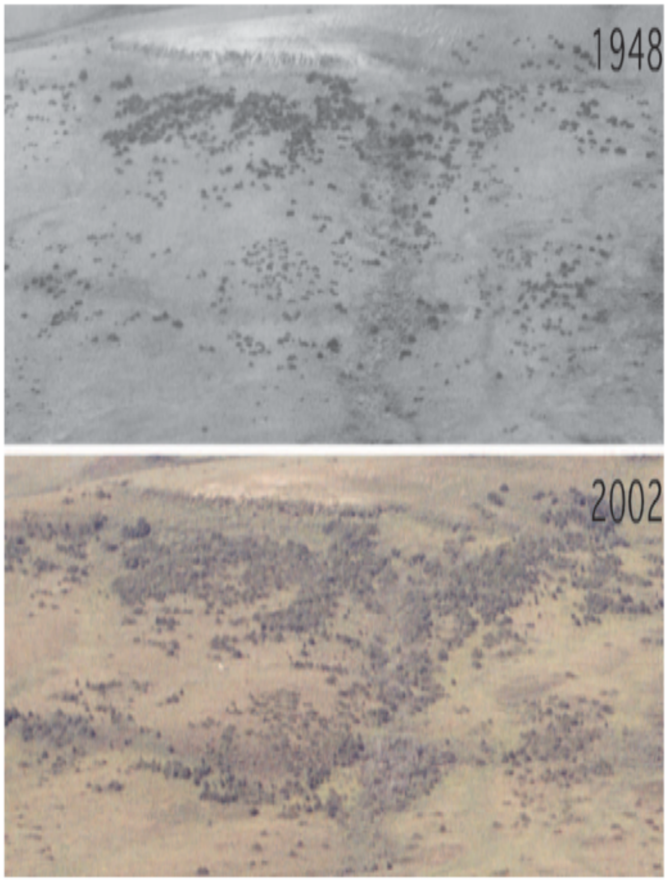
1.49 Tg CO_2e-C y^{-1}

50% higher GWP in WETSOIL case

Lawrence et al., ERL, 2015

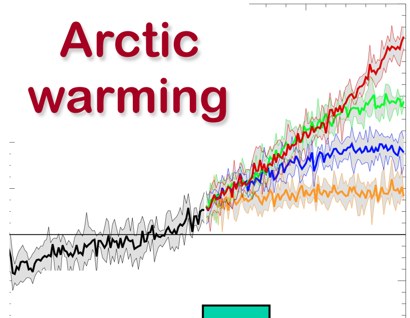
Photos: Bernhard Edmaier , National Geographic

Shrub – permafrost interactions

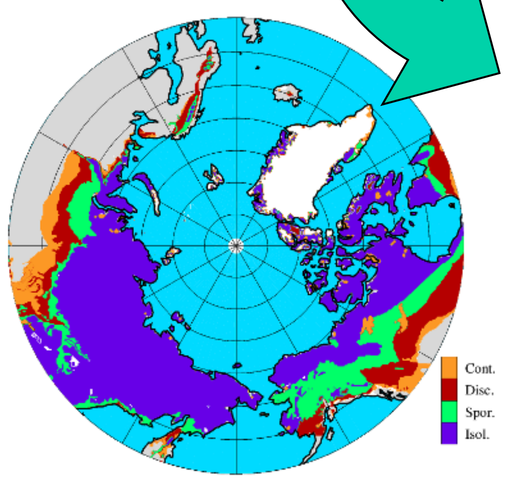


+7% increase in shrubs in Alaska, 1950 to 2005

Arctic warming



Permafrost warms and thaws



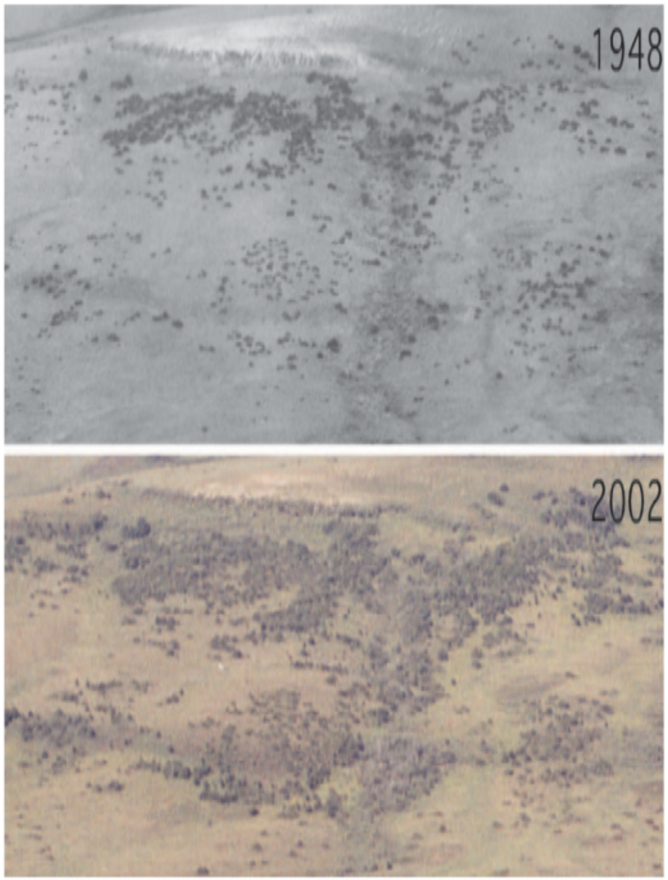
Microbial activity increases

Enhanced [nitrogen]

Shrub growth

Adapted from McGuire et al., 2006

Shrub – permafrost interactions



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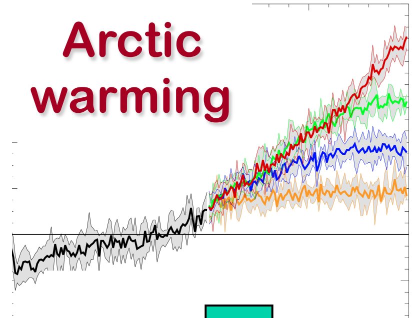
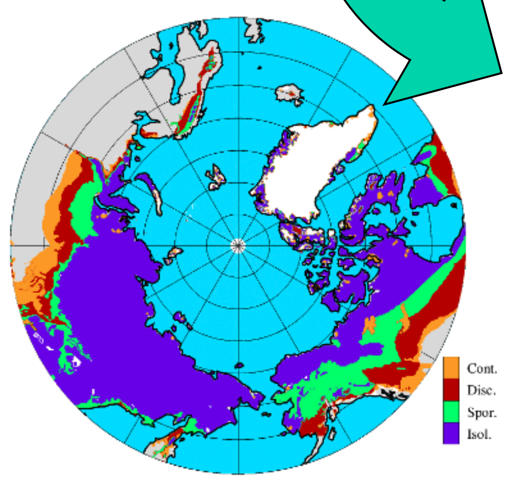


Permafrost warms and thaws



Microbial activity increases

Enhanced [nitrogen]

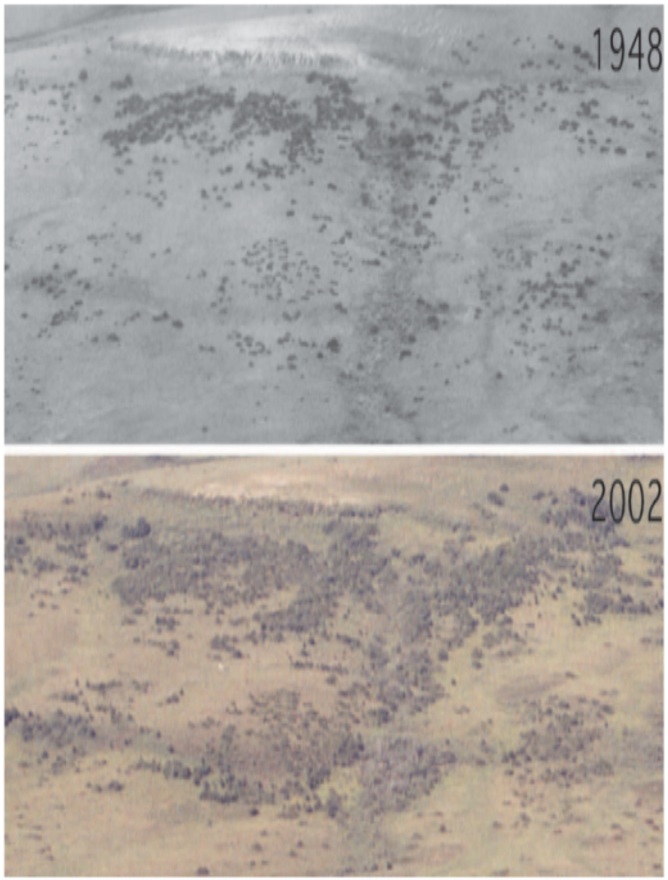
Shrub growth

Carbon Sequester

+20PgC for +20% shrub

Adapted from McGuire et al., 2006

Shrub – permafrost interactions



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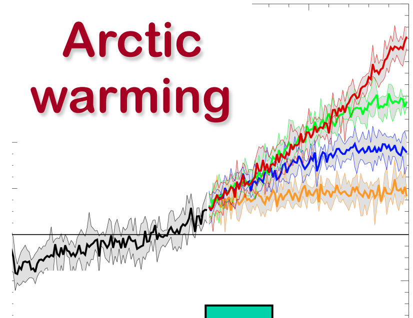


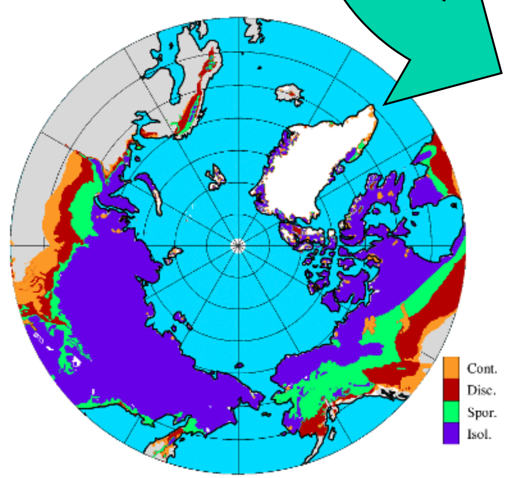
Permafrost warms and thaws

Microbial activity increases

Enhanced [nitrogen]

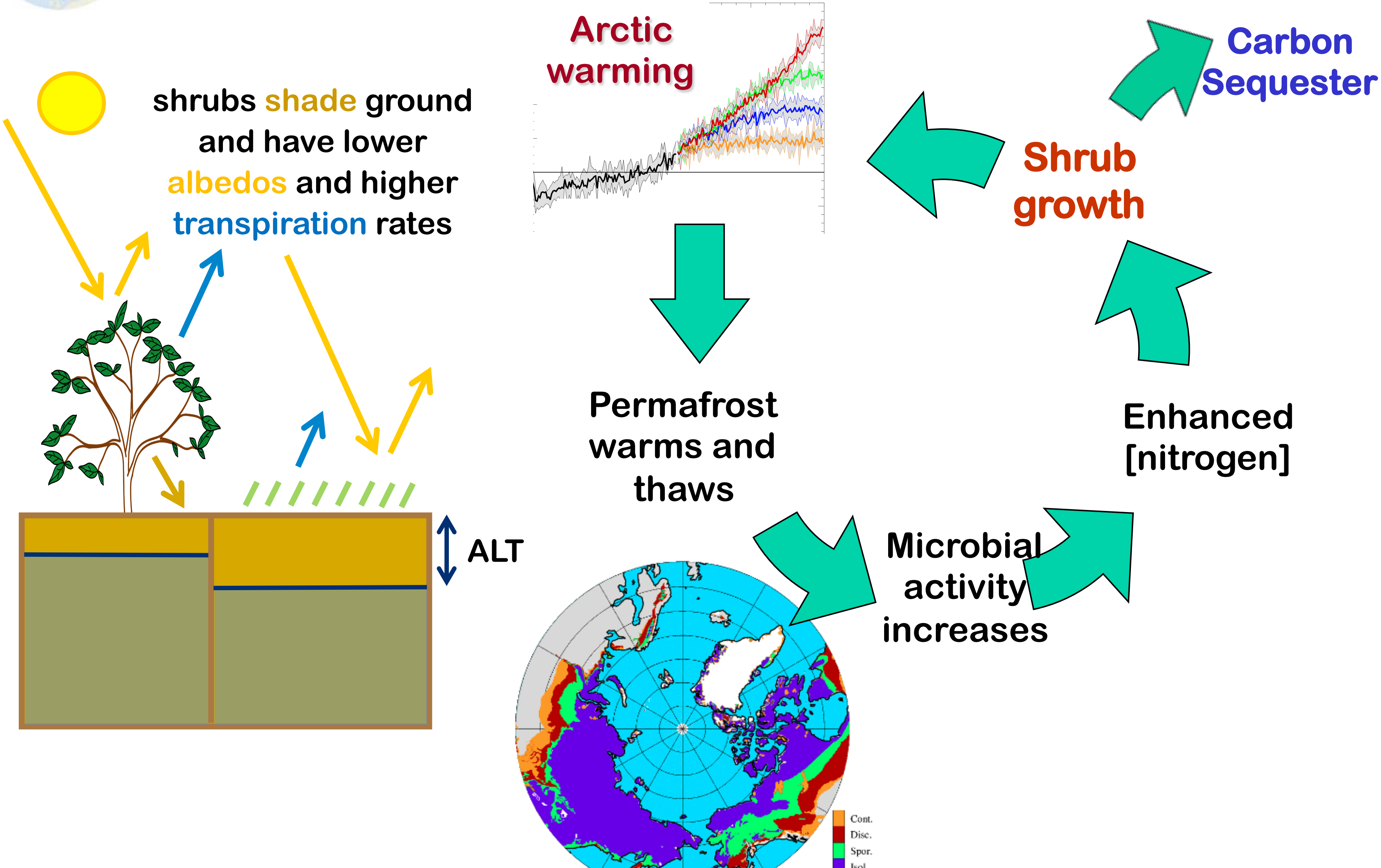
Shrub growth

Carbon Sequester



Adapted from McGuire et al., 2006

Potential Arctic terrestrial climate-change feedbacks



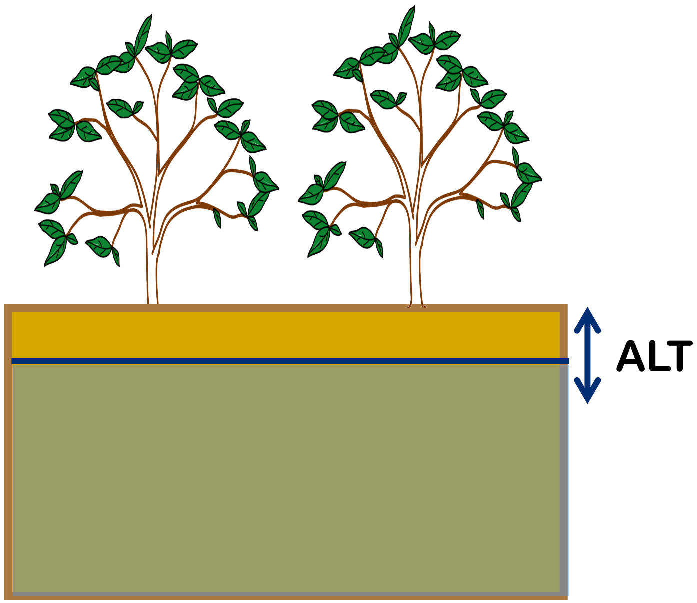
Adapted from McGuire et al., 2006

Global Change Biology

Global Change Biology (2010) 16, 1296–1305, doi: 10.1111/j.1365-2486.2009.02110.x

Shrub expansion may reduce summer permafrost thaw in Siberian tundra

D. BLOK*, M. M. P. D. HEIJMANS*, G. SCHAEPMAN-STRUB*†, A. V. KONONOV‡, T. C. MAXIMOV‡ and F. BERENDSE*



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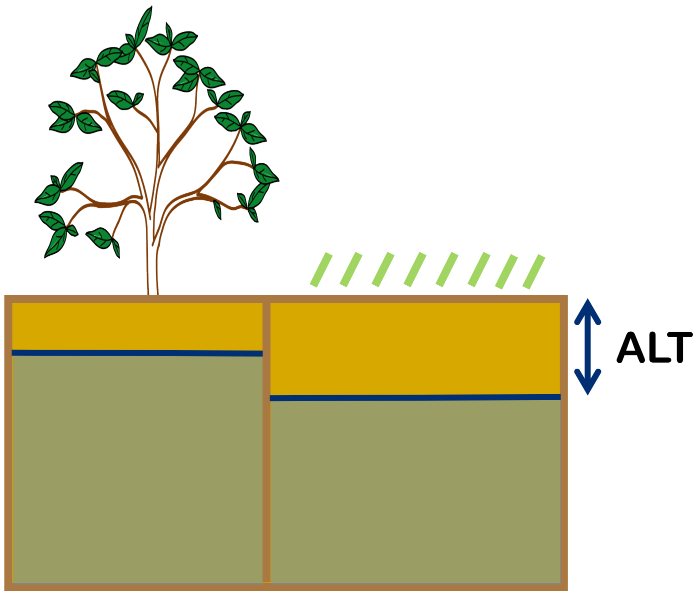
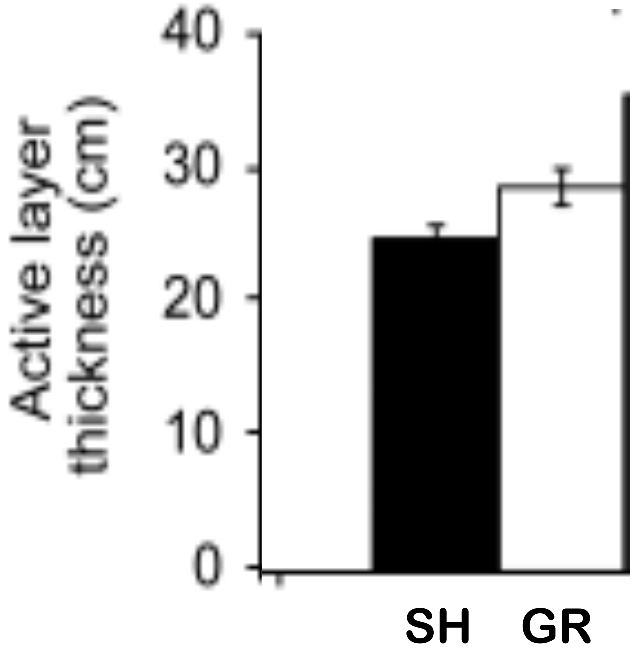
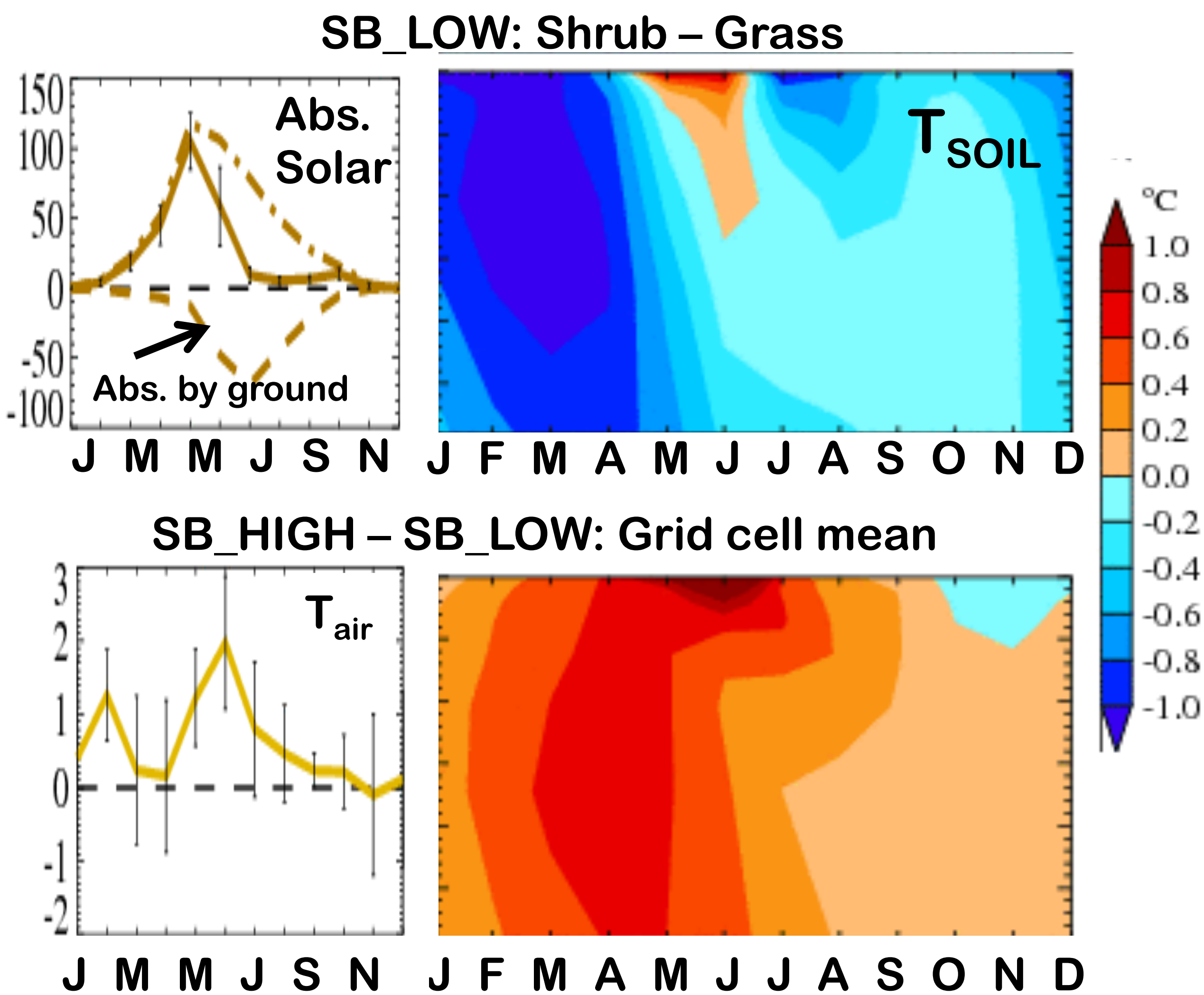


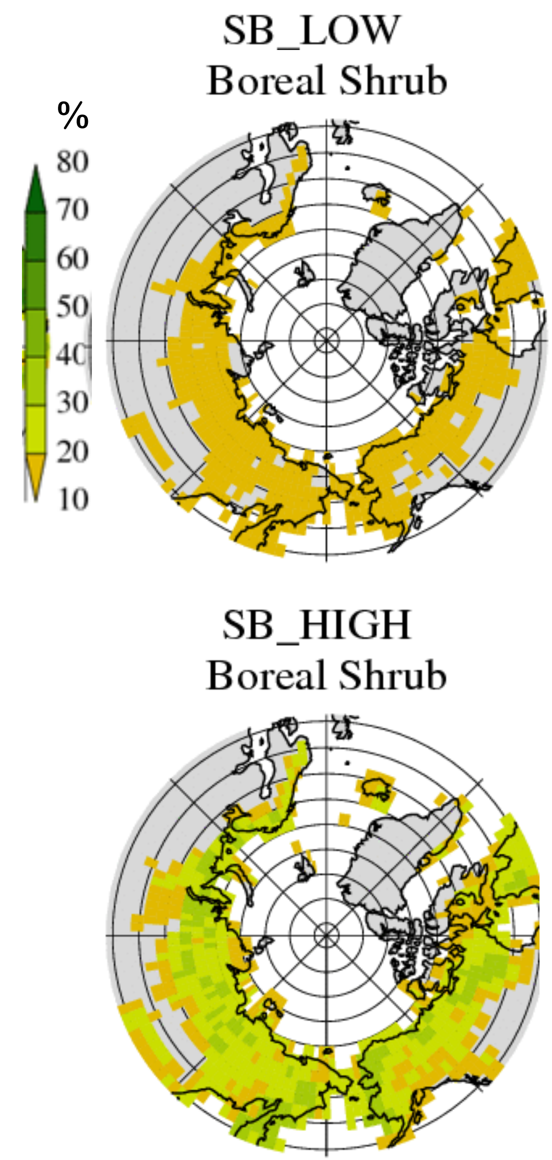


"These results suggest that the expected expansion of deciduous shrubs in the Arctic region, triggered by climate warming, may reduce summer permafrost thaw."

Evaluate this hypothesis using CCSM4

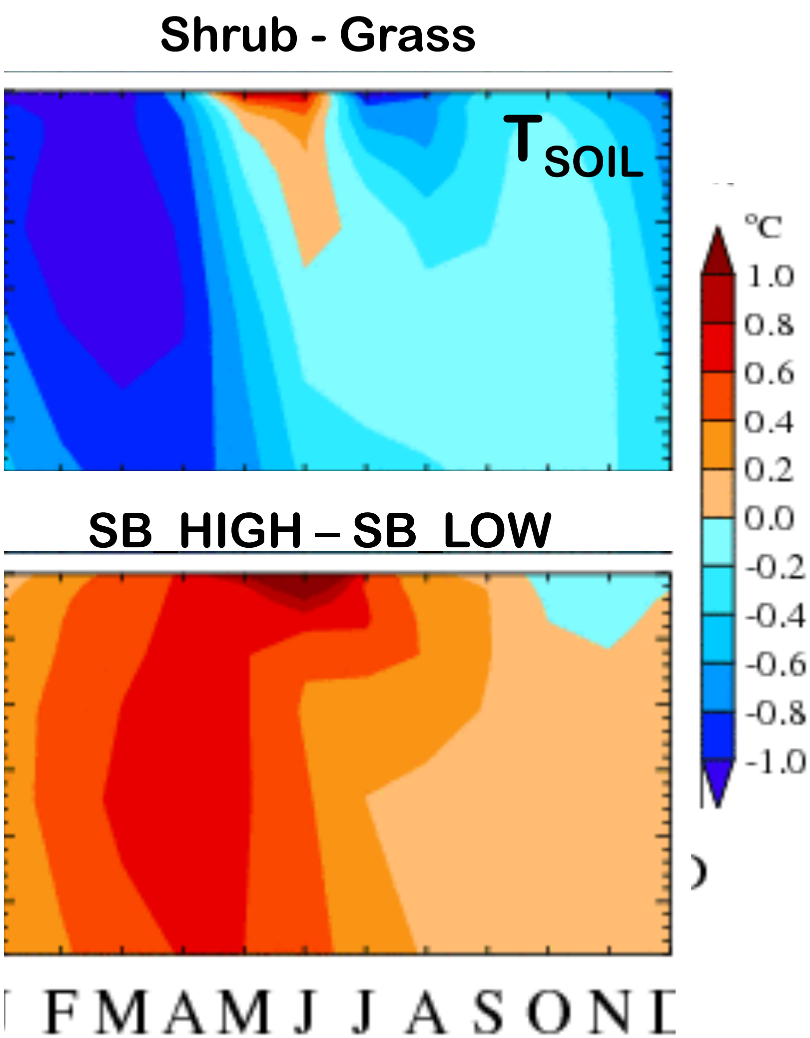
Examining impact of shrubs on permafrost using CESM





Lawrence and Swenson, 2011

Impact of shrubs on permafrost



Will expanding Arctic shrub cover decrease permafrost vulnerability to climate change?

A. Not necessarily. Depends on whether direct local cooling or indirect climate warming dominates.

CAM/CLM results indicate that shrub expansion may actually increase rather than decrease permafrost vulnerability to climate change.

Lawrence and Swenson, ERL, 2011
Bonfils et al, ERL, 2012


Snow-Hydro


Summary

• Substantial near-surface permafrost degradation is projected for 21st century

• Process-rich enhancements to CLM (soil thermodynamics and hydrology, soil biogeochemistry, CH_4 emissions, prognostic wetlands) are enabling study of permafrost dynamics and feedbacks

• Initial results suggest that feedbacks will amplify climate change, though magnitude is highly uncertain

- Warming feedbacks related to shrub encroachment may dominate in 21st century
- Permafrost-carbon feedback might be relatively small in 21st century but likely to amplify and extend into 22nd century and beyond as soils warm and dry
- Permafrost soils may dry after permafrost thaws, which enhances aerobic SOM decomposition and limits increase in CH_4 emissions

Summary

• Substantial near-surface permafrost degradation is projected for 21st century and beyond, likely initiating several feedbacks that could amplify Arctic and global climate change

• Using CLM4.5BGC, we identify several potential controls on the strength permafrost-carbon feedback

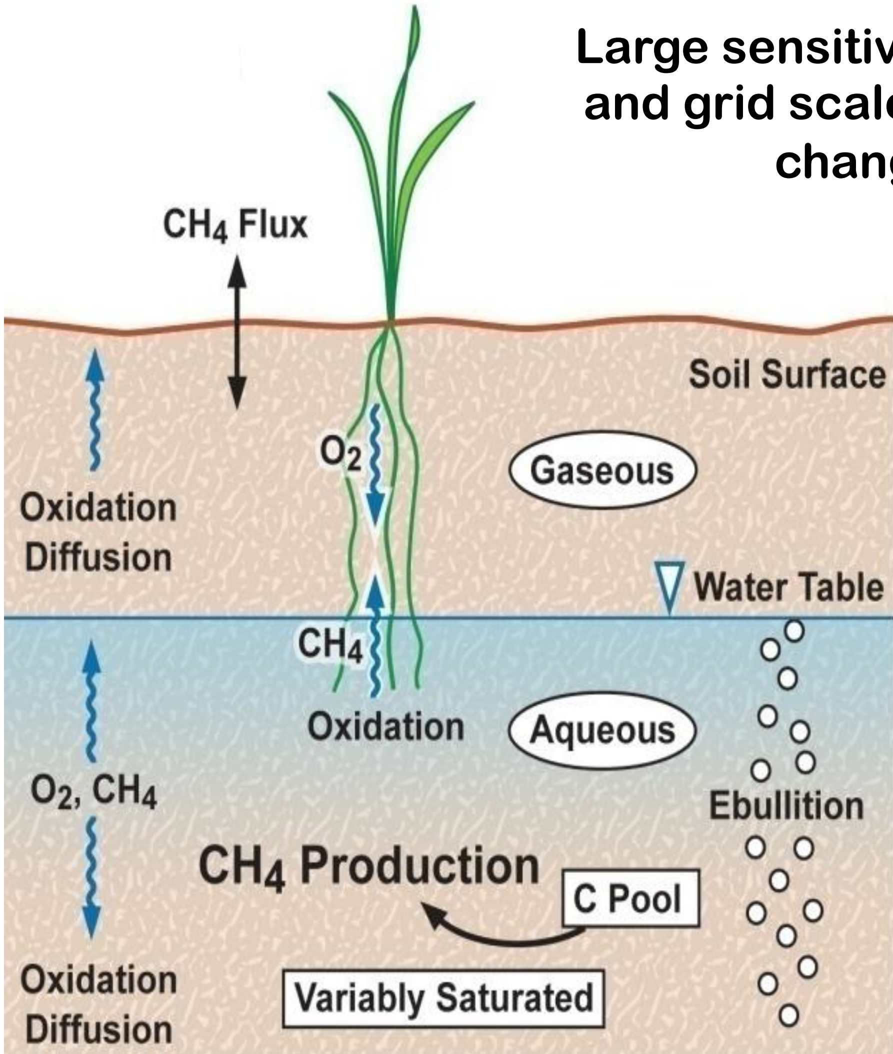
1: Deeper (0.5-3m) soil carbon decomposability is first order determinant of amplitude of permafrost-carbon feedback

2. Deep soil N mineralization doesn't strongly fertilize plants due to asynchrony of plant N demand (summer) and additional deep N supply (fall)

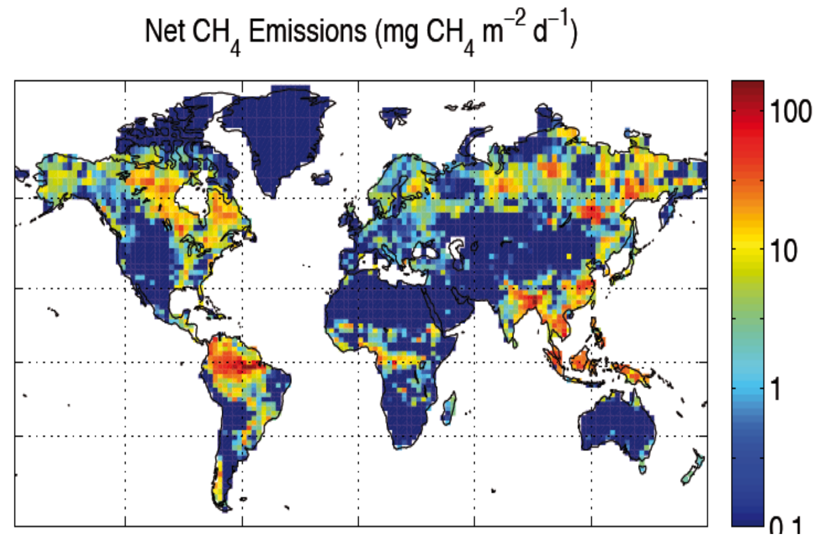
3: Permafrost soils will dry after permafrost thaws, which enhances aerobic SOM decomposition and limits increase in CH_4 emissions

Process based methane emissions model

"Barriers to predicting changes in global terrestrial methane fluxes"



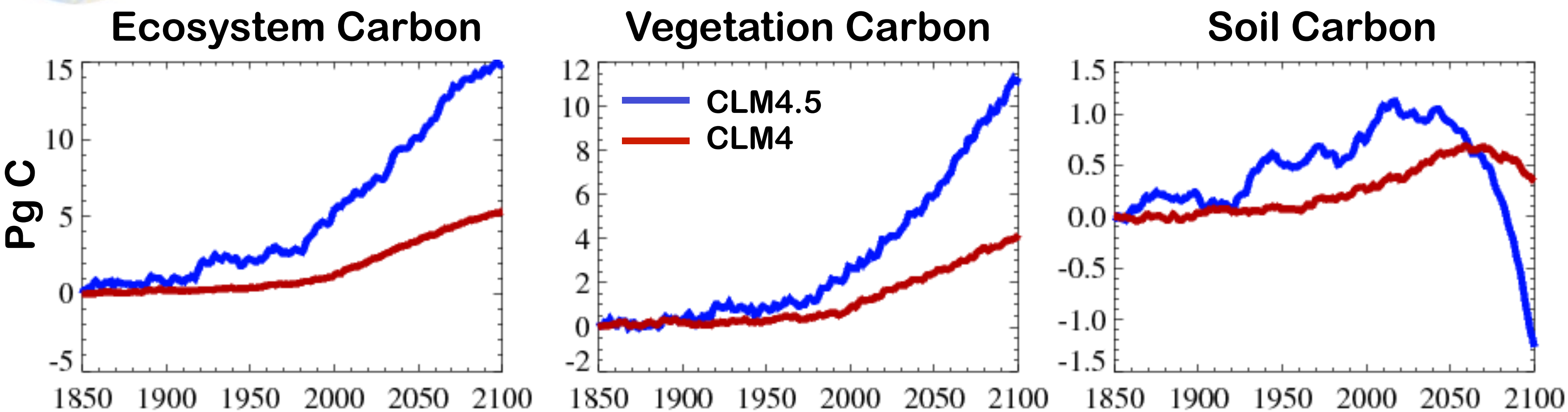
Large sensitivities (up to 4x and 10x at regional and grid scales) in CH_4 fluxes from reasonable changes in model parameters

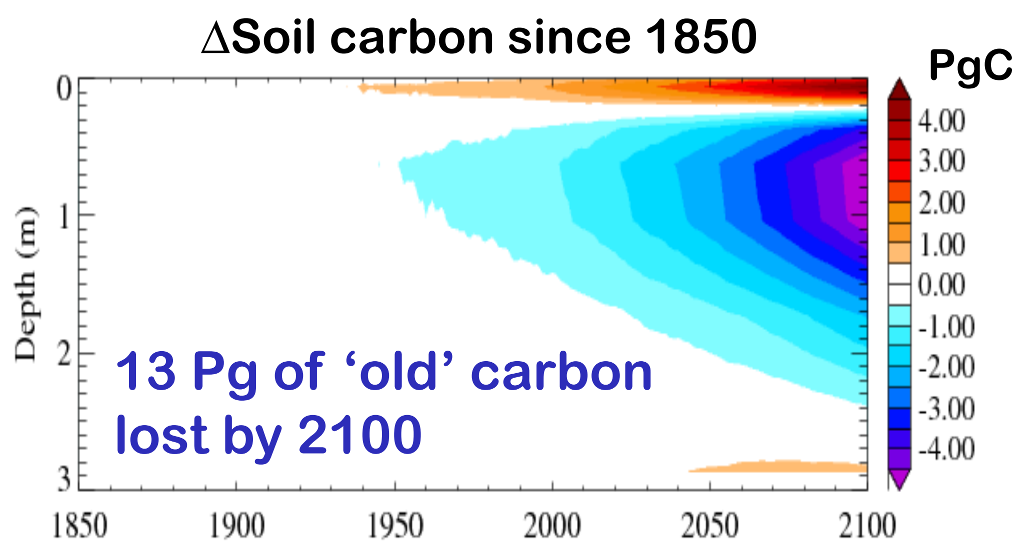


Projections highly uncertain, but with default parameters ~ +20% increase in high-lat CH_4 emissions (A1B)

Riley et al., 2011, Biogeosciences

Carbon stock trends in permafrost zone



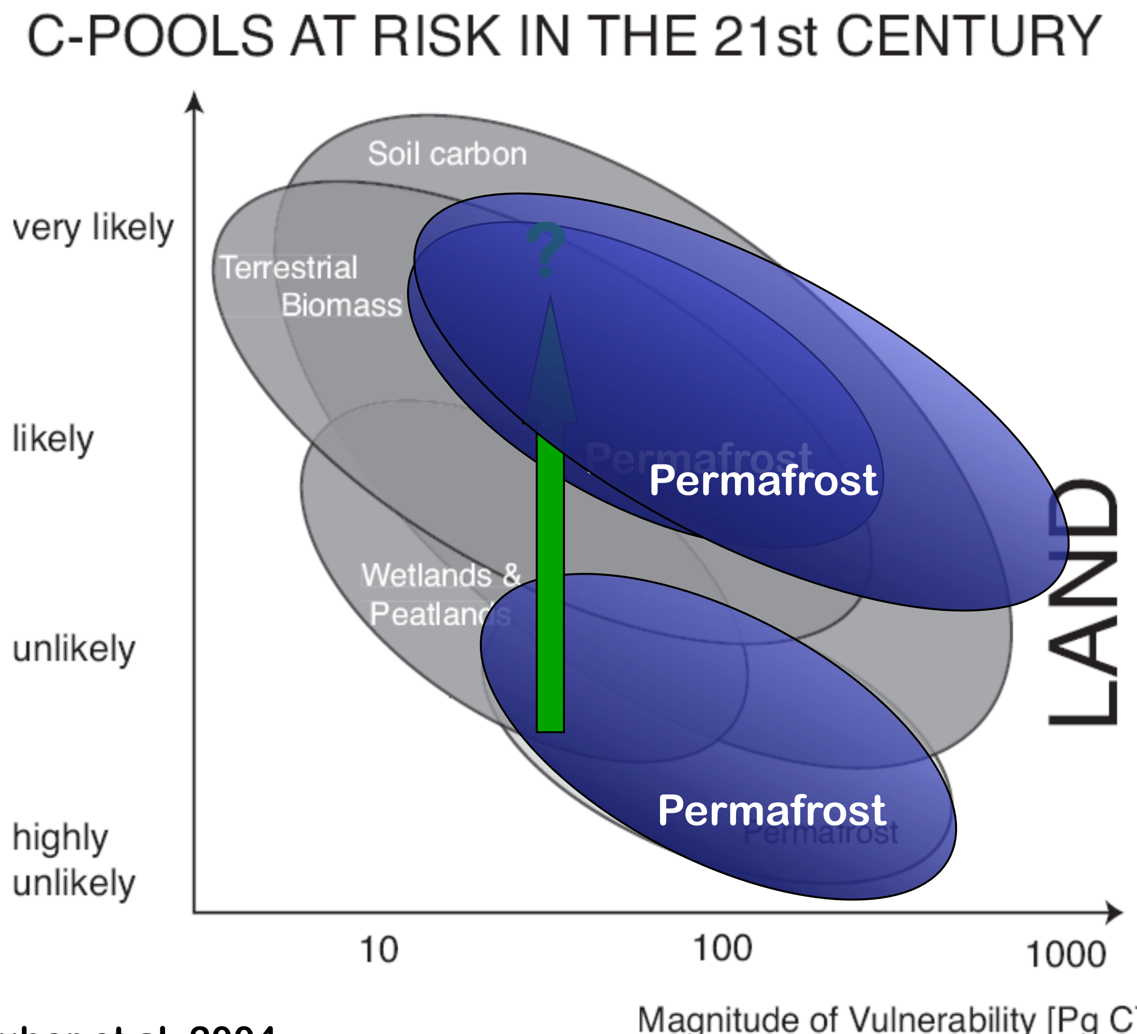


<u>Prior estimates of carbon loss (PgC)</u>

- 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)

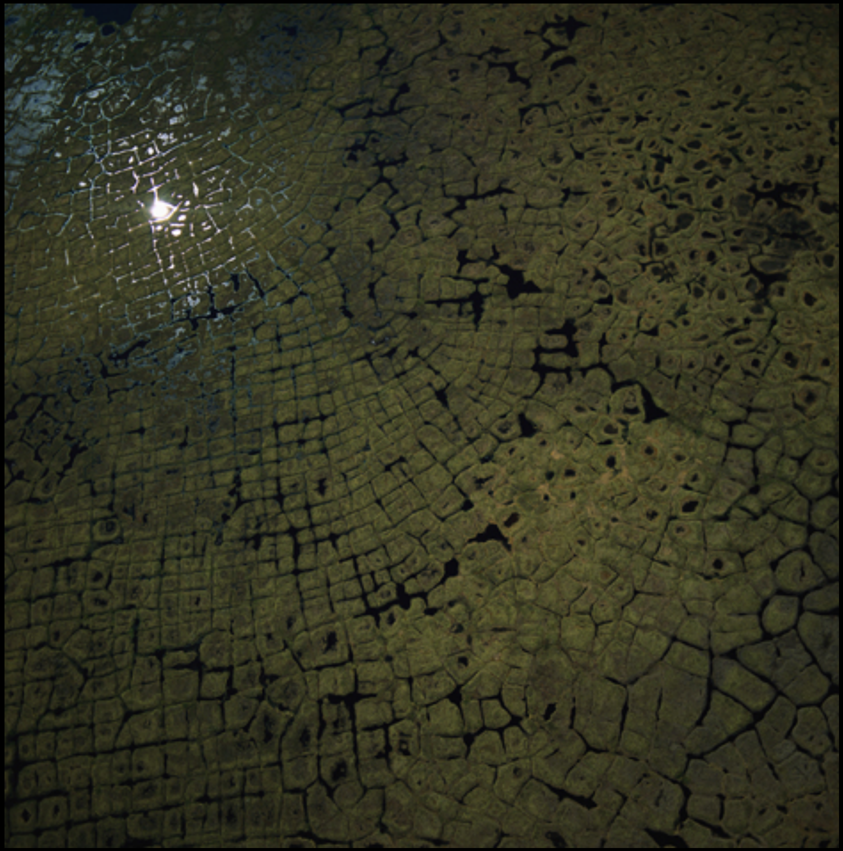
Release of Soil Carbon Frozen in Permafrost

Global Carbon Project



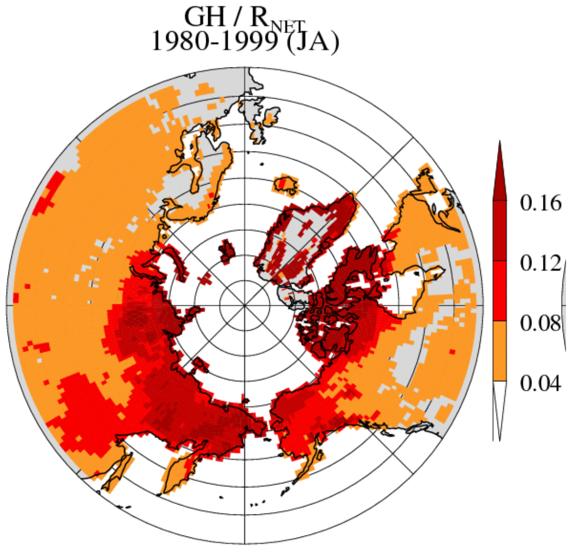
Gruber et al. 2004

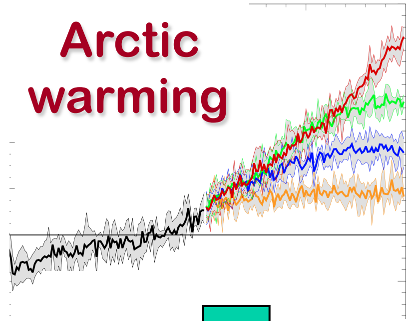
Extra Slides



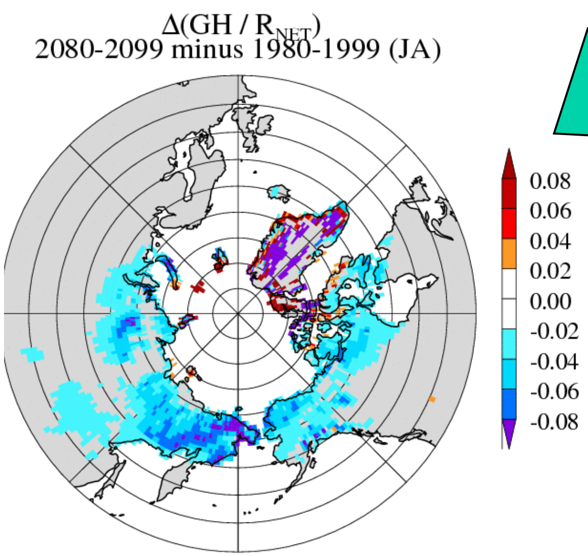
Bernhard Edmaier
National Geographic

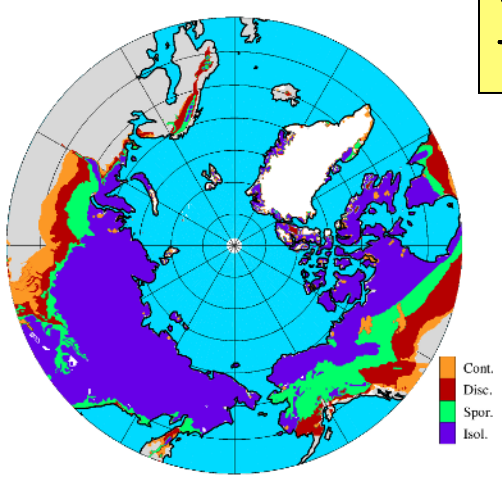
Potential Arctic terrestrial climate change feedbacks





Permafrost warms and thaws





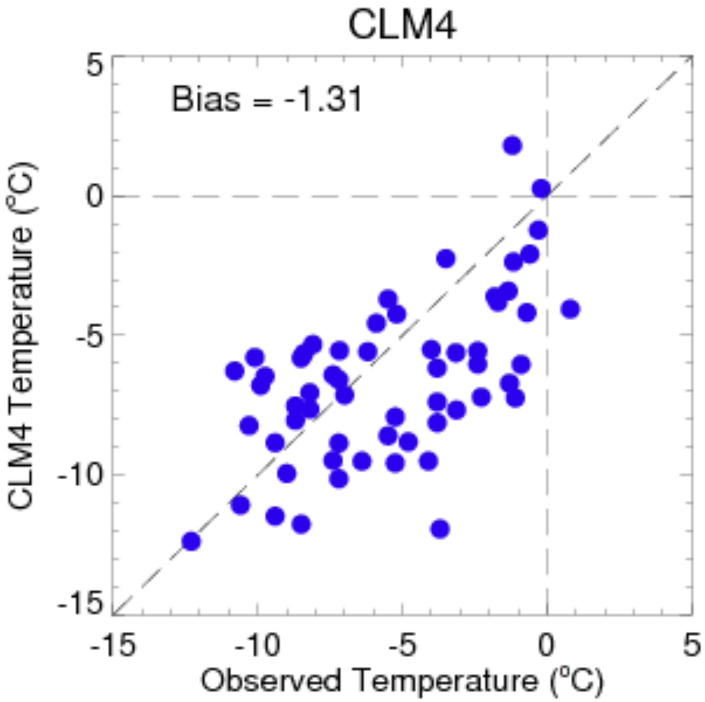
Direct feedback

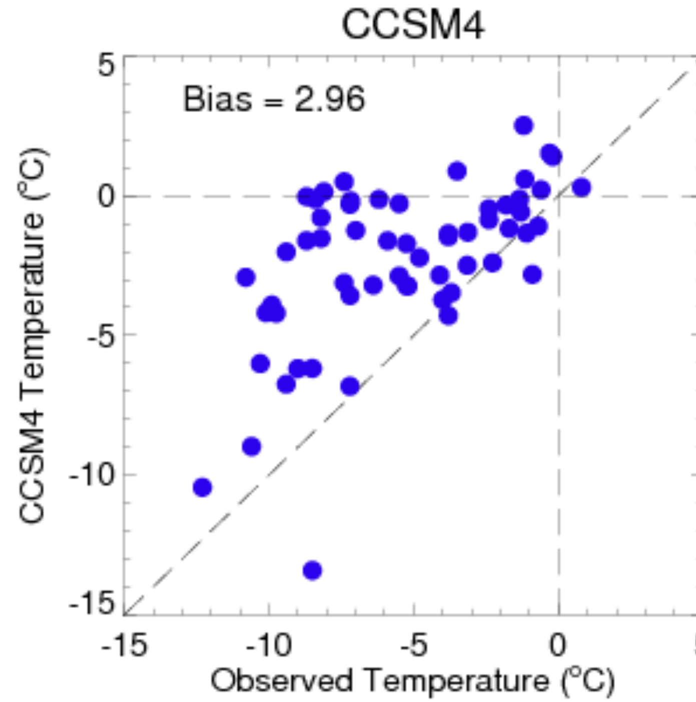
Surface energy partitioning

Permafrost state (especially presence or absence of soil ice) affects partitioning of net radiation into ground, latent, and sensible heat fluxes

Lawrence et al., 2012

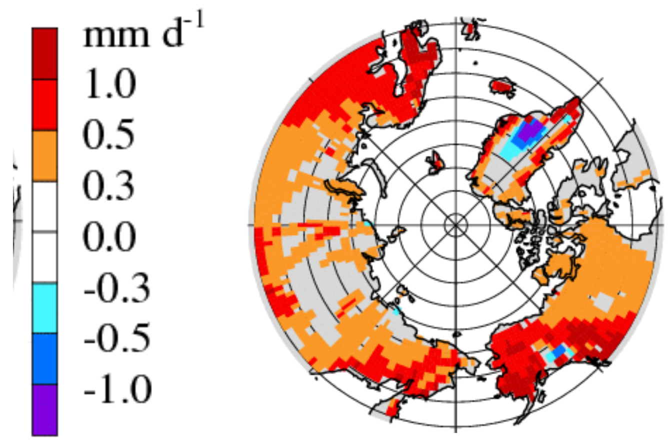
Offline (CLM) vs coupled (CCSM) model deep (> 15m) ground temperatures



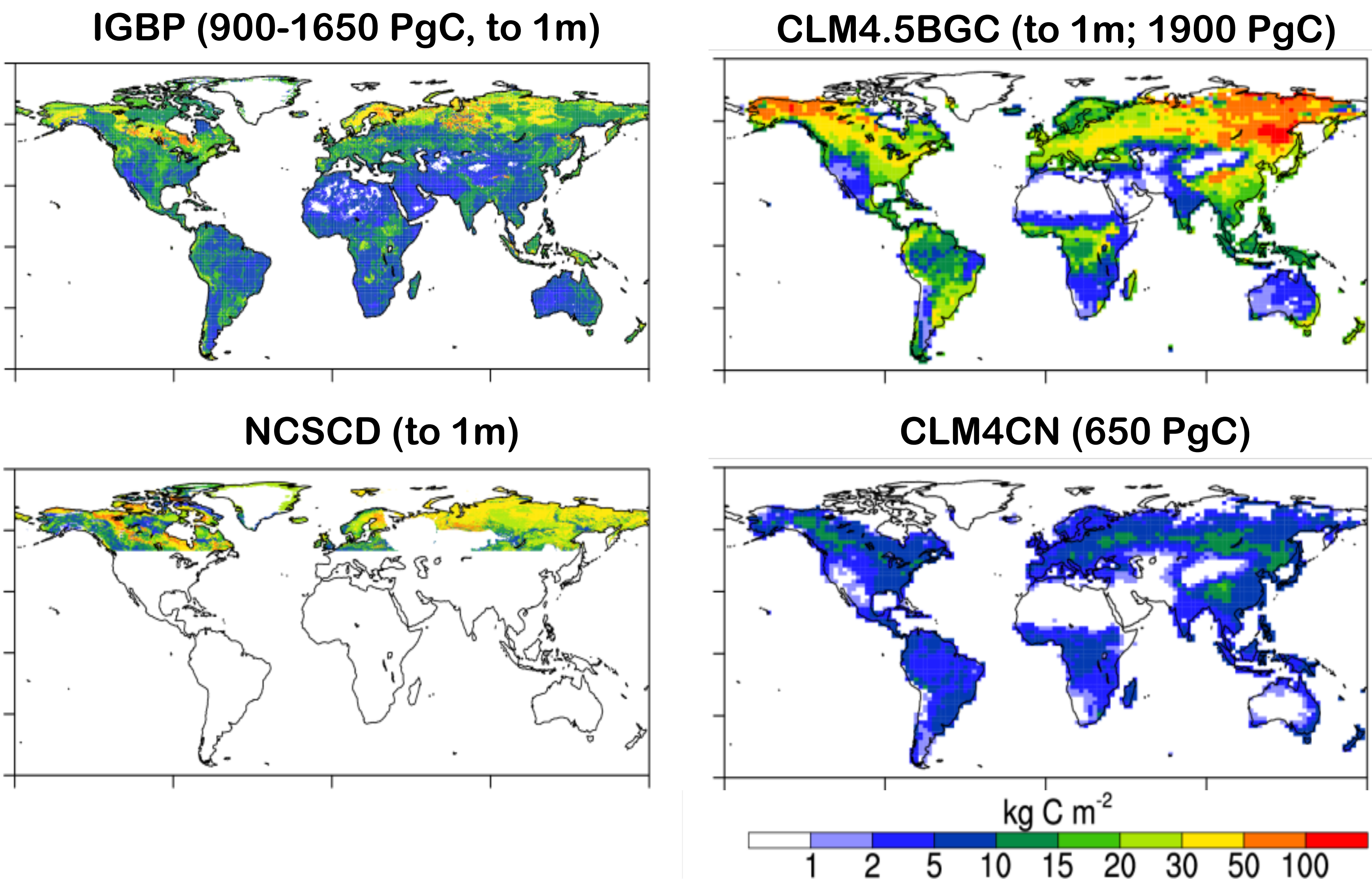


Cold bias because soils too dry?

CCSM4 Snowfall bias



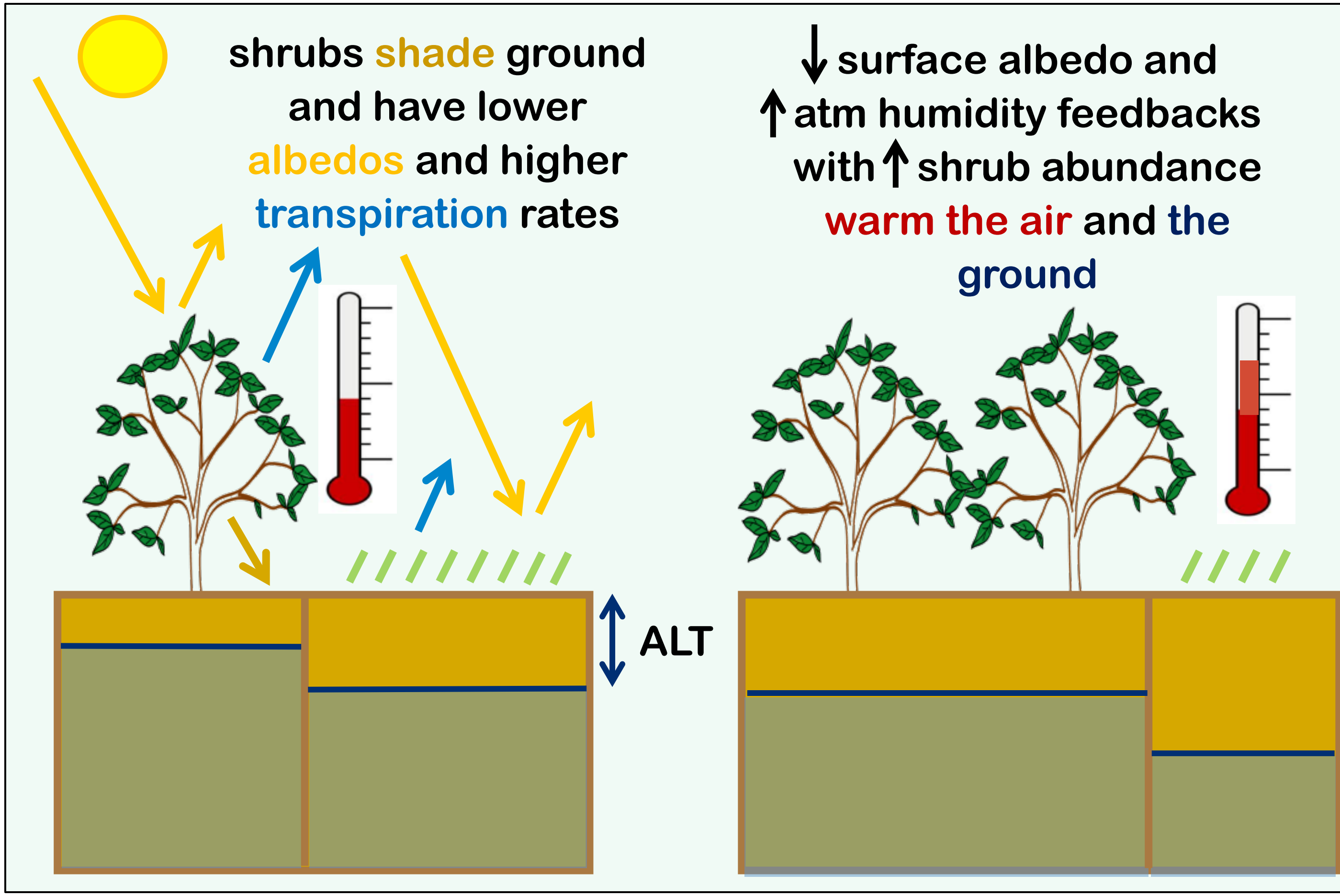
Soil carbon in CLM



Koven et al., in prep

Summary (Lawrence and Swenson, ERL, 2011)

Will expanding Arctic shrub cover decrease permafrost vulnerability to climate change?



A. Not necessarily. Depends on whether the direct local cooling or the indirect climate warming dominates. Our results indicate that shrub expansion may increase rather than decrease permafrost vulnerability to climate change.

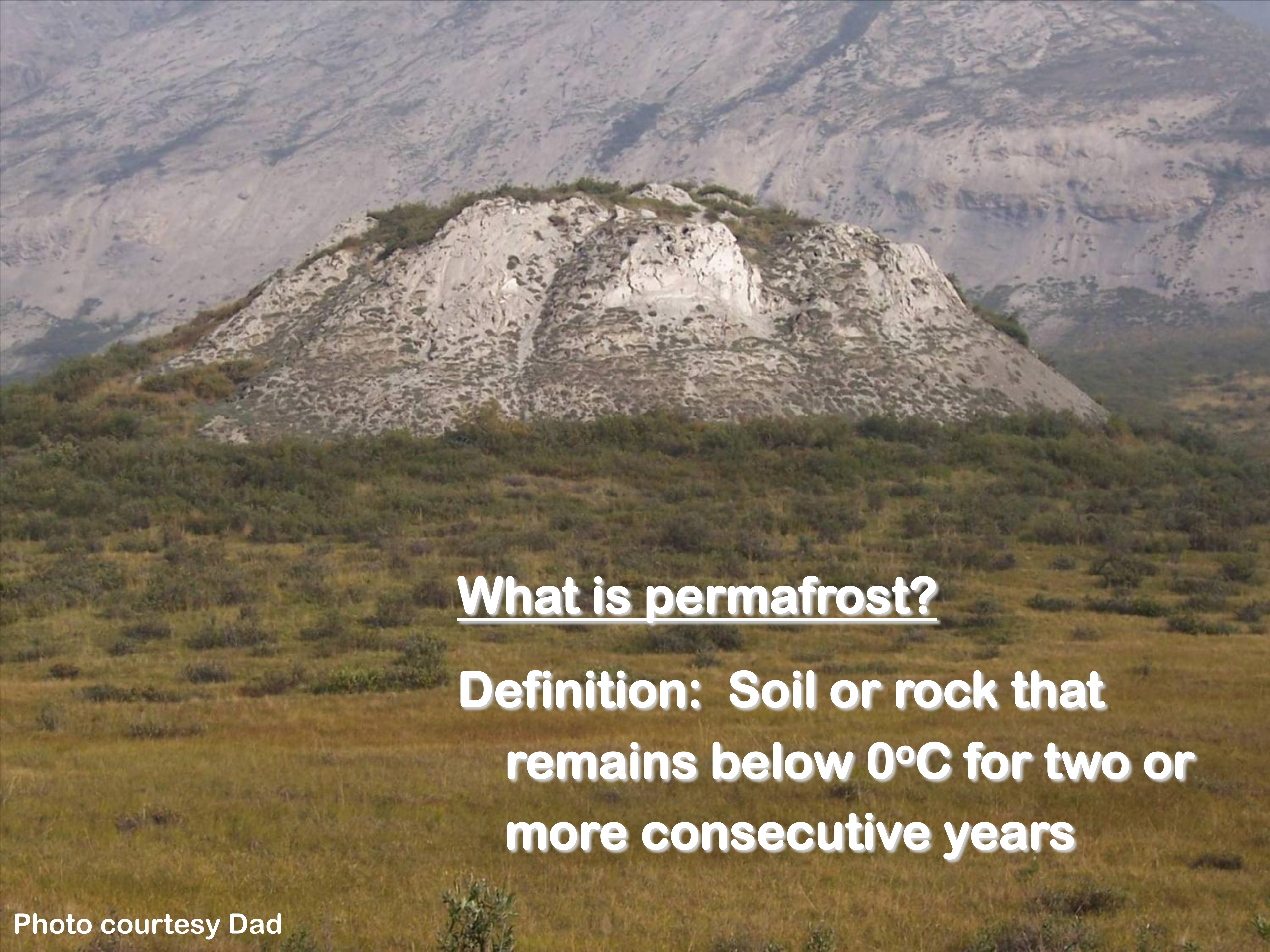


Photo courtesy Dad