Permafrost-climate feedbacks in CESM/CLM

David Lawrence

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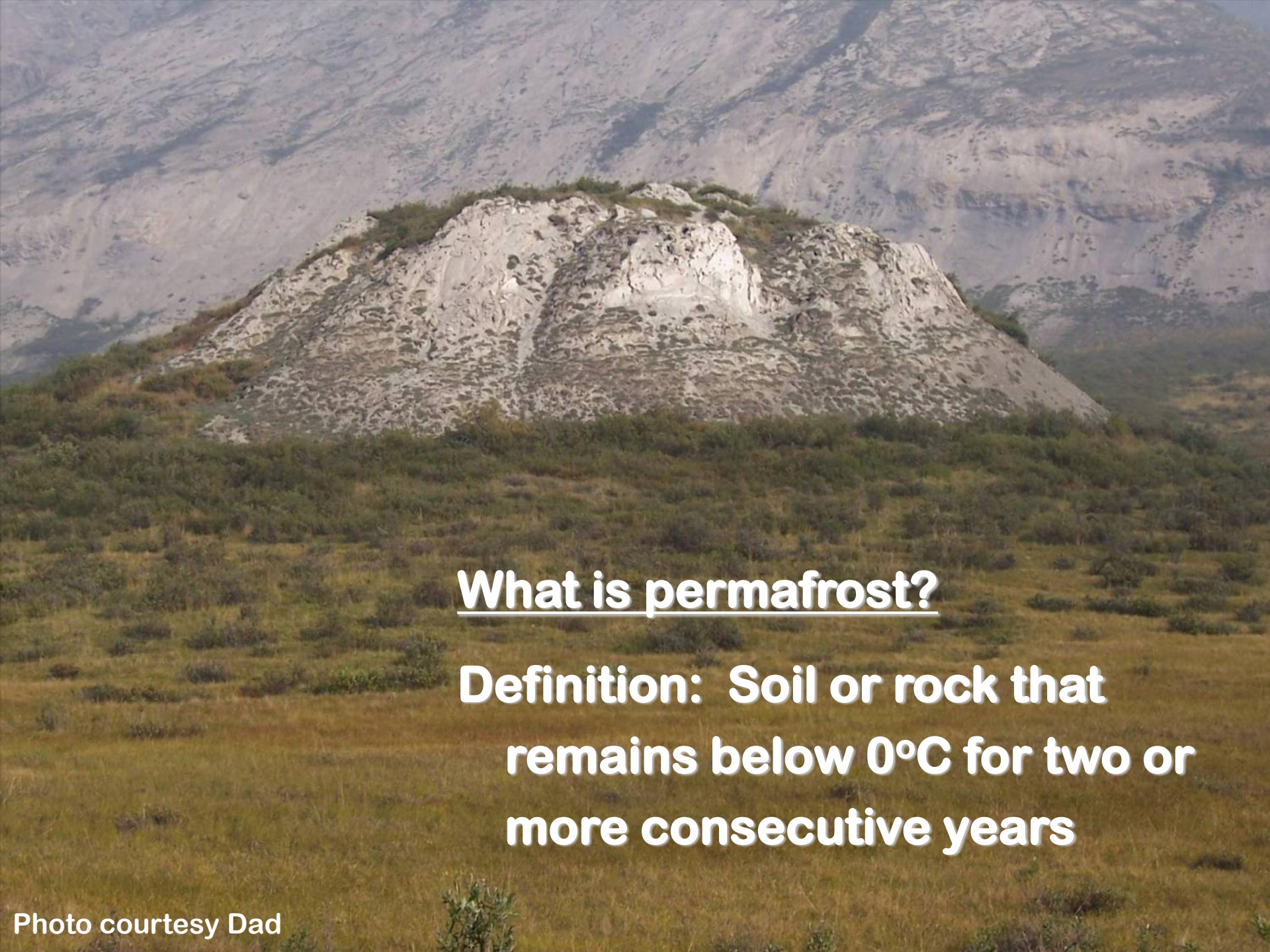
NCAR is sponsored by the National Science Foundation

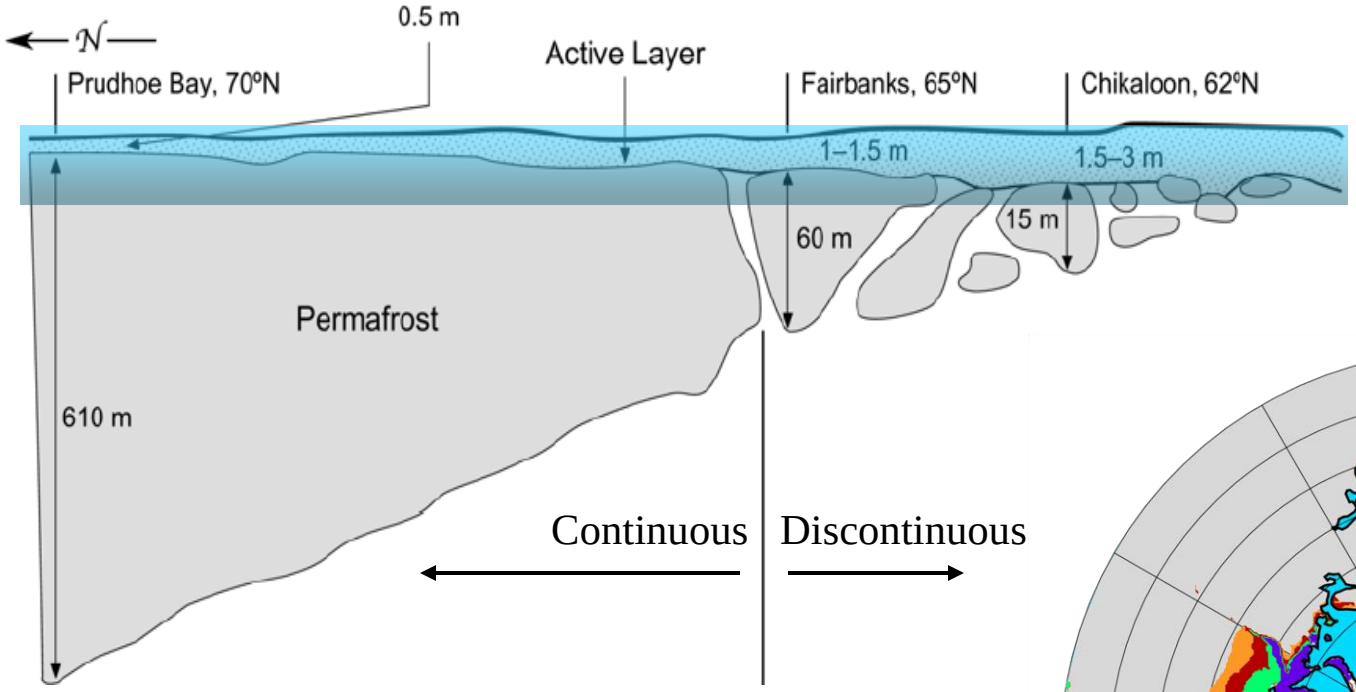


What is permafrost?

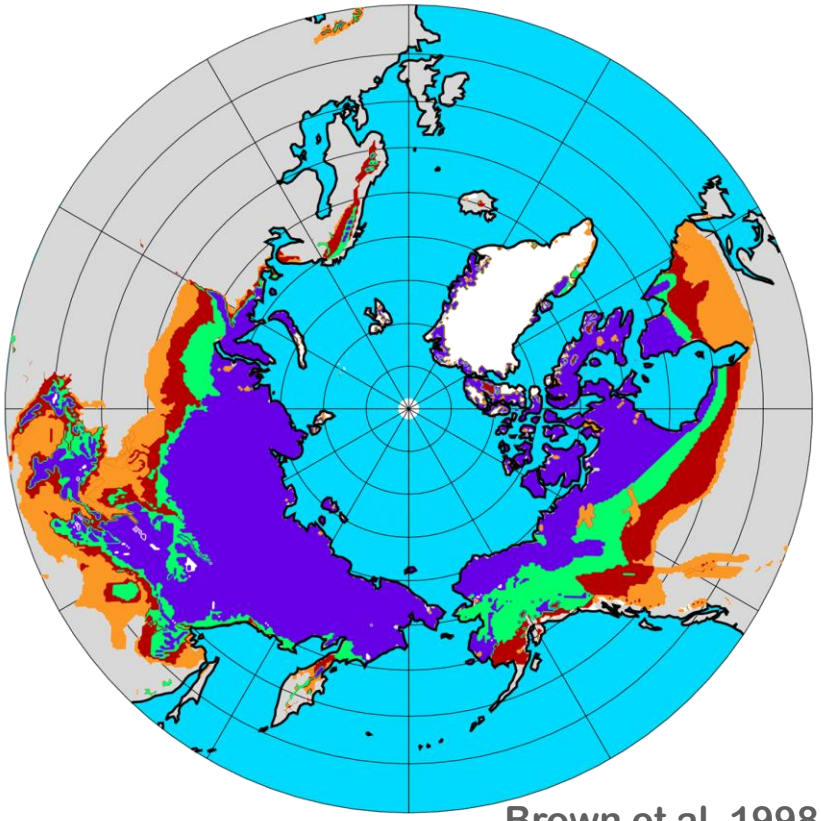
Definition: Soil or rock that remains below 0°C for two or more consecutive years

Photo courtesy Dad

Global Permafrost Distribution



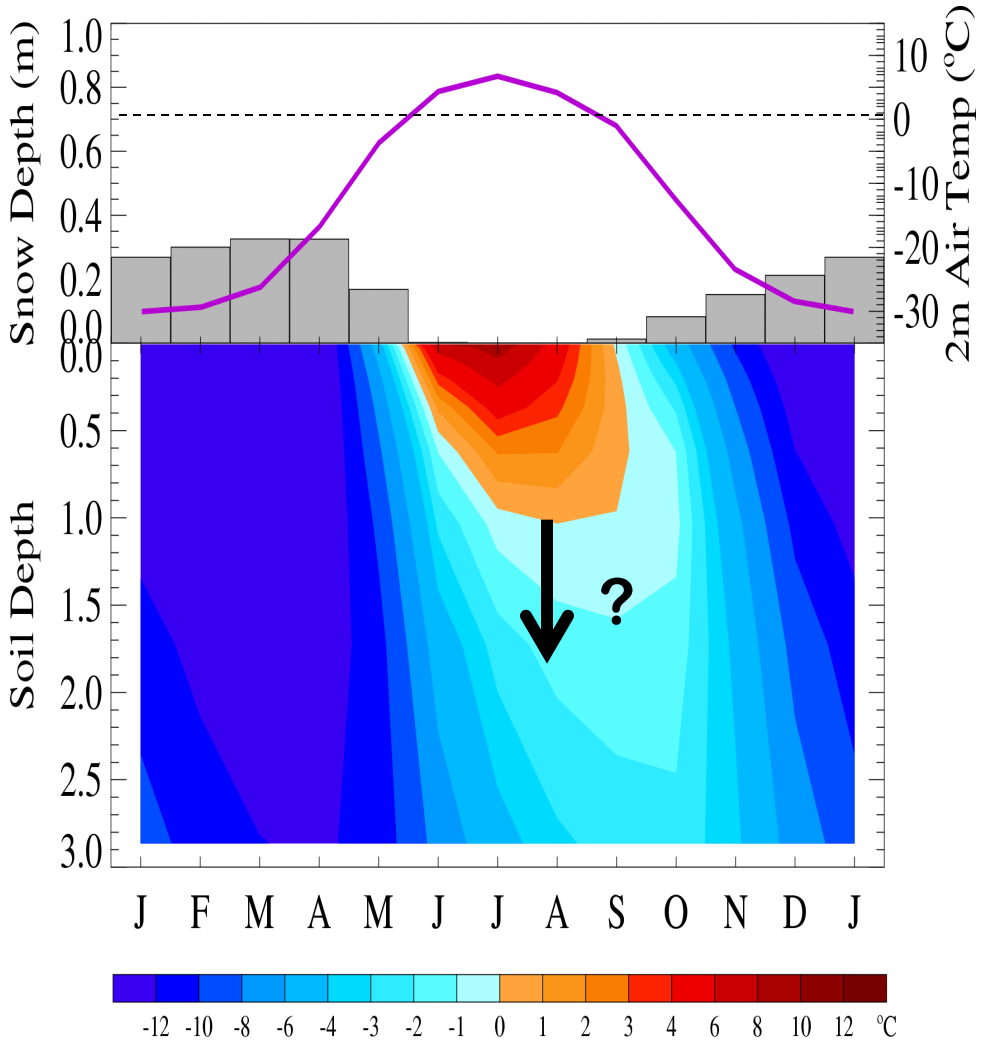
IPA Permafrost Distribution Map



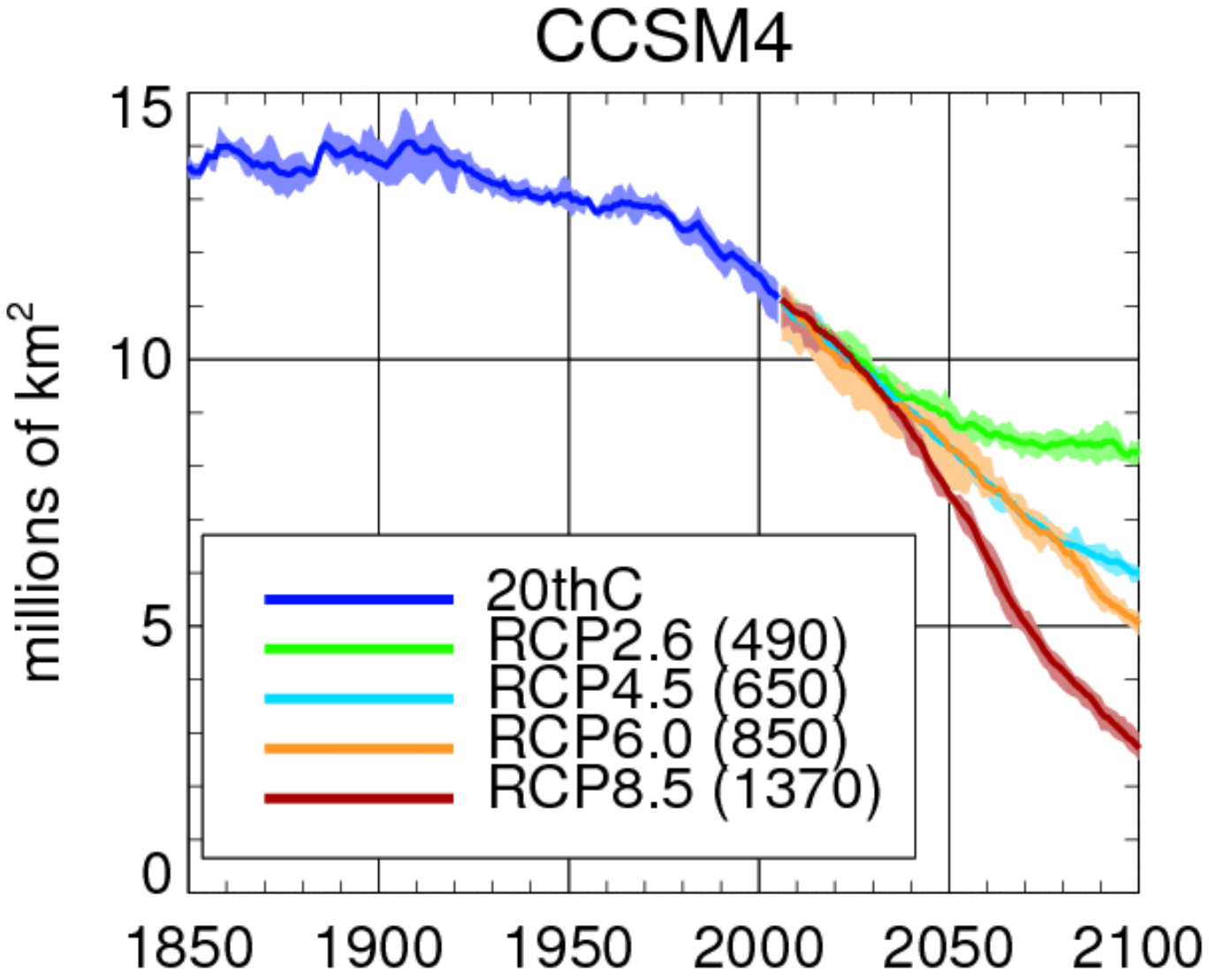
- Continuous (90 – 100% coverage)
- Discontinuous (50 – 90%)
- Sporadic (10 – 50%)
- Isolated (0 – 10%)

Brown et al. 1998

Active Layer Thickness (ALT)

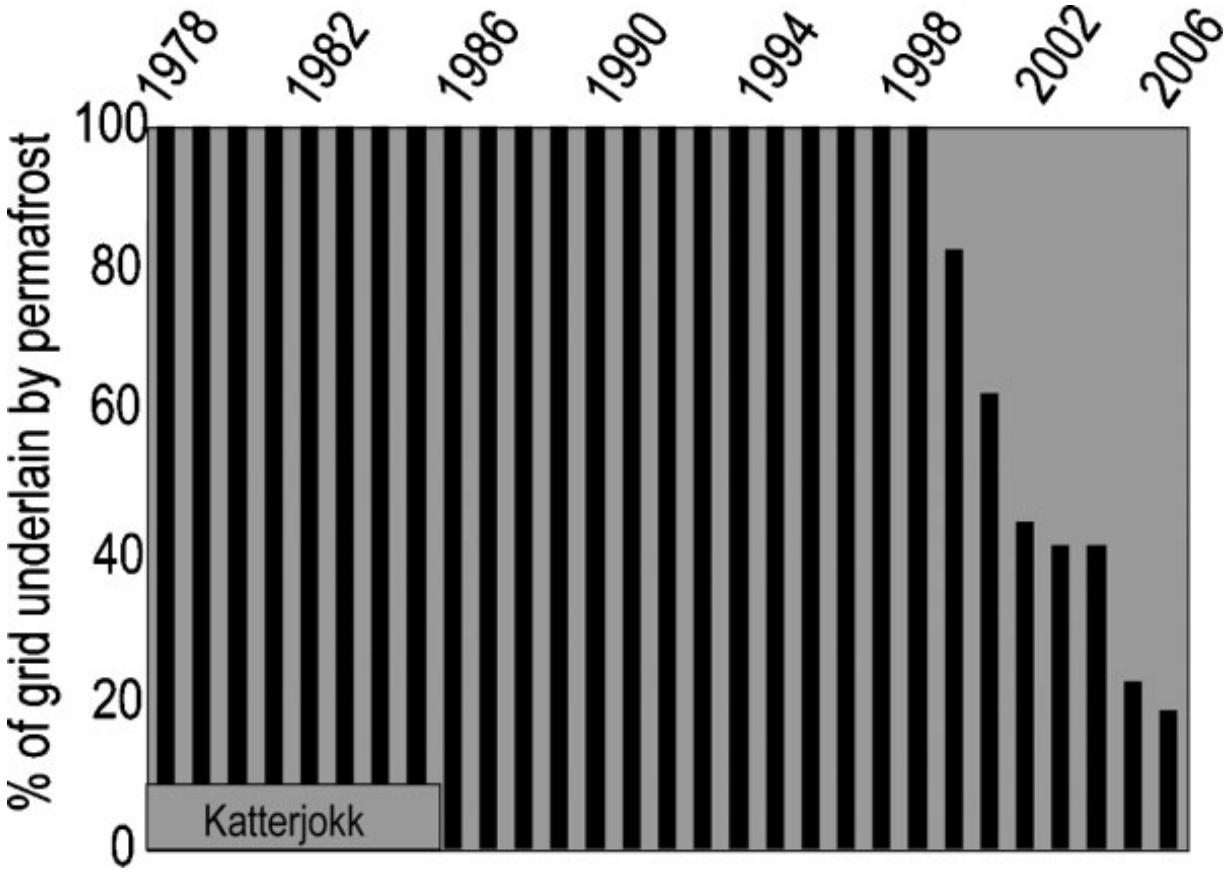


Projections of near-surface permafrost thaw



Lawrence et al., J.Clim, 2012

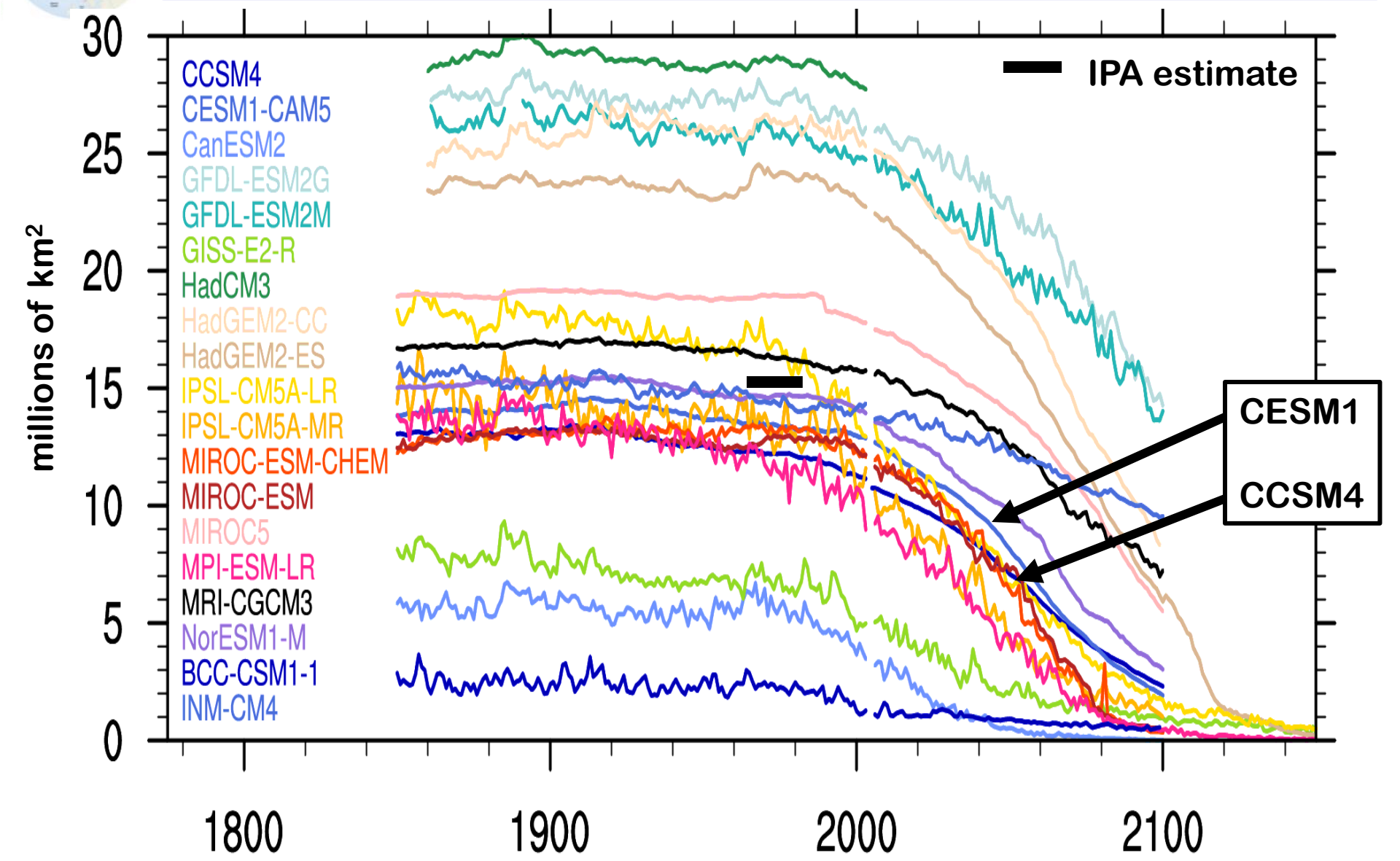
Observed rapid permafrost degradation



Akerman and Johansson, 2008

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

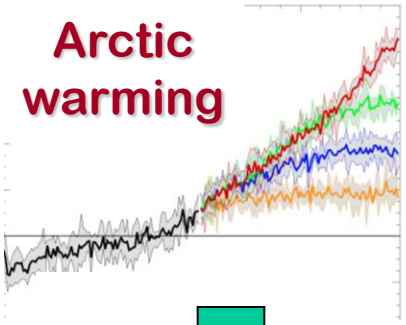
CMIP5 Models: Near-surface permafrost extent (RCP 8.5)



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

Potential Arctic terrestrial climate-change feedbacks

Arctic warming



Carbon sequester

Shrub growth

Enhanced [nitrogen]

Microbial activity increases

Permafrost warms and thaws

Expanded wetlands

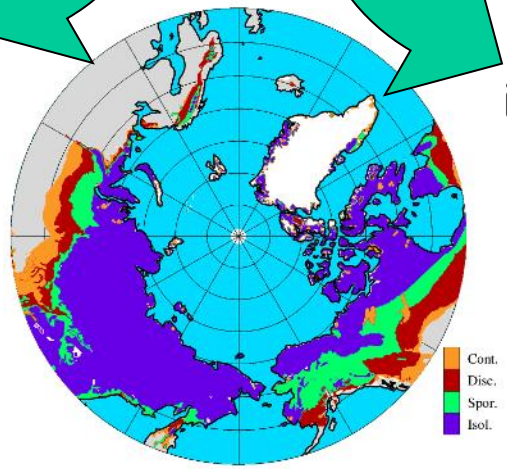
Lakes drain, soil dries

Arctic runoff increases

CO_2 efflux

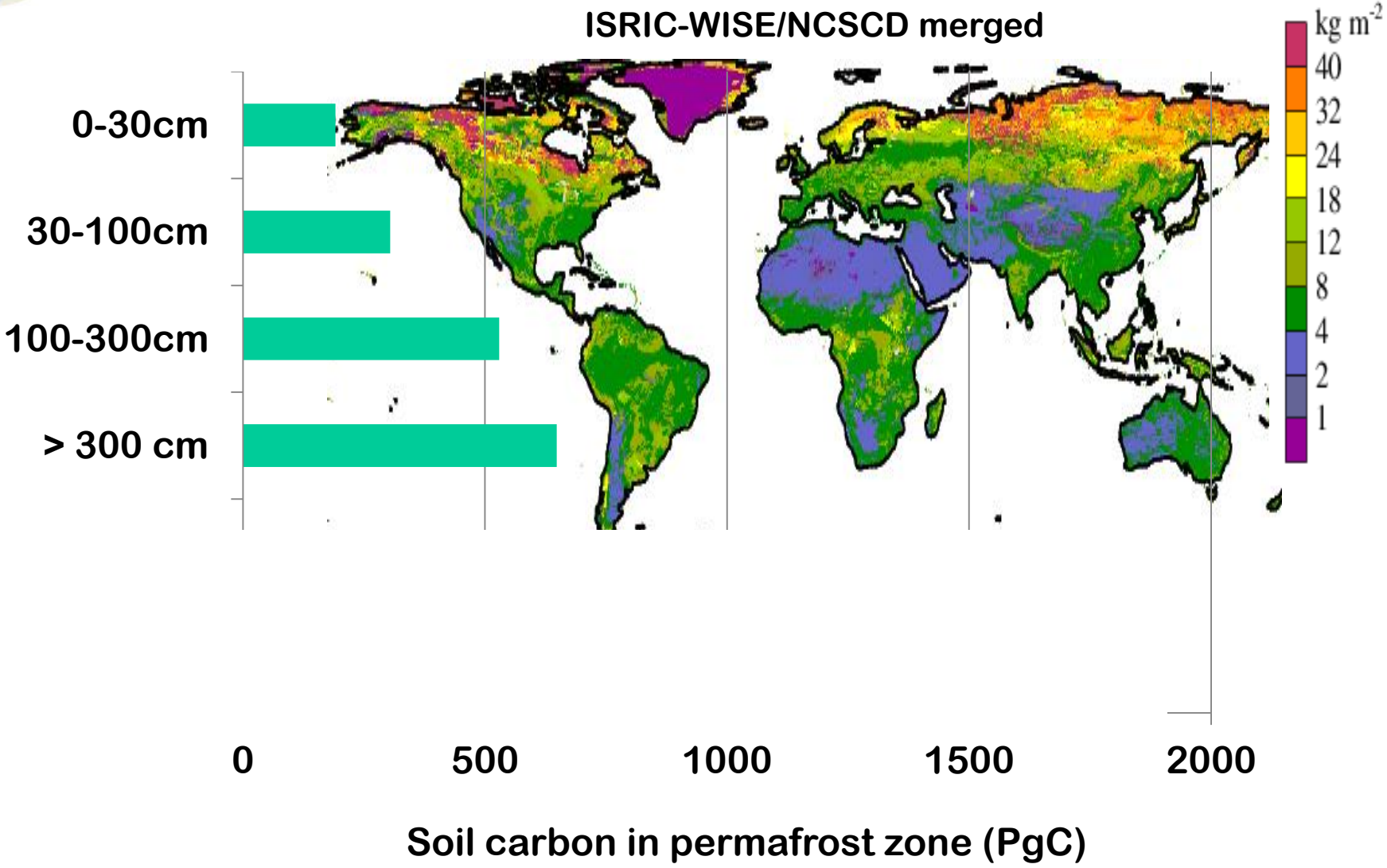
CH_4 efflux

Global warming



Adapted from McGuire et al., 2006

Soil carbon in permafrost zone



Tarnocai et al. 2009

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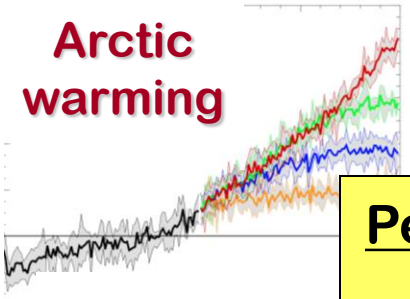

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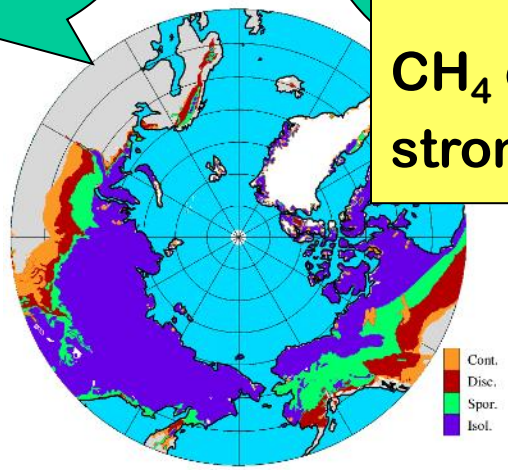


Permafrost-Carbon feedback

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

Adapted from McGuire et al., 2006

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

dry, well-drained soil

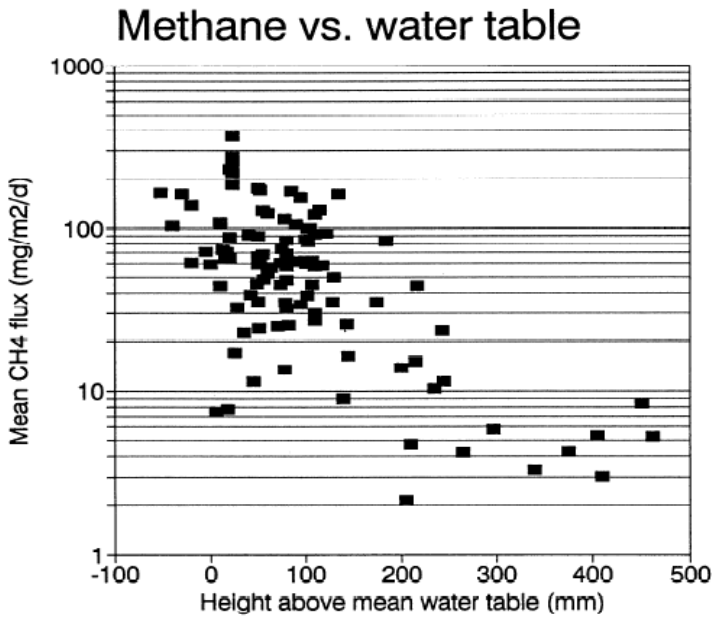
aerobic decomposition

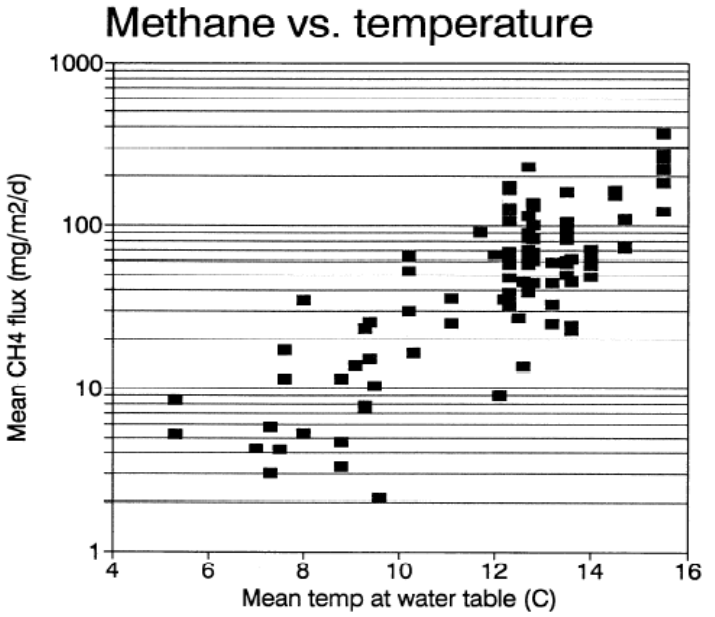
→ CO_2 emissions

increased wetlands and warmer soil

anaerobic decomposition

→ CH_4 production (25x GWP)





Bubier et al. 1995

Potential Arctic terrestrial climate-change feedbacks

Arctic warming

Carbon sequester

Global

CO_2 efflux

What is the integrated effect of Arctic land feedbacks?

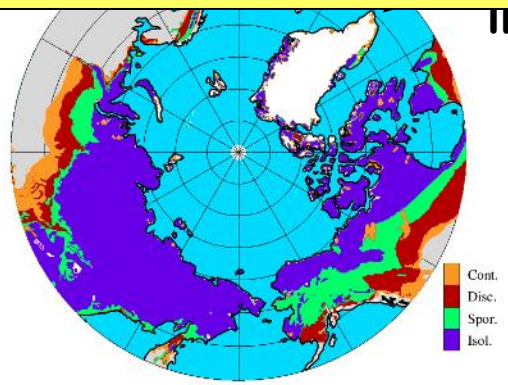
Is it + or − ?

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

increases

Lakes drain, soil dries



Arctic runoff increases

Adapted from McGuire et al., 2006

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

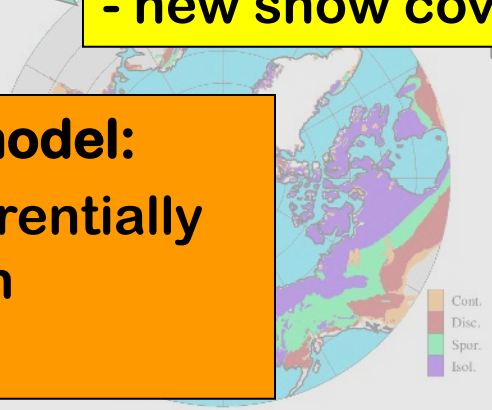
Soil biogeochemistry: vertically resolved soil carbon model; accounts for limitations on decomposition in cold/saturated conditions

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

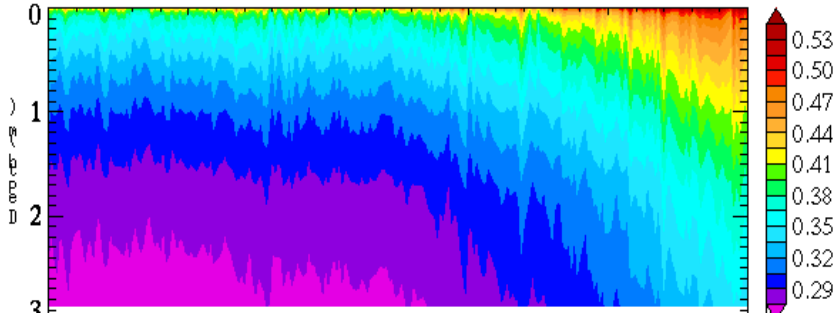
Prognostic wetland model:
- wetlands form preferentially in low gradient terrain
- flooding



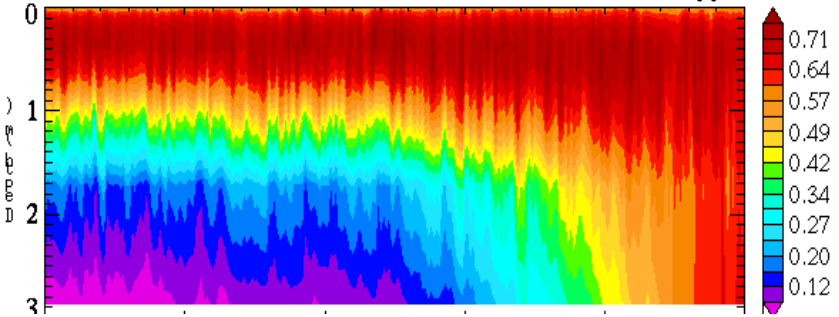
Adapted from McGuire et al., 2006

Soil carbon decomposition in CLM4.5
Permafrost zone

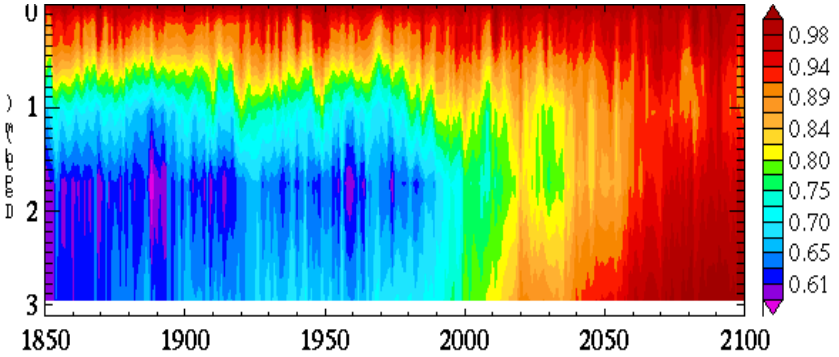
Temperature scalar (r_T)



Soil liquid water scalar (r_W)

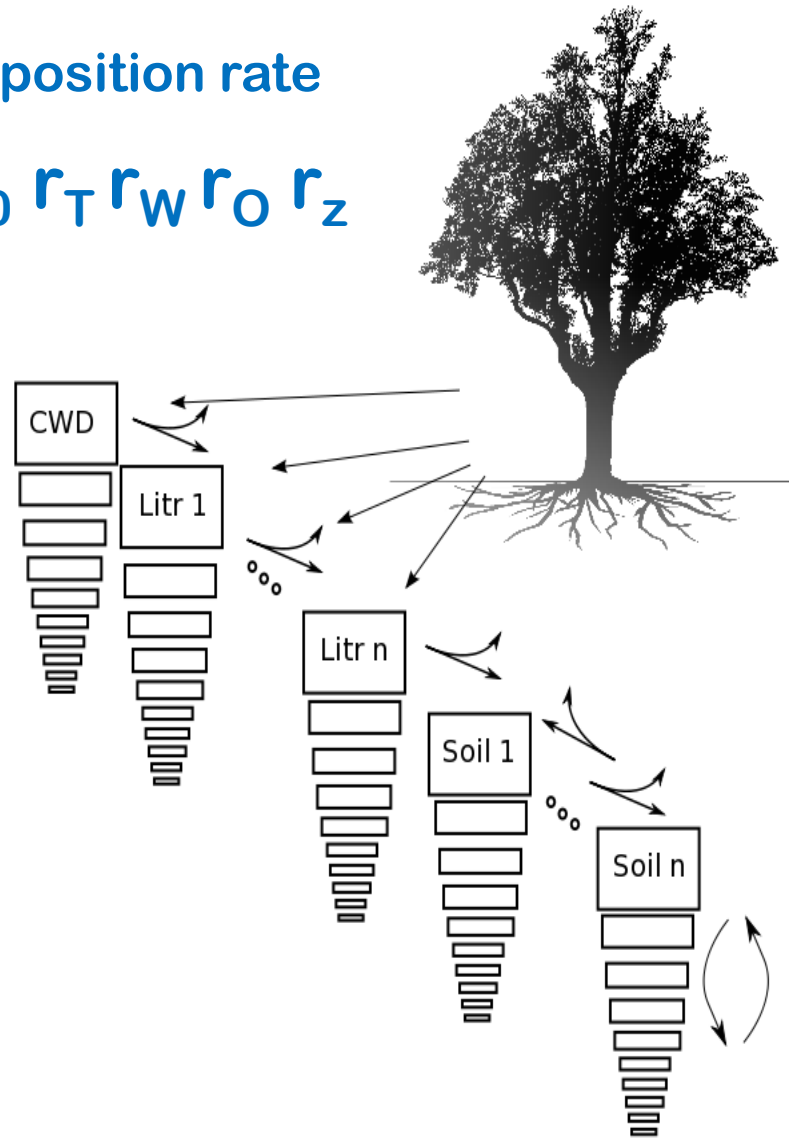


Oxygen availability scalar (r_O)

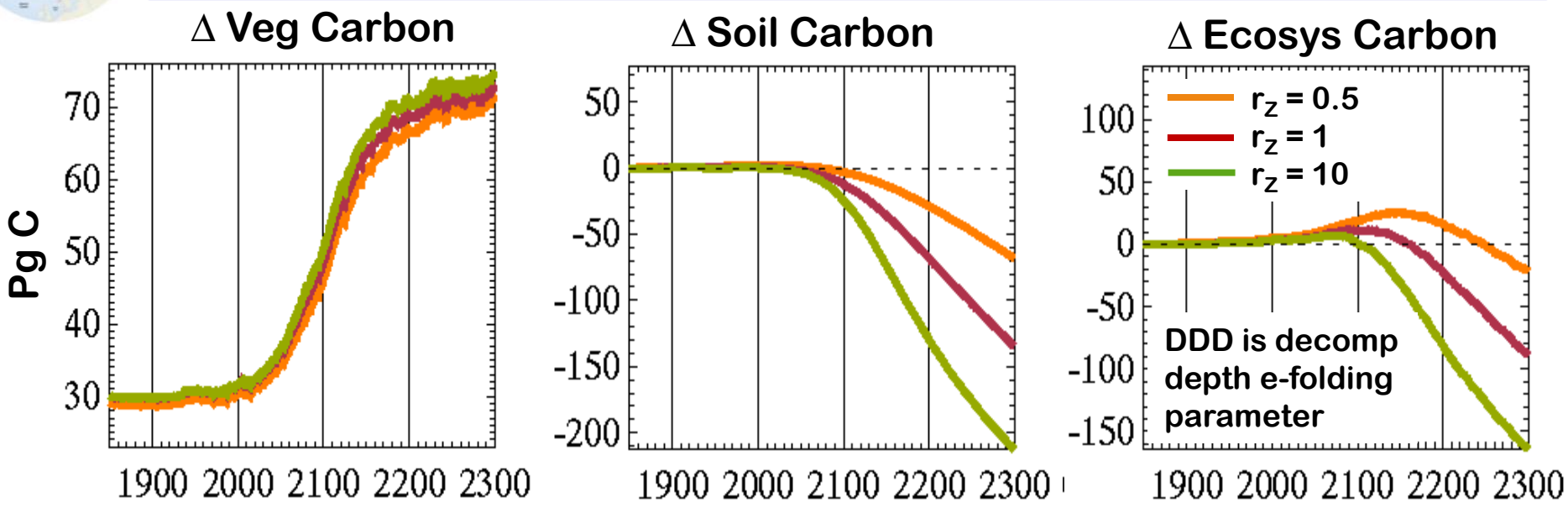


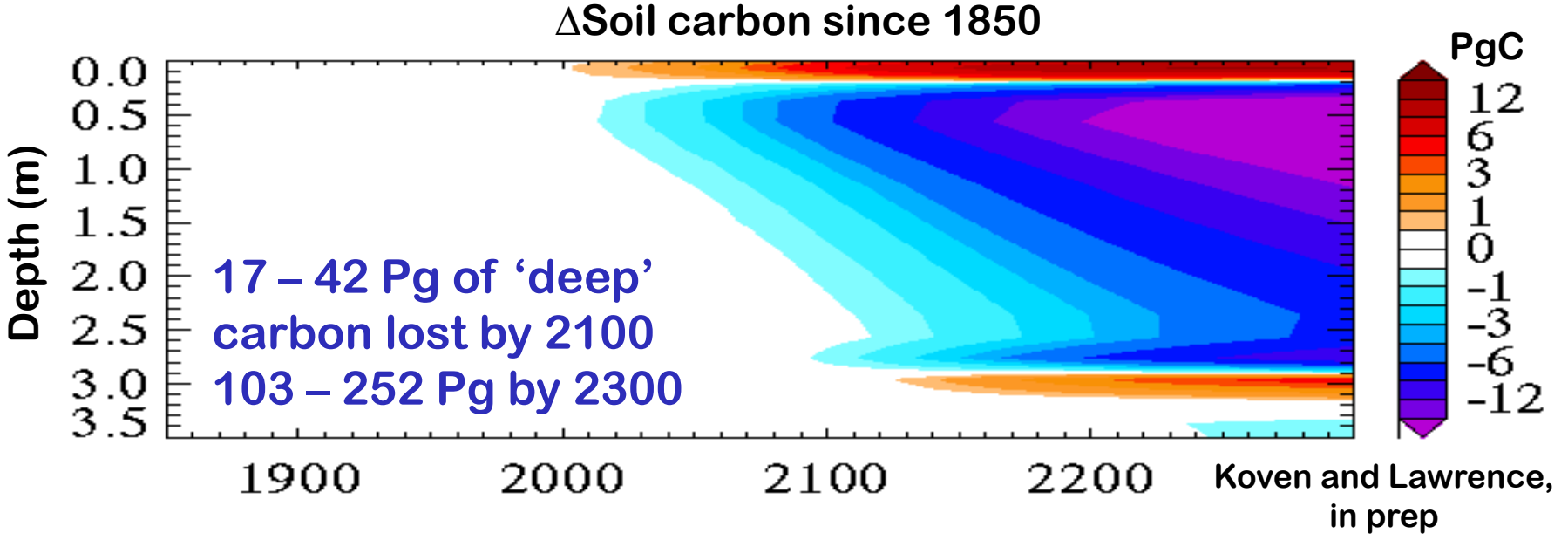
Decomposition rate

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



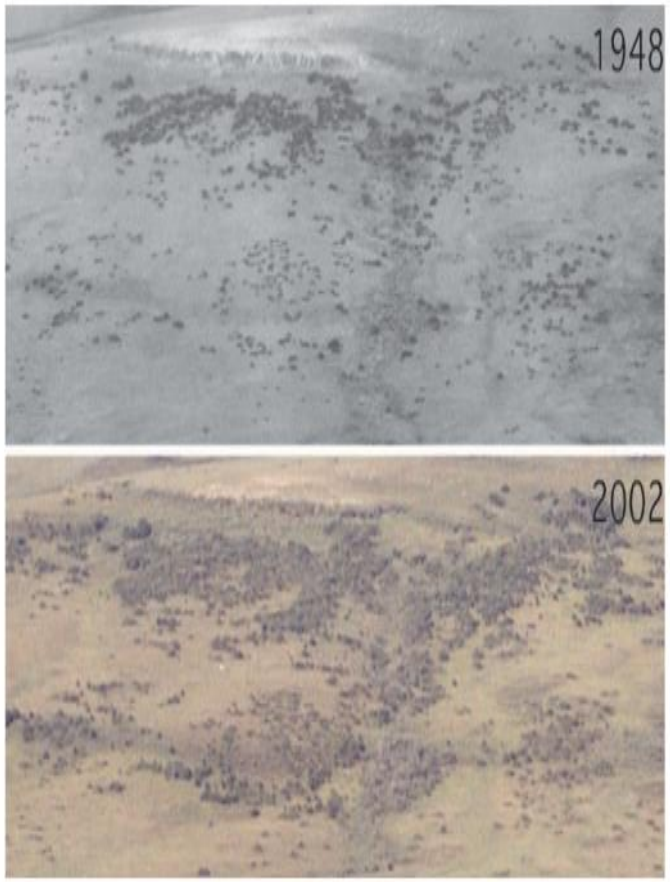
Projected carbon stock trends in permafrost zone (preliminary results, CLM4.5BGC)



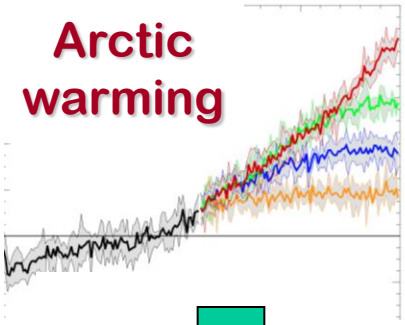


Photos: Bernhard Edmaier , National Geographic

Shrub – permafrost interactions



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



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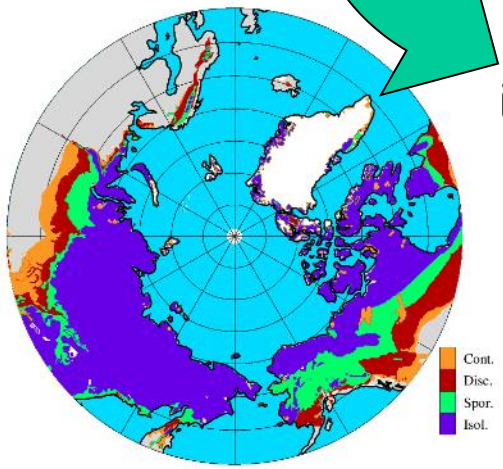
Shrub growth



Adapted from McGuire et al., 2006

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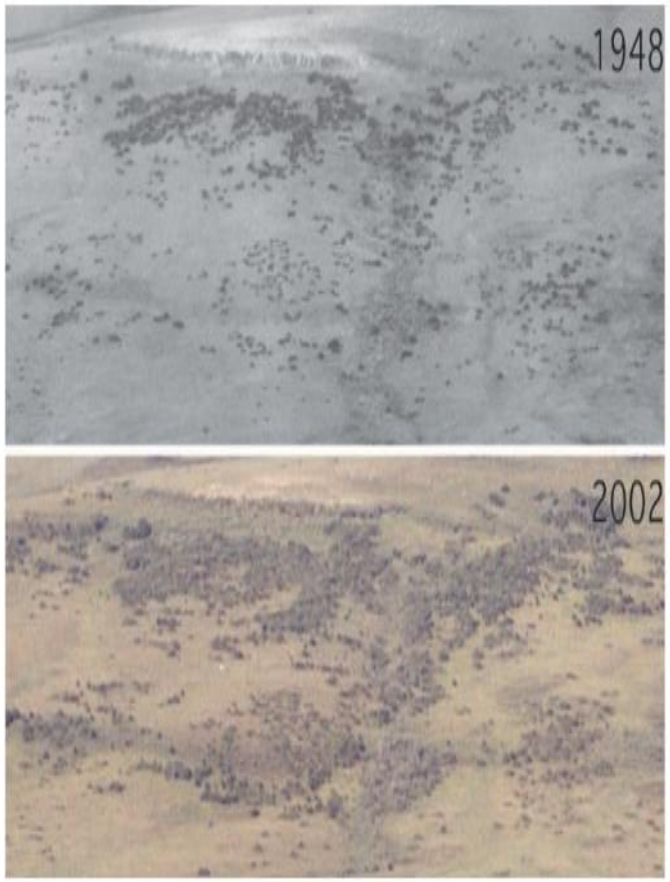

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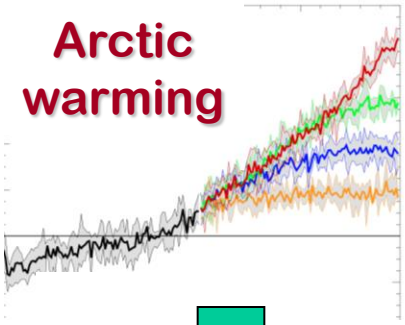

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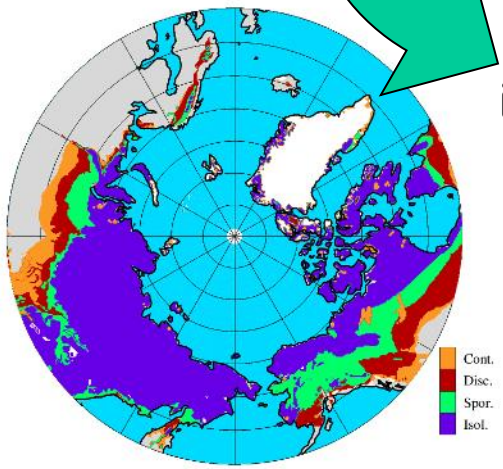
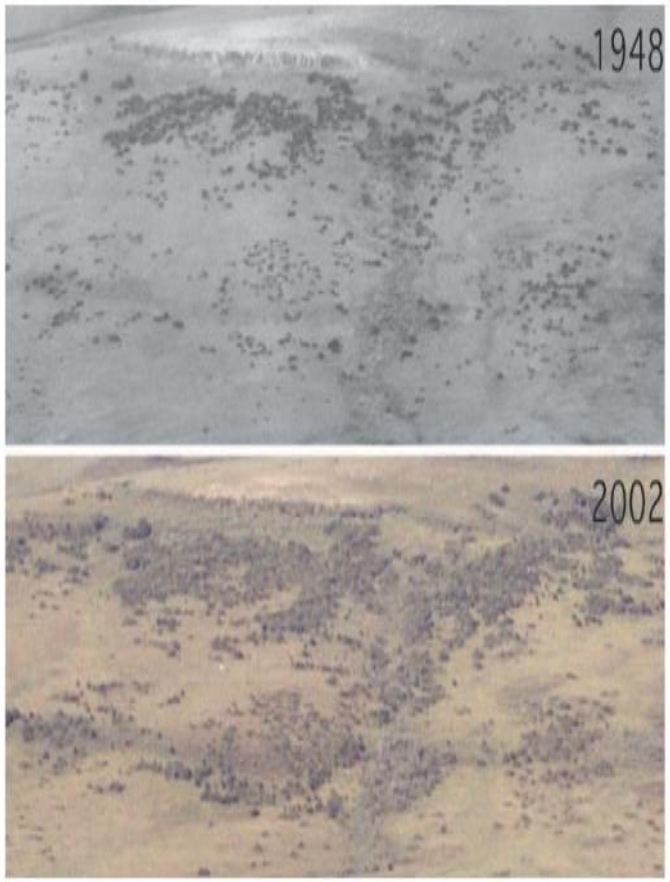
Carbon Sequester



+20PgC for +20% shrub

Adapted from McGuire et al., 2006

Shrub – permafrost interactions



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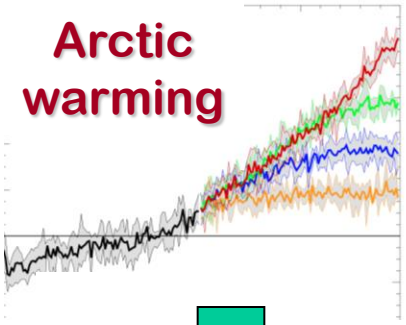

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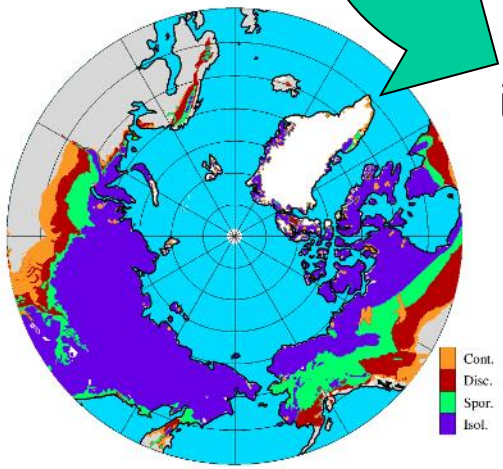

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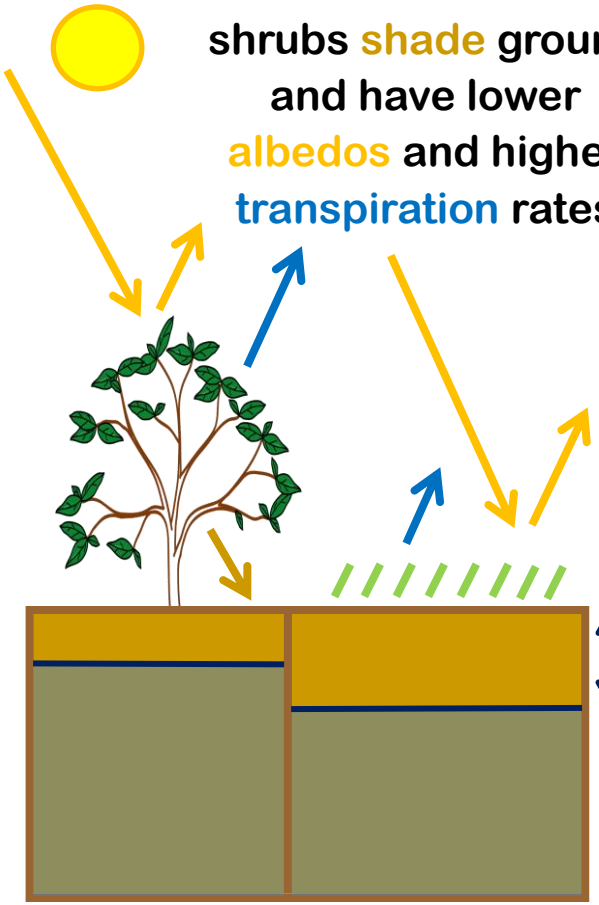
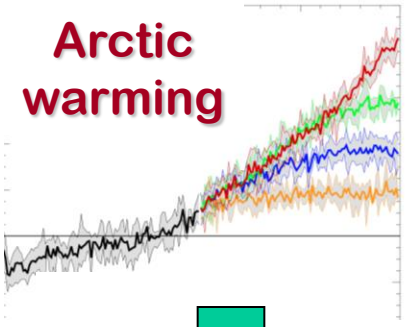
Potential Arctic terrestrial climate-change feedbacks

shrubs shade ground and have lower albedos and higher transpiration rates





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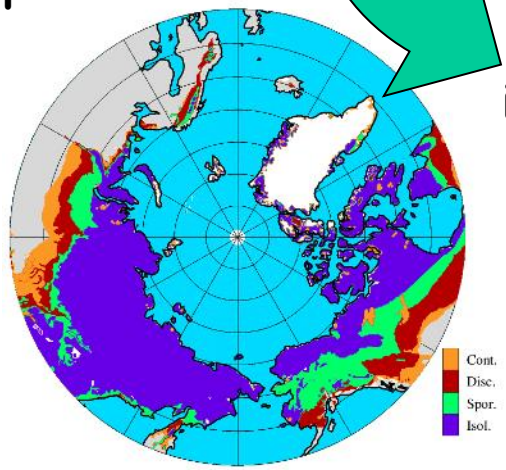

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Global Change Biology

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

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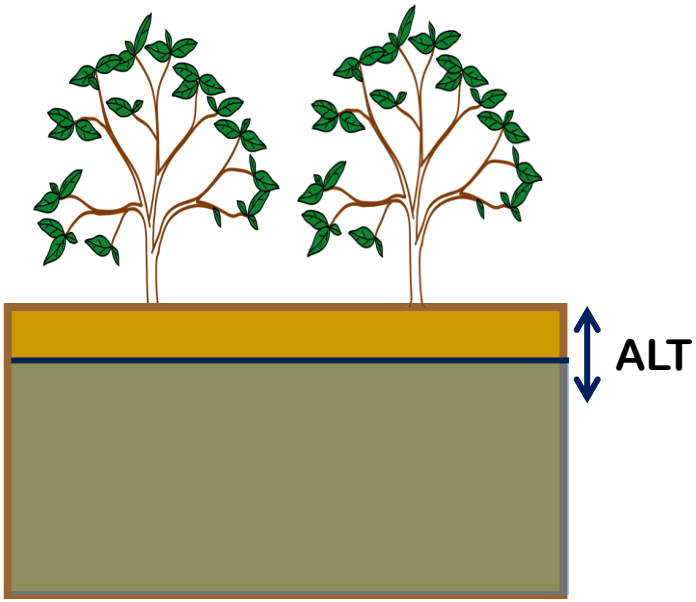

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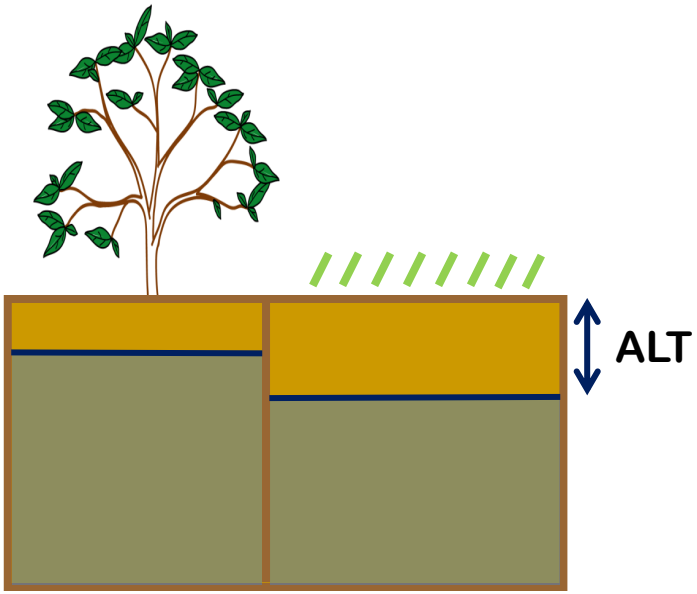
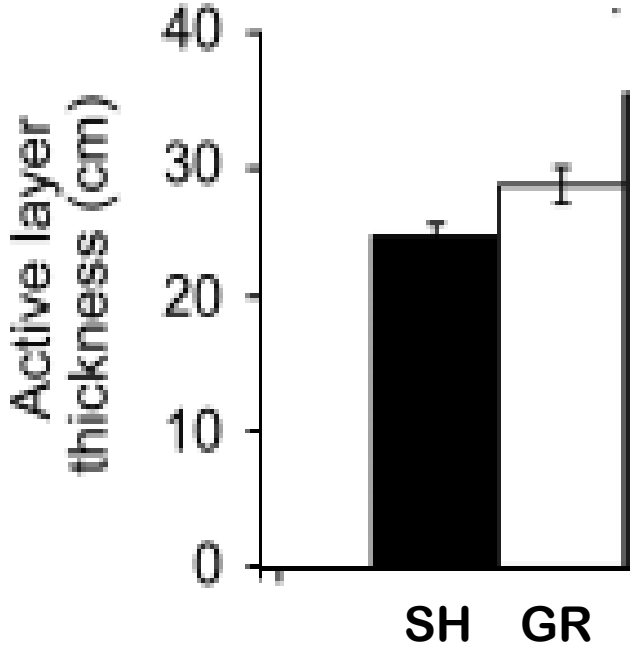


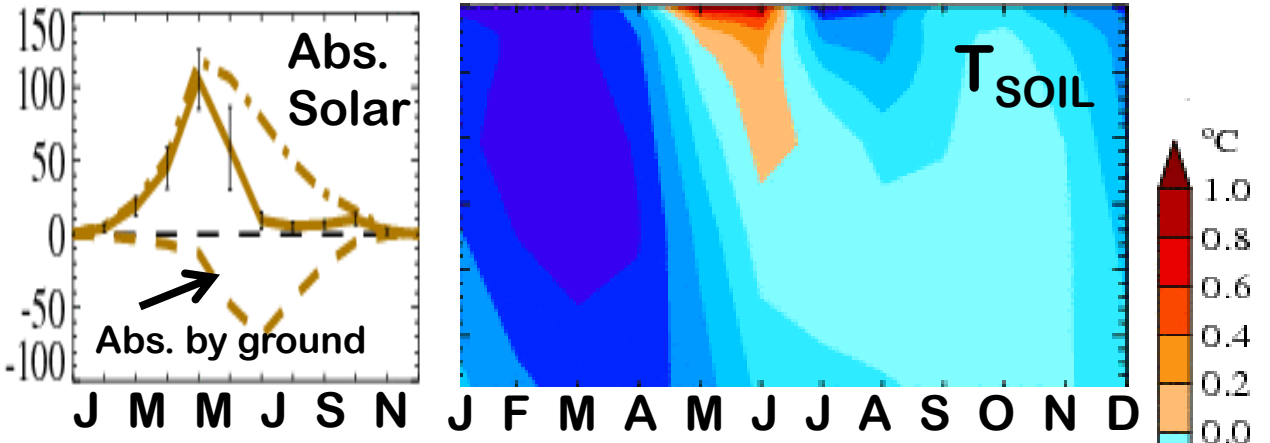


"These results suggest that the expected expansion of deciduous shrubs in the Arctic region, triggered by climate warming, may reduce summer permafrost thaw."

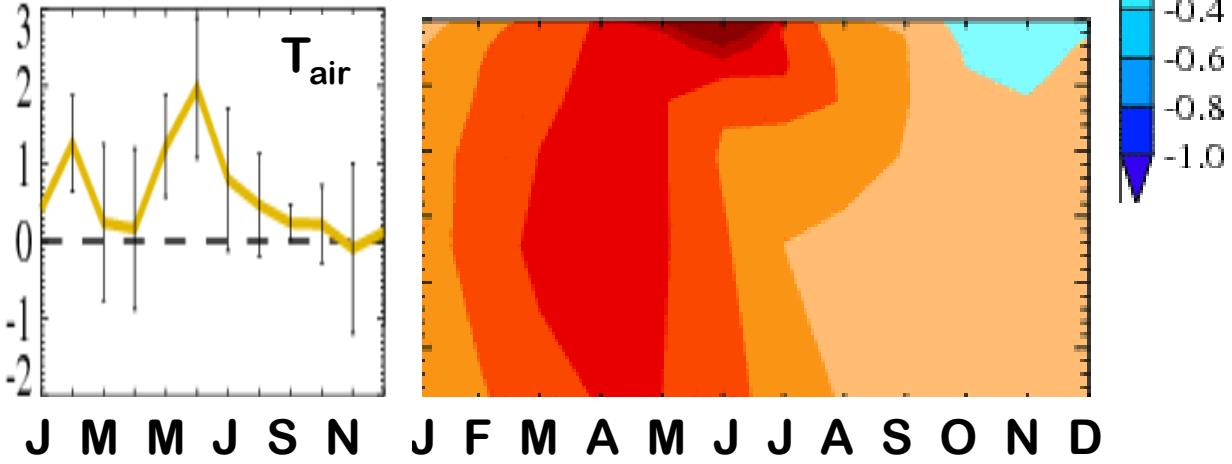
Evaluate this hypothesis using CCSM4

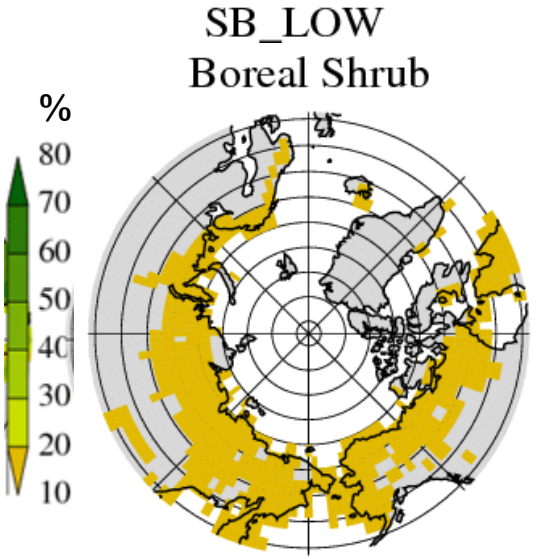
Examining impact of shrubs on permafrost using CESM

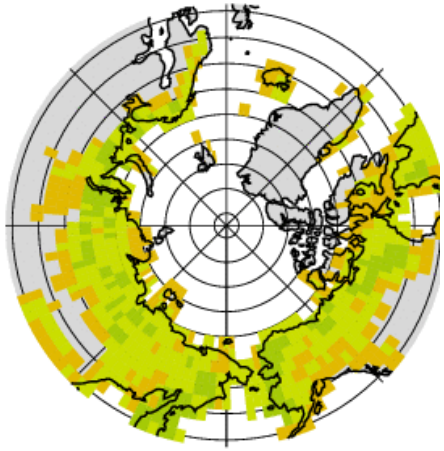
SB_LOW: Shrub – Grass



SB_HIGH – SB_LOW: Grid cell mean

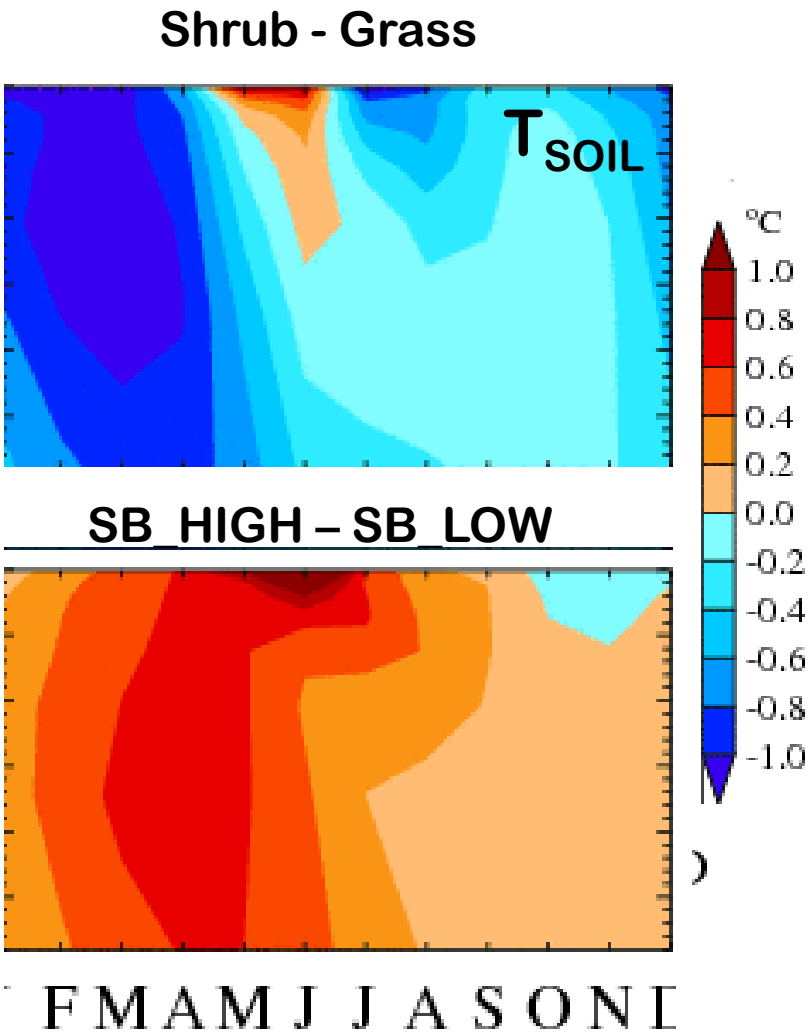






Lawrence and Swenson, 2011

Impact of shrubs on permafrost

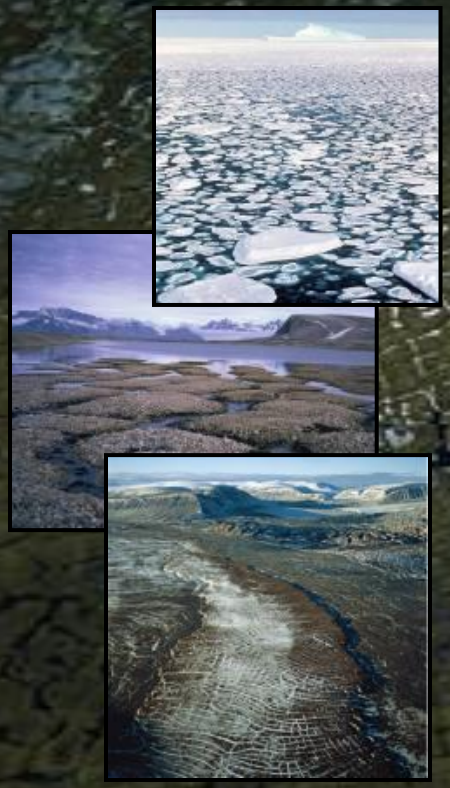


Will expanding Arctic shrub cover decrease permafrost vulnerability to climate change?

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



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

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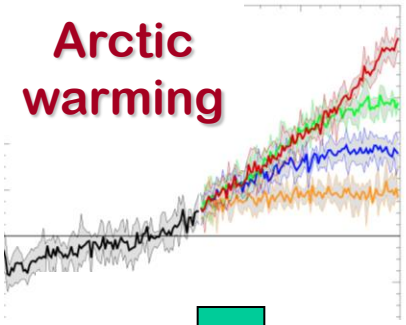
Potential Arctic terrestrial climate-change feedbacks

Arctic warming



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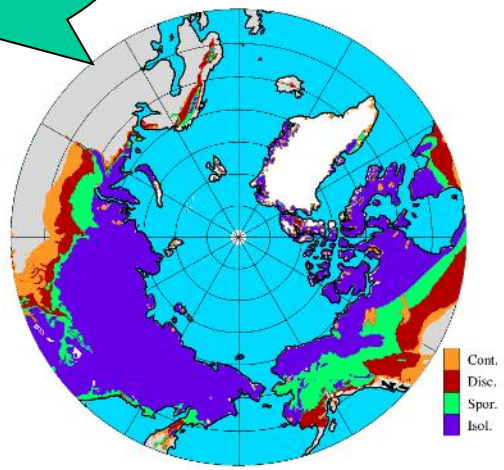
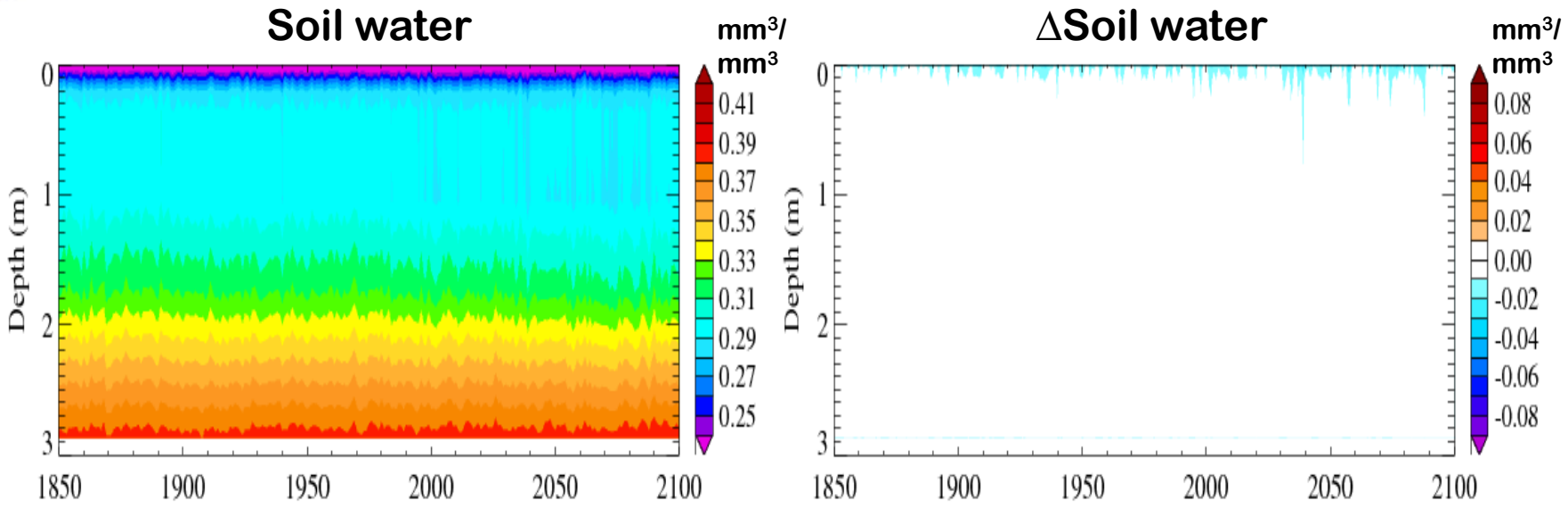


Adapted from McGuire et al., 2006

Soil hydrologic response to permafrost thaw (RCP8.5)

CLM4



Problems with CLM4 active layer hydrology

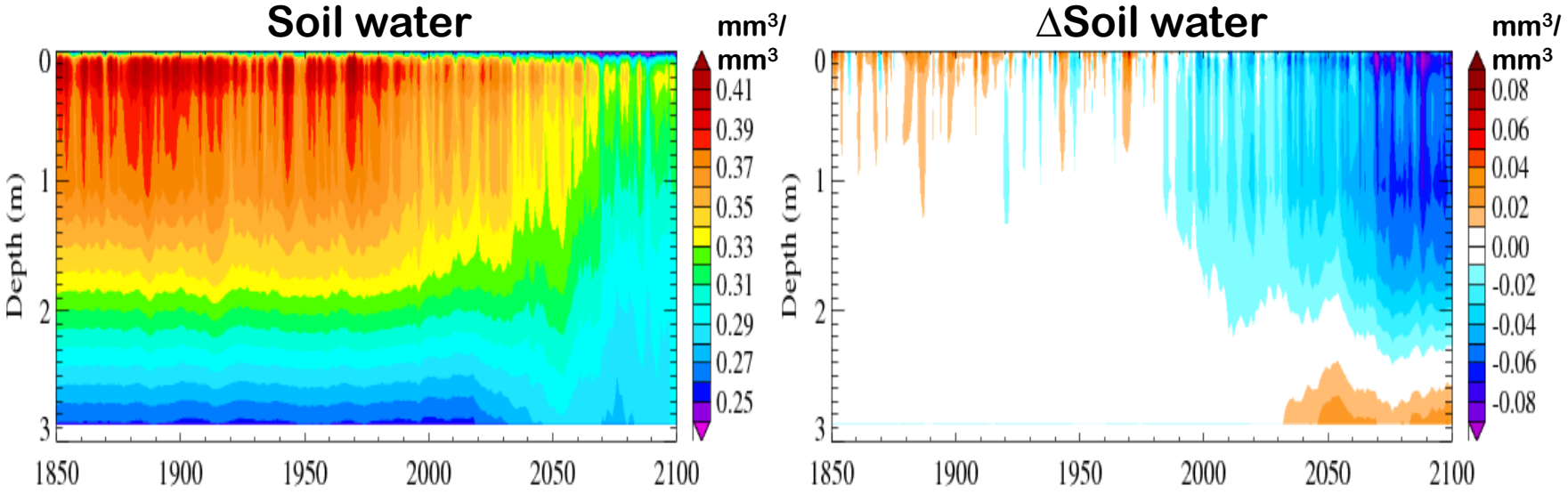
Surface soils are very dry

(some locations are too dry to support vegetation)

No soil moisture response to climate change or permafrost thaw

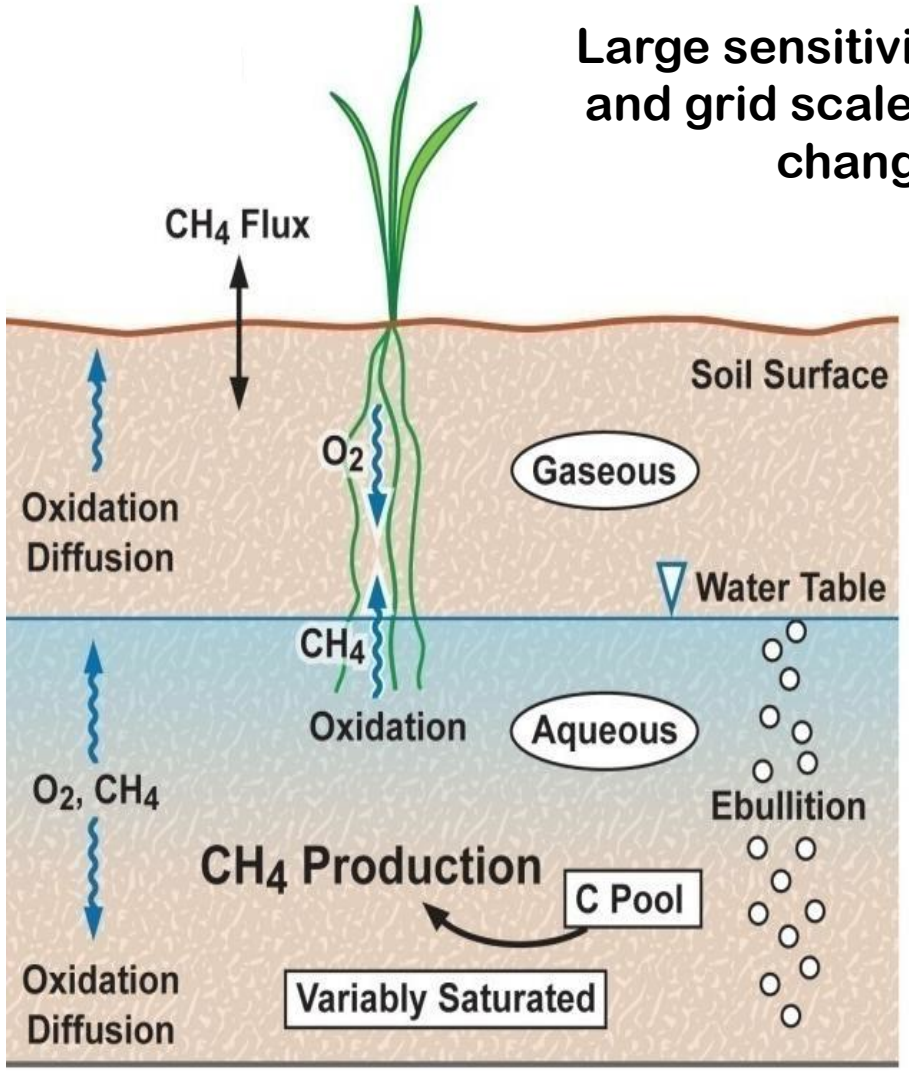
Soil hydrologic response to permafrost thaw (RCP8.5)

CCSM4

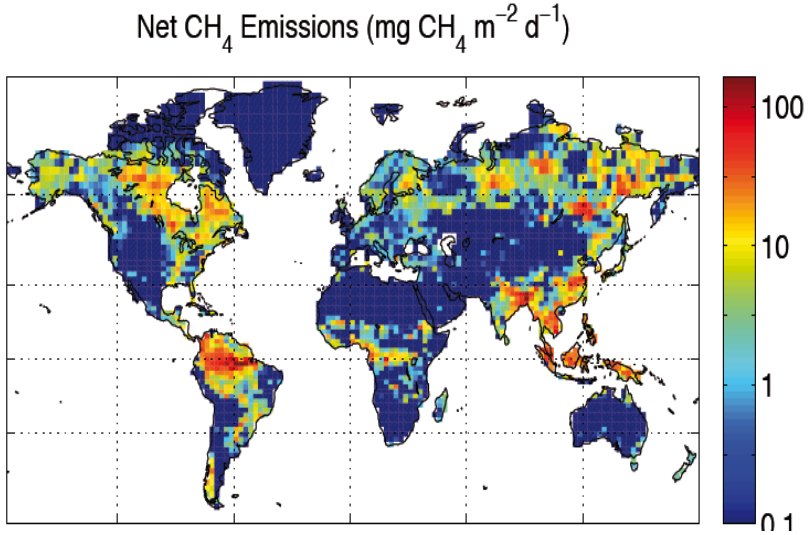


Process based methane emissions model

"Barriers to predicting changes in global terrestrial methane fluxes"



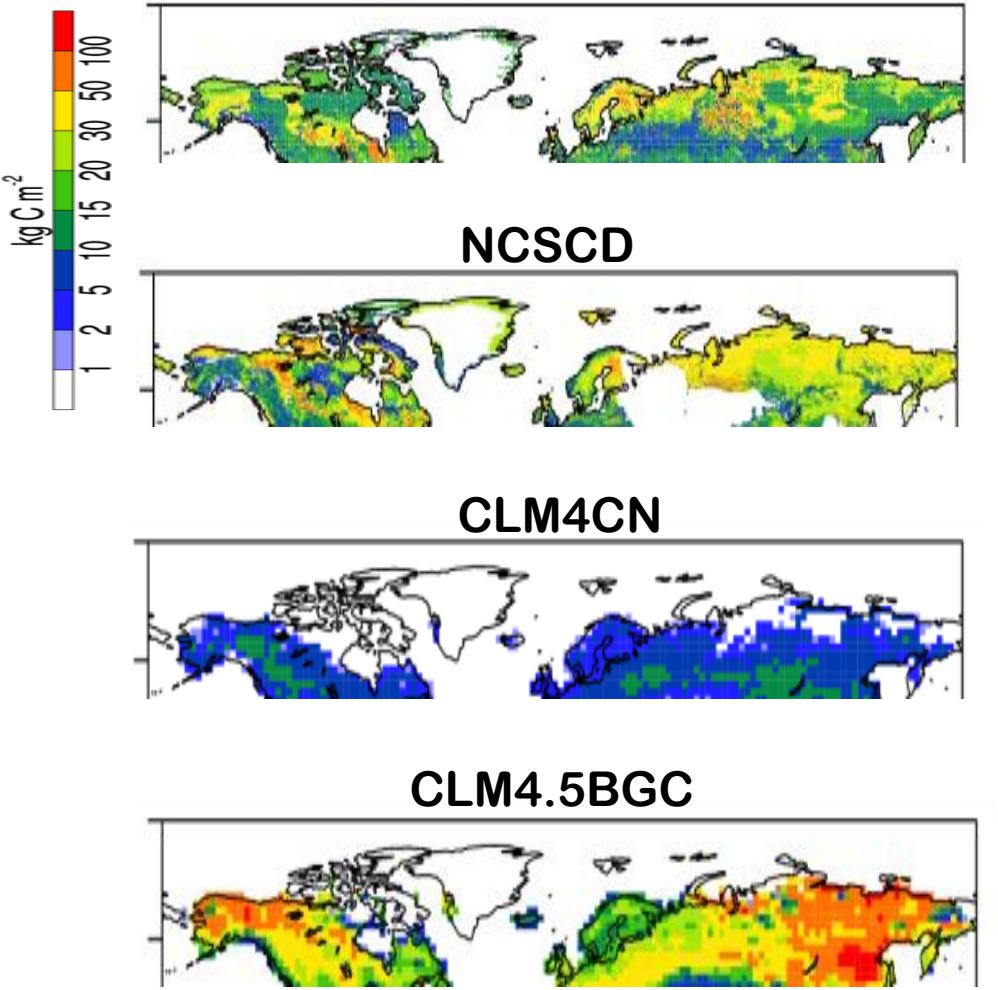
Large sensitivities (up to 4x and 10x at regional and grid scales) in CH_4 fluxes from reasonable changes in model parameters

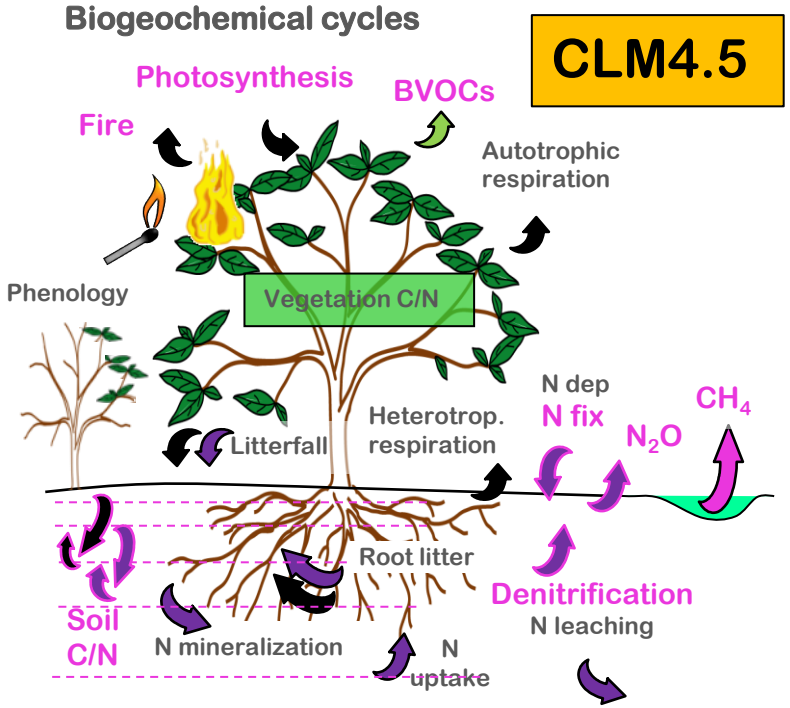


Projections highly uncertain, but with default parameters ~ +20% increase in high-lat CH_4 emissions (A1B)

Riley et al., 2011, Biogeosciences

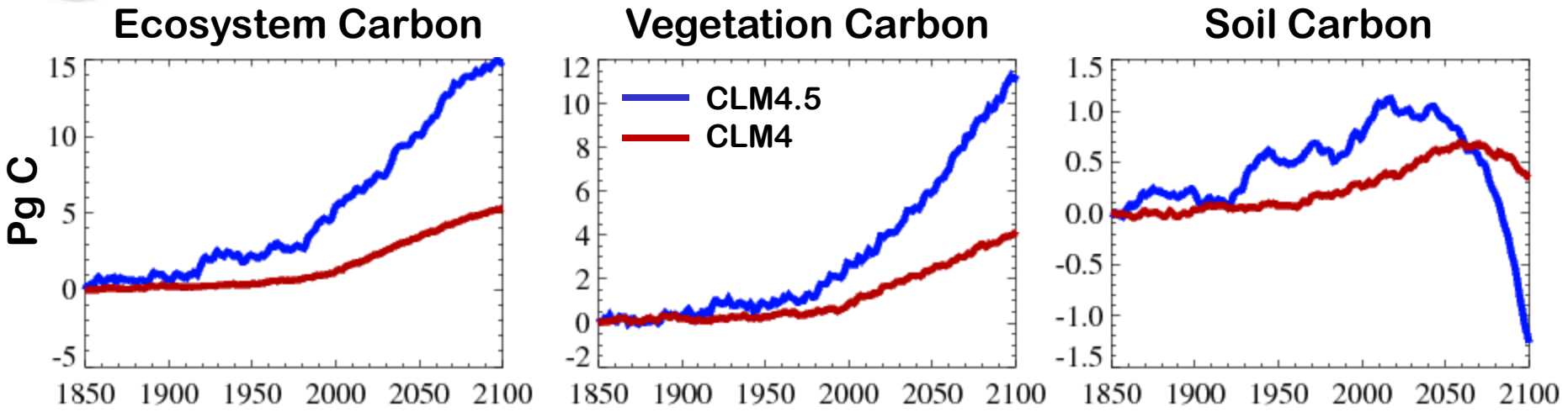
Soil carbon in CLM





Koven et al., 2013

Carbon stock trends in permafrost zone



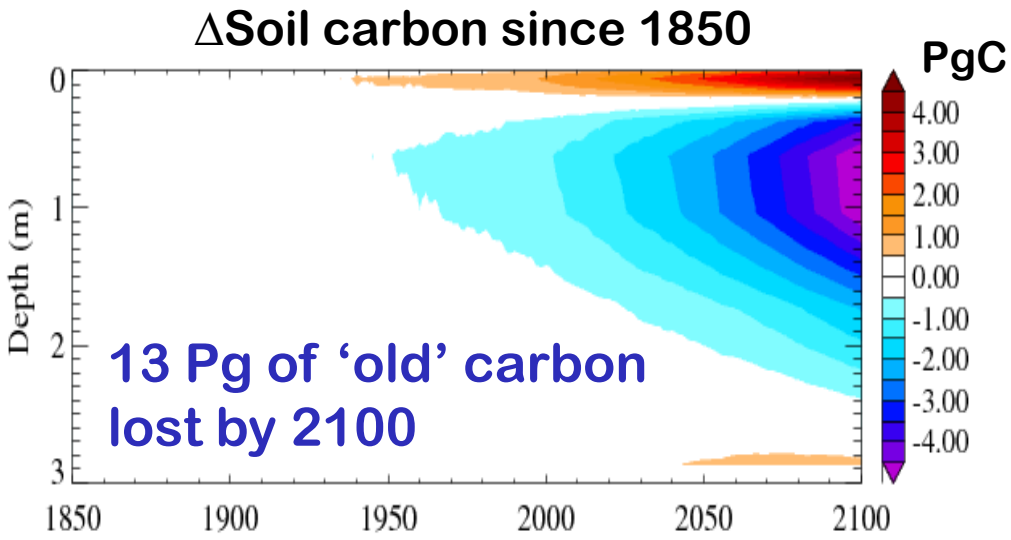
Prior estimates of carbon loss (PgC)

62 ± 6 **ORCHIDEE** (Koven et al., 2011)

100 ± 40 **SibCASA** (Schaefer et al. 2011)

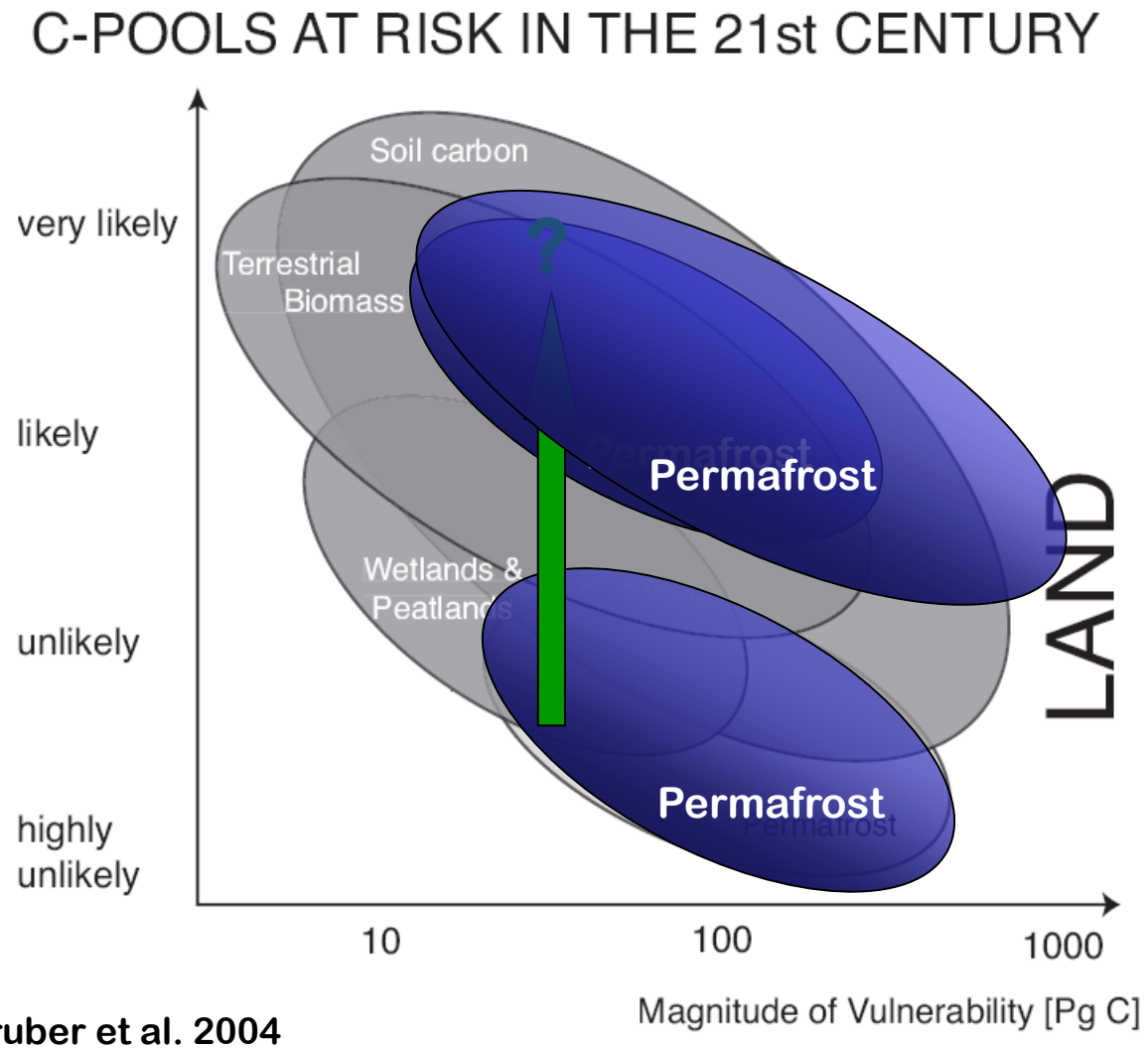
72 ± 40 **MAGICC** (Deimling et al., 2011)

12 ± 6 **TEM** (Zhuang et al. 2006)



Release of Soil Carbon Frozen in Permafrost

Global Carbon Project

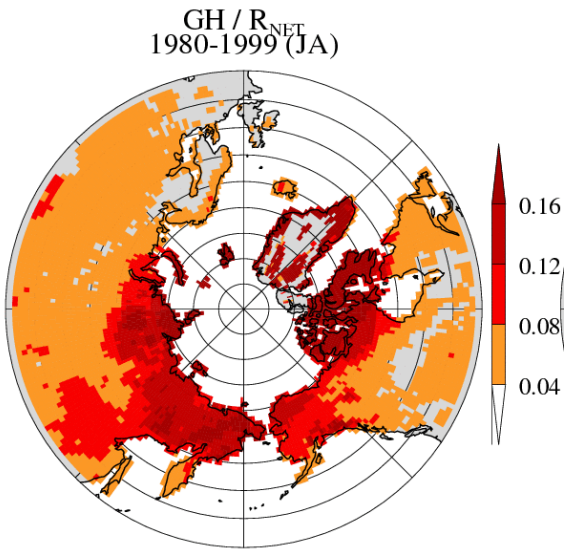


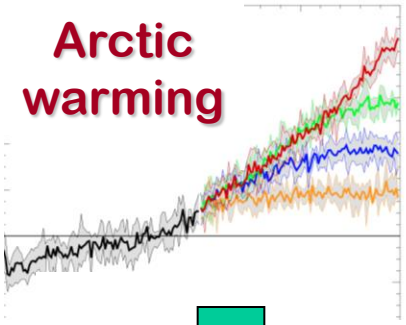
Gruber et al. 2004

Extra Slides

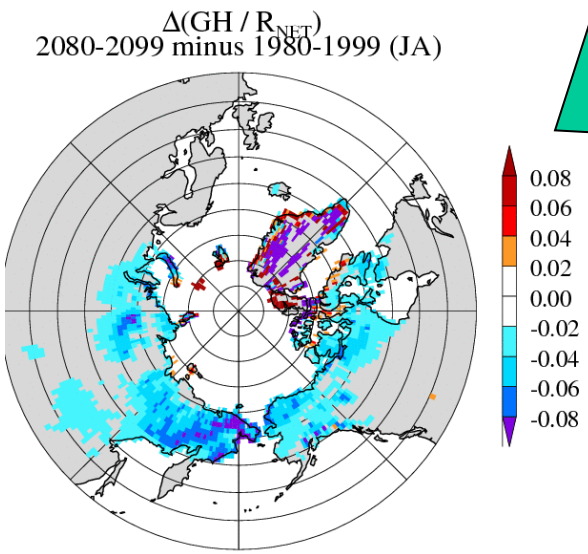
Bernhard Edmaier
National Geographic

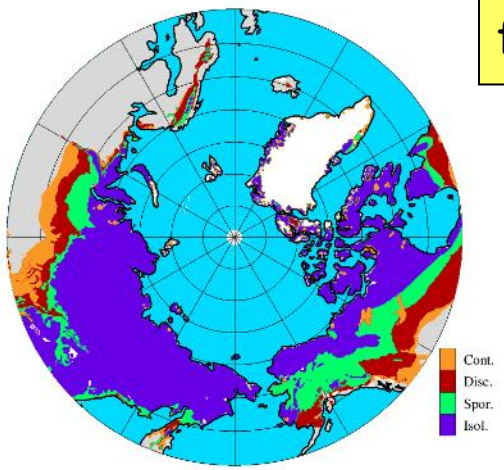
Potential Arctic terrestrial climate change feedbacks





Permafrost warms and thaws





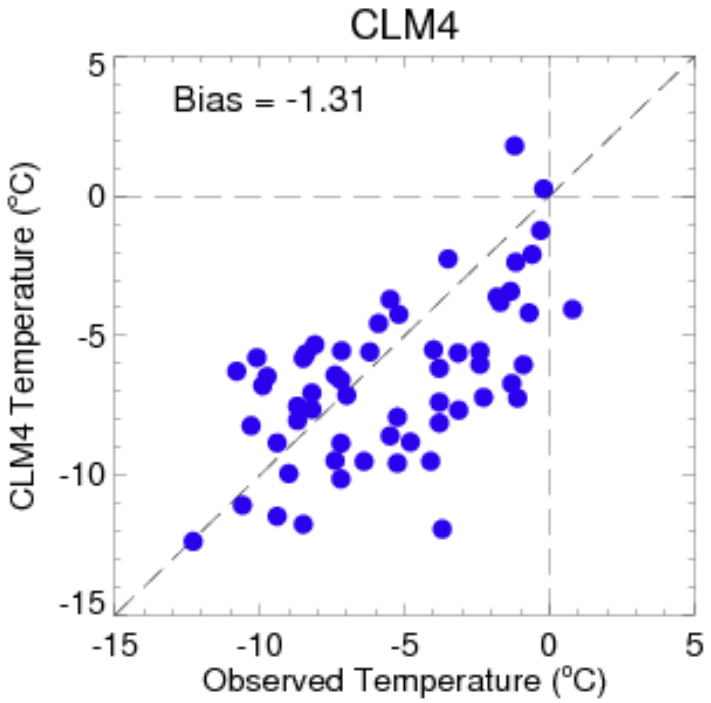
Direct feedback

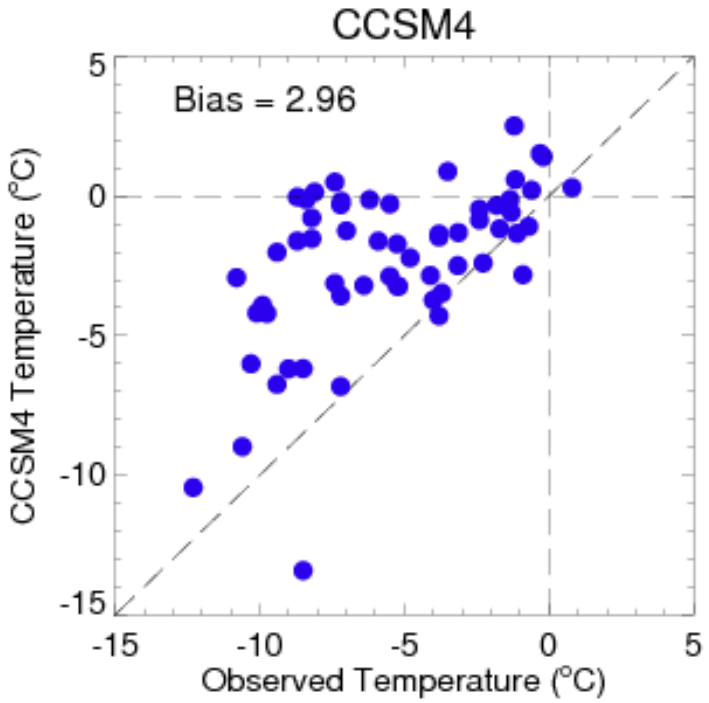
Surface energy partitioning

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

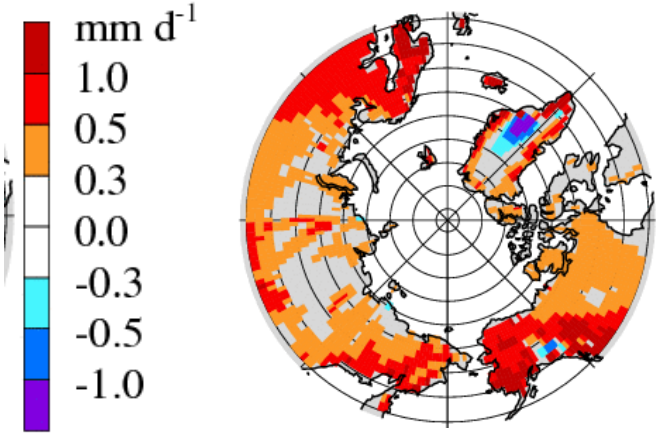
Offline (CLM) vs coupled (CCSM) model deep (> 15m) ground temperatures



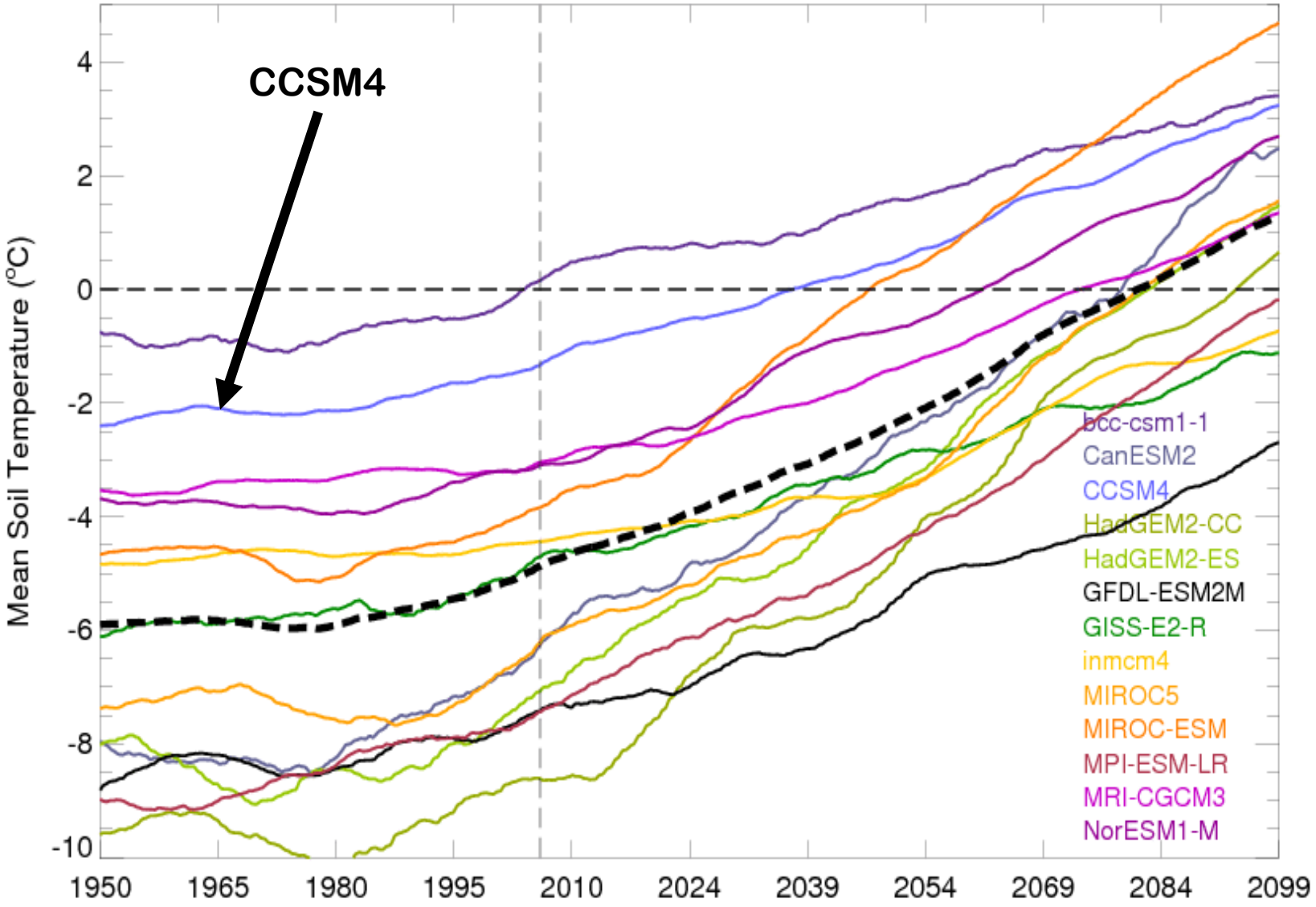


Cold bias because soils too dry?

CCSM4 Snowfall bias



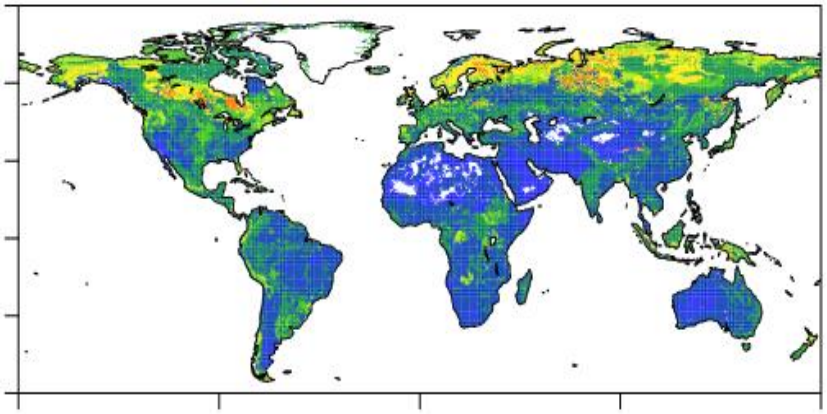
CMIP5 Models: Mean Soil Temperature across permafrost domain @ 3.3m (RCP 8.5)



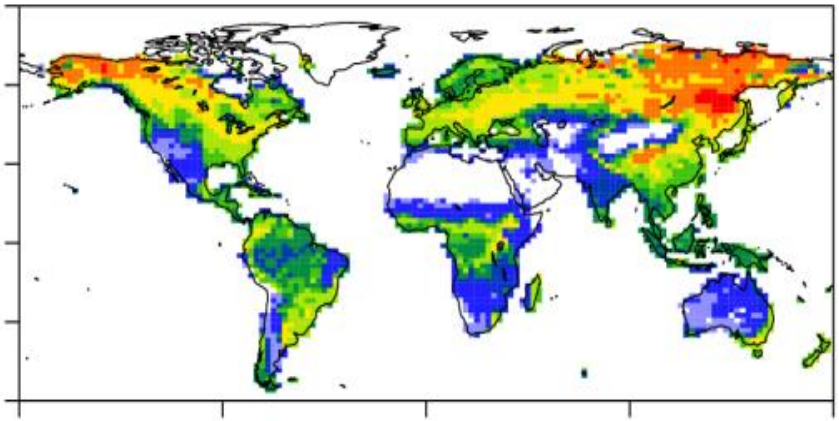
Slater and Lawrence, J.Clim, 2013

Soil carbon in CLM

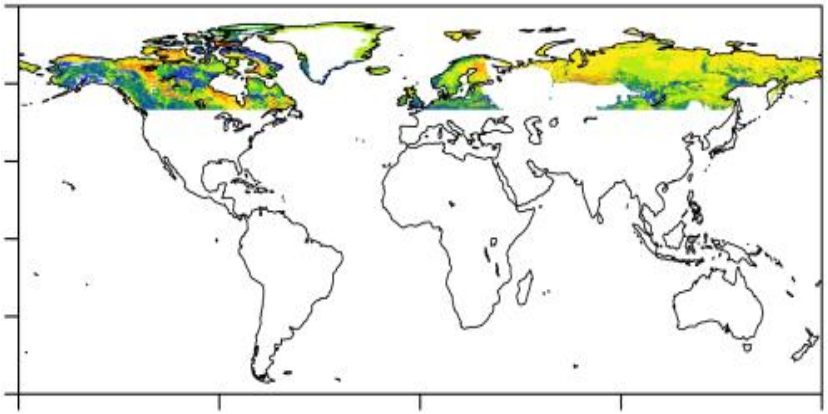
IGBP (900-1650 PgC, to 1m)



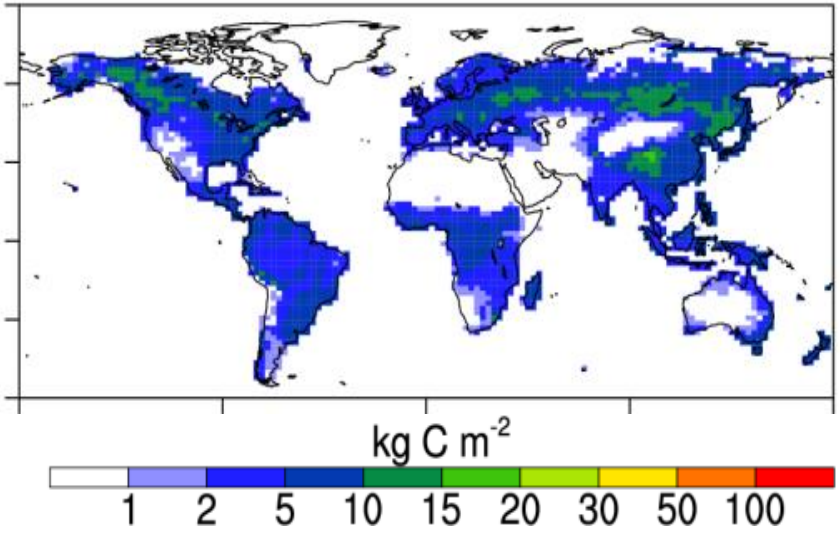
CLM4.5BGC (to 1m; 1900 PgC)



NCSCD (to 1m)



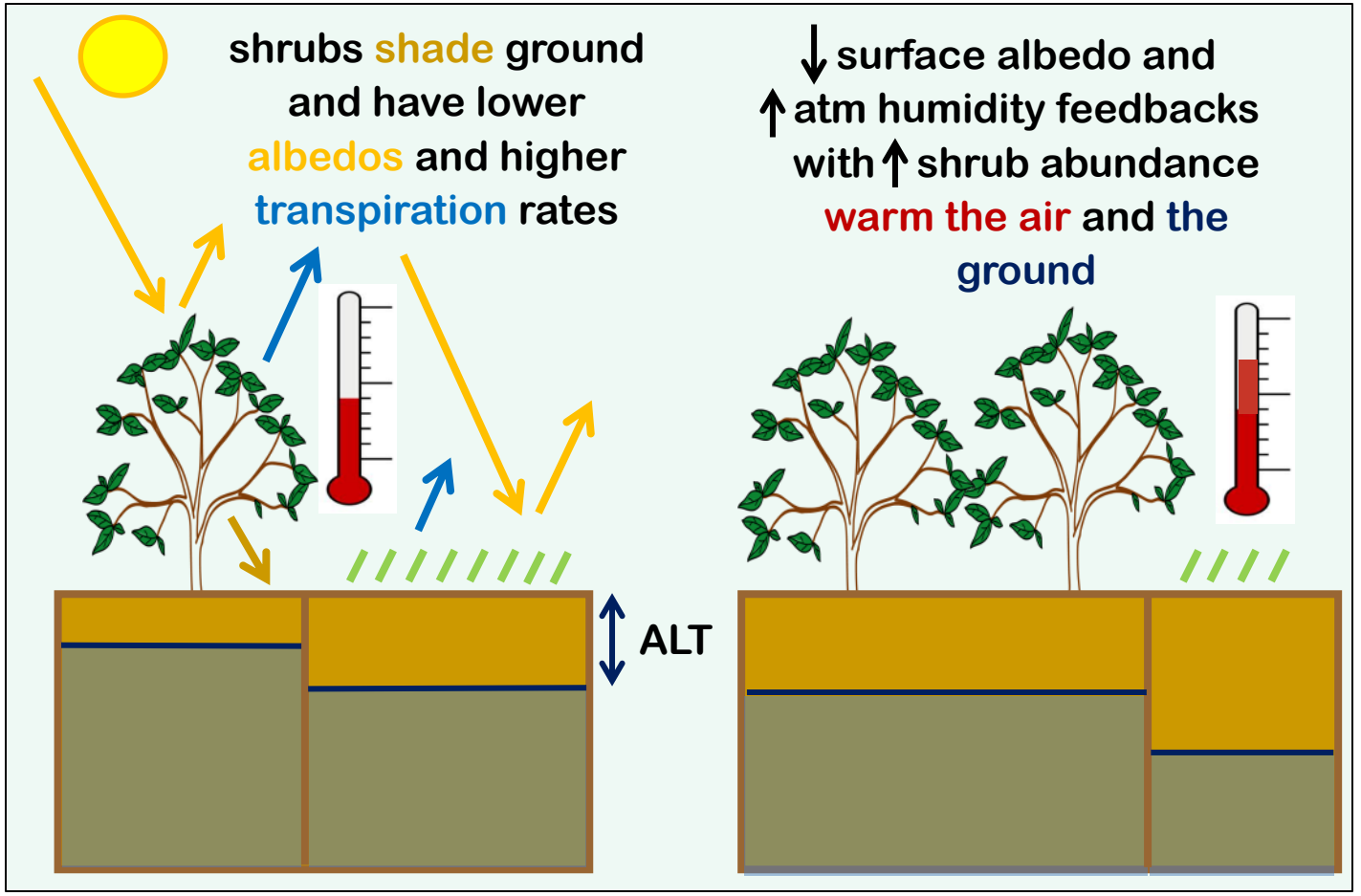
CLM4CN (650 PgC)



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.