Biogeochemistry in the Arctic-Boreal Climate System

Steve Frolking, University of New Hampshire

ARCTIC-BOREAL ZONE MODELING WORKSHOP

NASA GSFC, 22-24 May 2012

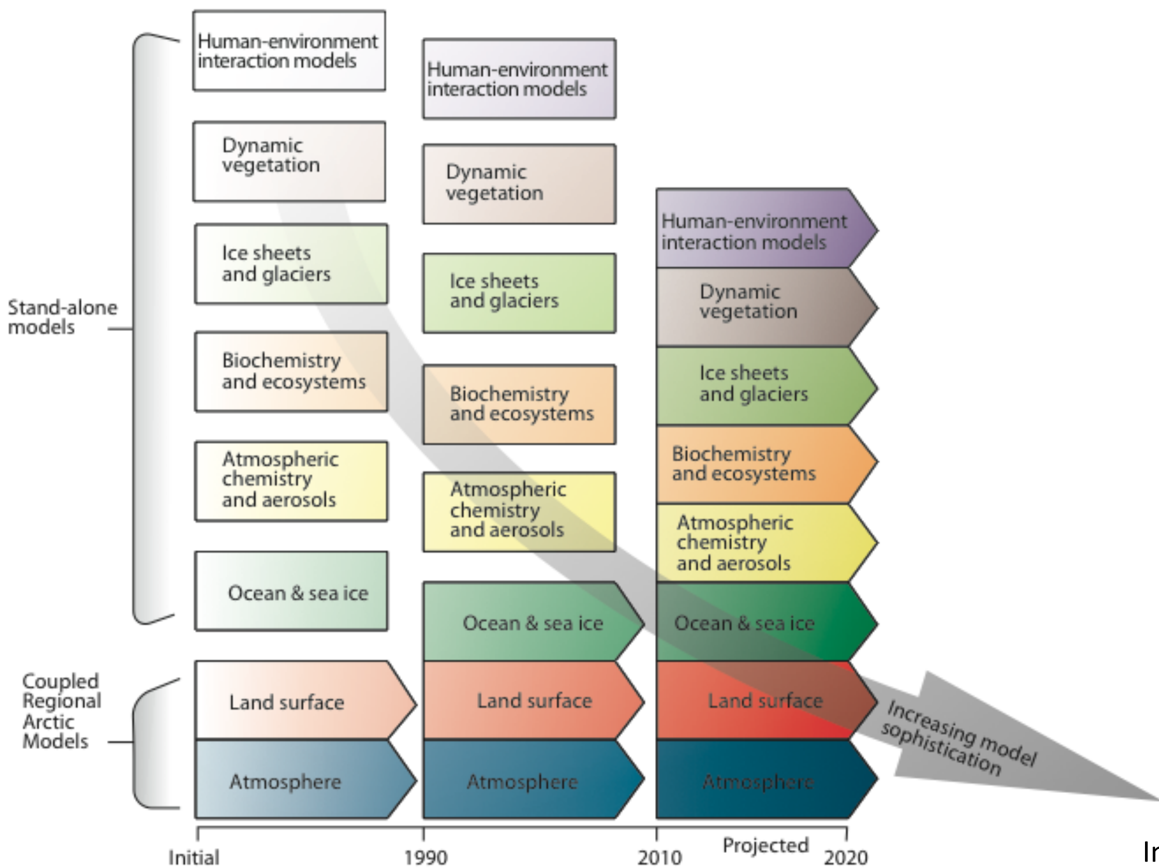
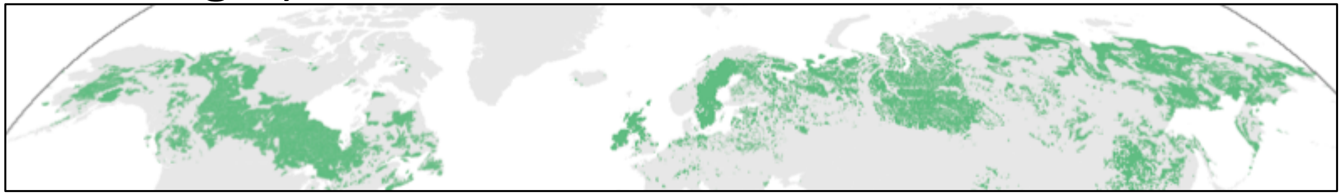


Image from *A Science Plan for Regional Arctic Modeling*

Carbon

(1000-2000 Pg C)

Permafrost



Peatlands

Disturbance

Scaling & heterogeneity

Decadal-centennial change

Land use

Some recent permafrost modeling work

1 April 2012 LAWRENCE ET AL. 2207

SPECIAL
Community Climate System Model CCSM4
COLLECTION

Simulation of Present-Day and Future Permafrost and Seasonally Frozen Ground Conditions in CCSM4

David M. Lawrence

Earth System Laboratory, Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado

Andrew G. Slater

Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado

Sean C. Swenson

Earth System Laboratory, Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado

Tellus (2011), 63B, 165–180
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TELLUS

Amount and timing of permafrost carbon release in response to climate warming

By KEVIN SCHAEFER[1]*, TINGJUN ZHANG[1], LORI BRUHWILER[2] and ANDREW P. BARRETT[1], [1]*National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, CO 80309, USA;* [2]*National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Boulder, CO, USA*

ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2009, Vol. 45, No. 3, pp. 271–283. © Pleiades Publishing, Ltd., 2009.
Original Russian Text © A.V. Eliseev, M.M. Arzhanov, P.F. Demchenko, I.I. Mokhov, 2009, published in Izvestiya AN. Fizika Atmosfery i Okeana, 2009, Vol. 45, No. 3, pp. 291–304.

Changes in Climatic Characteristics of Northern Hemisphere Extratropical Land in the 21st Century: Assessments with the IAP RAS Climate Model

A. V. Eliseev, M. M. Arzhanov, P. F. Demchenko, and I. I. Mokhov

A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevskii per. 3, Moscow, 119017 Russia
e-mail: eliseev@ifaran.ru

PNAS PNAS PNAS

Permafrost carbon-climate feedbacks accelerate global warming

Charles D. Koven[a,b,1], Bruno Ringeval[a], Pierre Friedlingstein[c], Philippe Ciais[a], Patricia Cadule[a], Dmitry Khvorostyanov[d], Gerhard Krinner[e], and Charles Tarnocai[f]

www.pnas.org/cgi/doi/10.1073/pnas.1103910108

Biogeosciences, 9, 649–665, 2012
www.biogeosciences.net/9/649/2012/
doi:10.5194/bg-9-649-2012
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Biogeosciences

Estimating the near-surface permafrost-carbon feedback on global warming

T. Schneider von Deimling[1], M. Meinshausen[1,2], A. Levermann[1,5], V. Huber[1], K. Frieler[1], D. M. Lawrence[3], and V. Brovkin[4,1]

Earth Syst. Dynam., 2, 121–138, 2011
www.earth-syst-dynam.net/2/121/2011/
doi:10.5194/esd-2-121-2011
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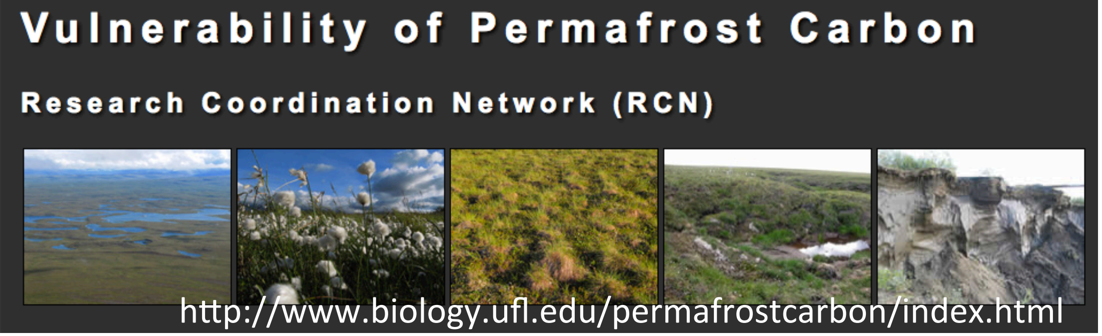
Earth System Dynamics

Soil temperature response to 21st century global warming: the role of and some implications for peat carbon in thawing permafrost soils in North America

D. Wisser[1], S. Marchenko[2], J. Talbot[1], C. Treat[1], and S. Frolking[1]



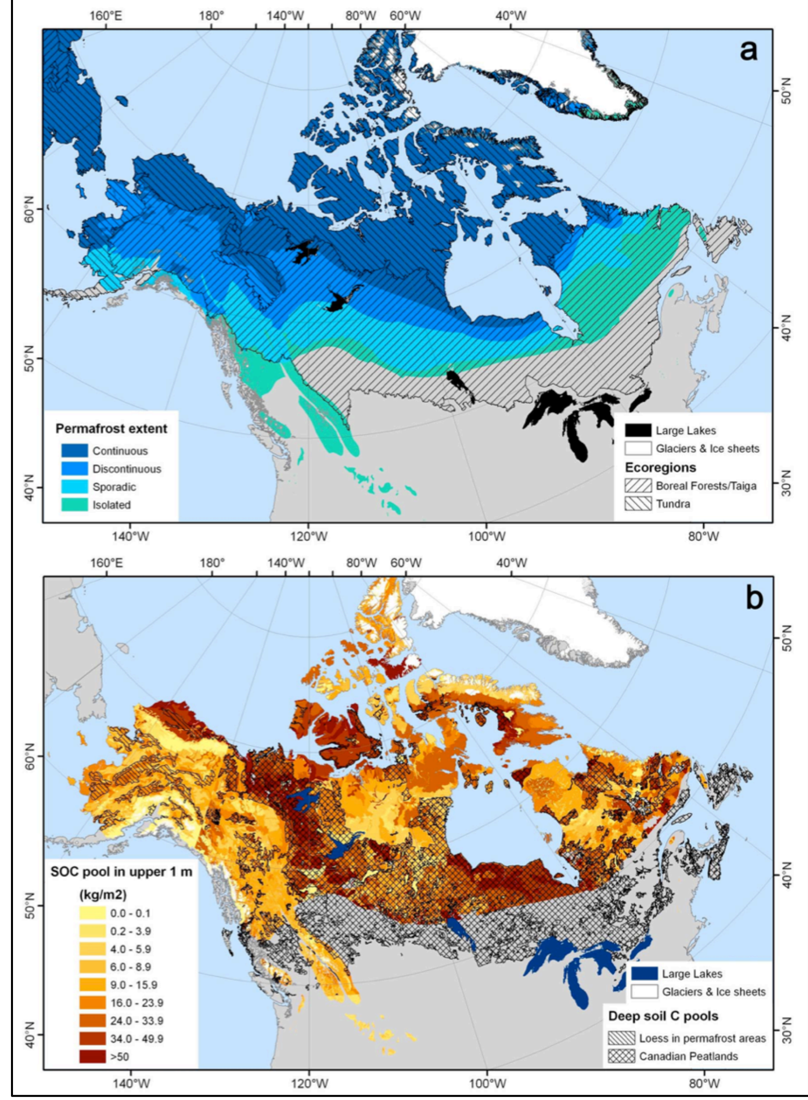

COMMENT

32 | NATURE | VOL 480 | 1 DECEMBER 2011

Abrupt thaw, as seen here in Alaska's Noatak National Preserve, causes the land to collapse, accelerating permafrost degradation and carbon release.

High risk of permafrost thaw

Northern soils will release huge amounts of carbon in a warmer world, say **Edward A. G. Schuur, Benjamin Abbott** and the Permafrost Carbon Network.

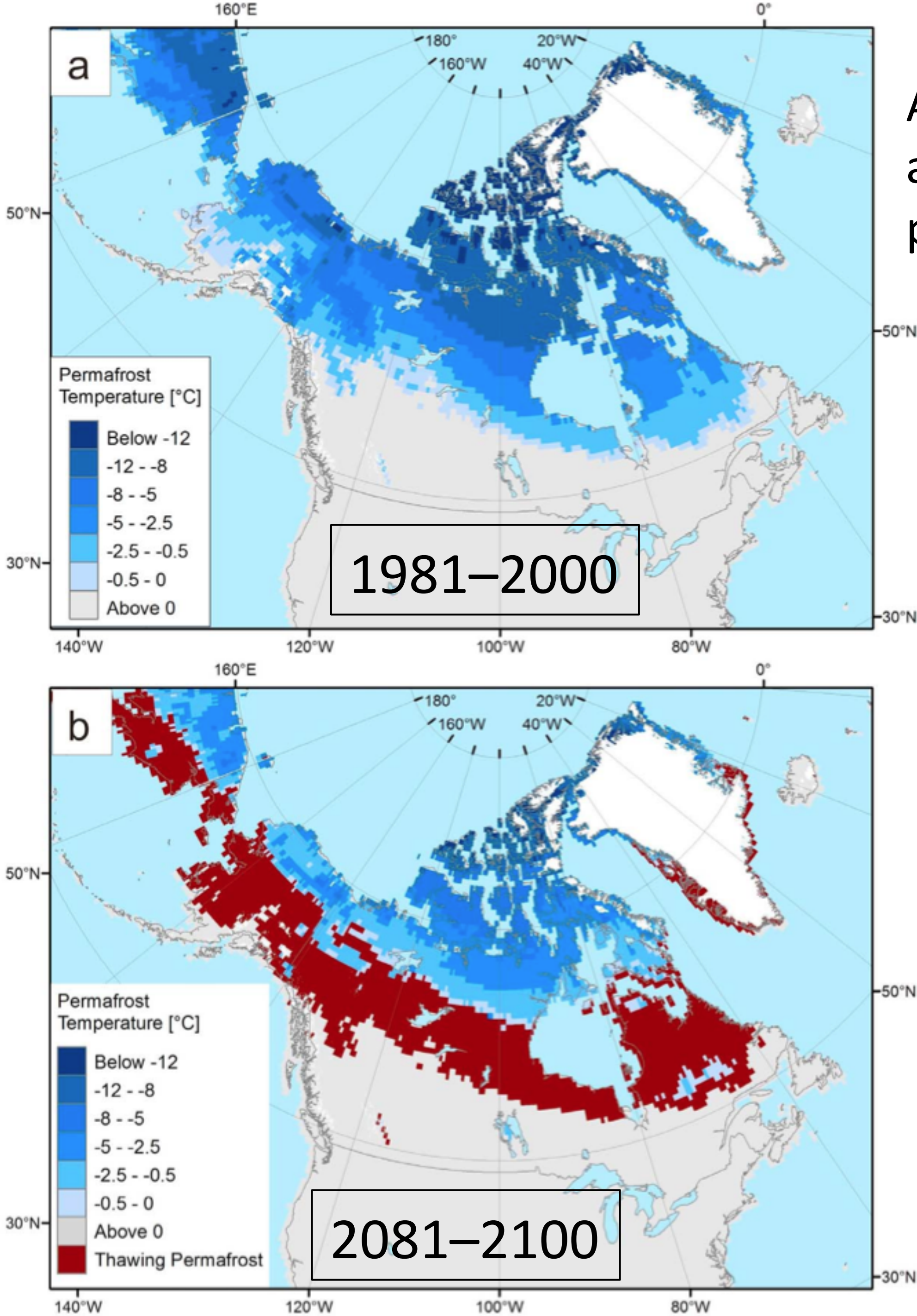


Grosse et al. (2011, *JGR*)

<u>'Known Knowns'</u>: • ~20M km^2 • ~1500 Pg C • decomposable

<u>'Known Unknowns'</u>: • thermokarst → landscape wetness → CO_2:CH_4?

Average distribution of permafrost and ground temperatures; permafrost modeling by S. Marchenko.



Grosse et al. (2011, *JGR*)

Shallow permafrost area

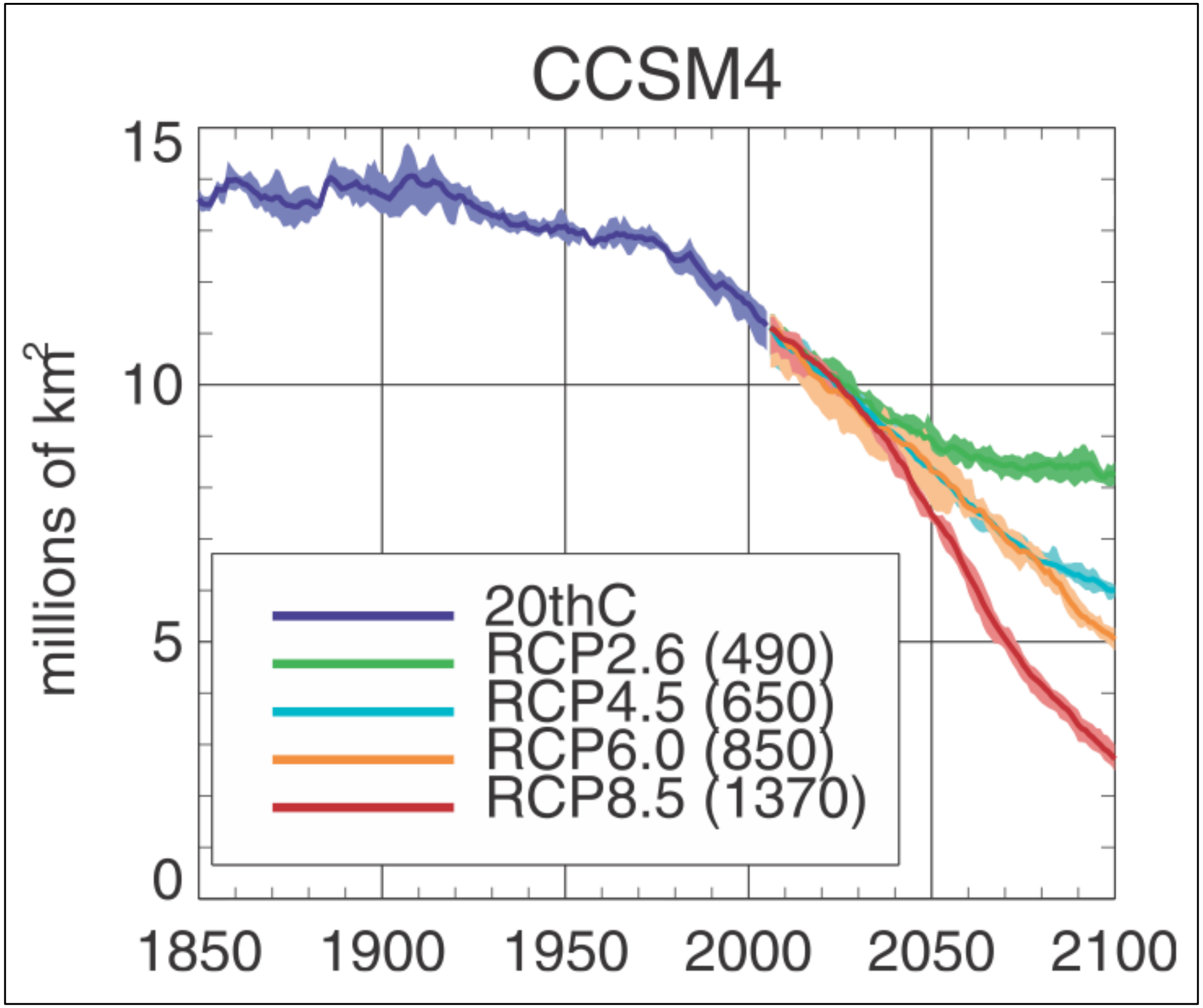
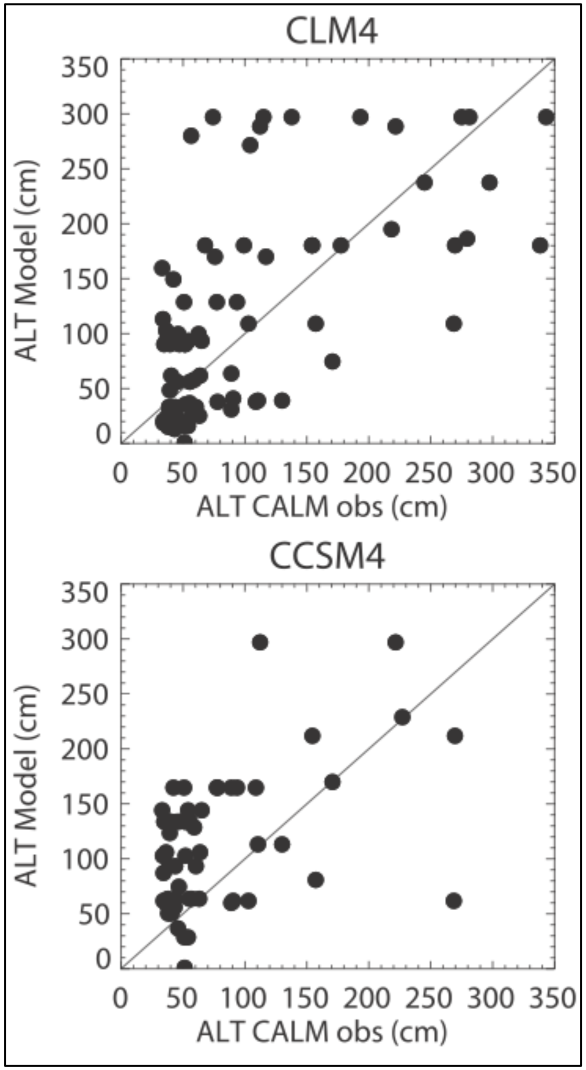


FIG. 6. Time series of Northern Hemisphere near-surface permafrost extent

Lawrence et al. (2012, *J Climate*)

Active Layer Thickness (ALT)



Deep ground temperature

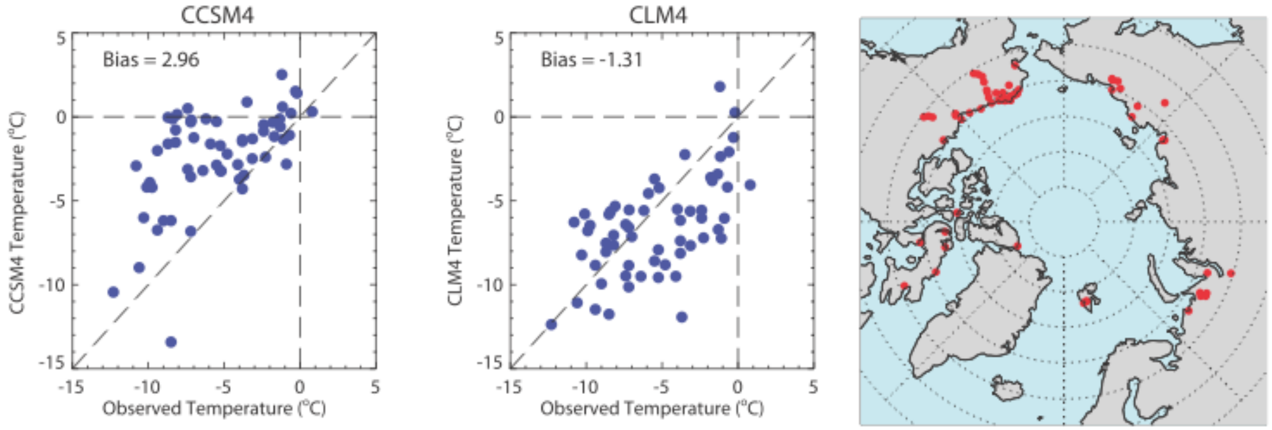
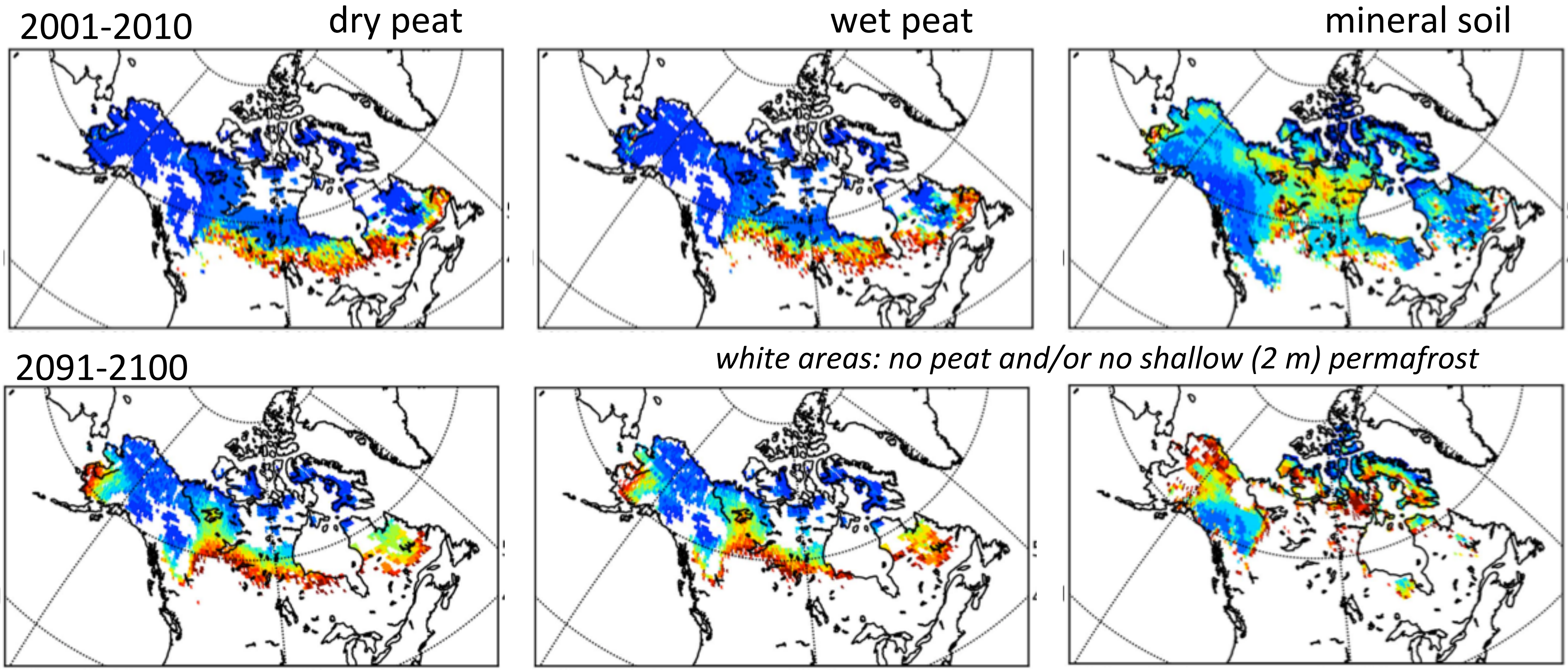
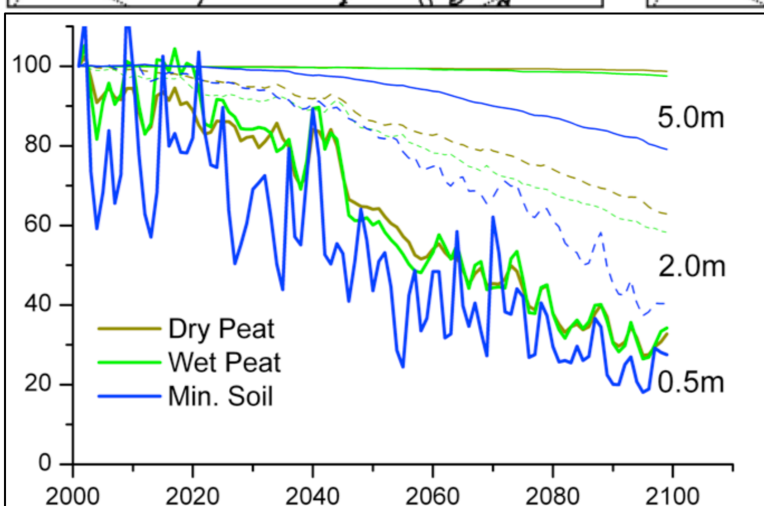


FIG. 5. Scatterplot of deep ground temperature for borehole sites (observed) vs model for (left) CCSM4 and (middle) CLM4. Model data are from ensemble mean year 2005 for CCSM4 and 2004 for CLM4. Observed data are from 2007/2008. (right) Borehole locations used. See text for further details.

Lawrence et al. (2012, *J Climate*)

Permafrost/peat interactions – ALT (m)





area % (relative to 2001) perennially frozen at 0.5m, 2.0 m, and 5.0m

About 30 Pg C peat in North America thaws in 21st century.

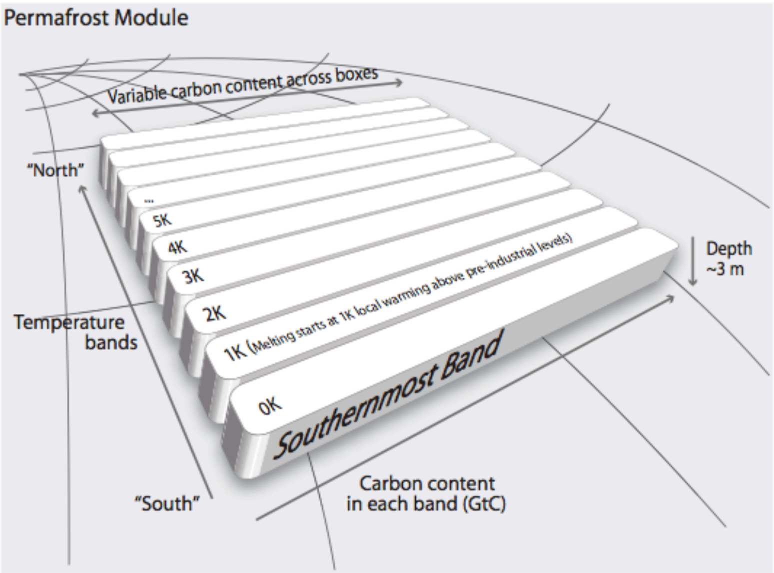
(one model, one climate change scenario)

Wisser et al. (2011, *ESD*)

Estimating the near-surface permafrost-carbon feedback on global warming

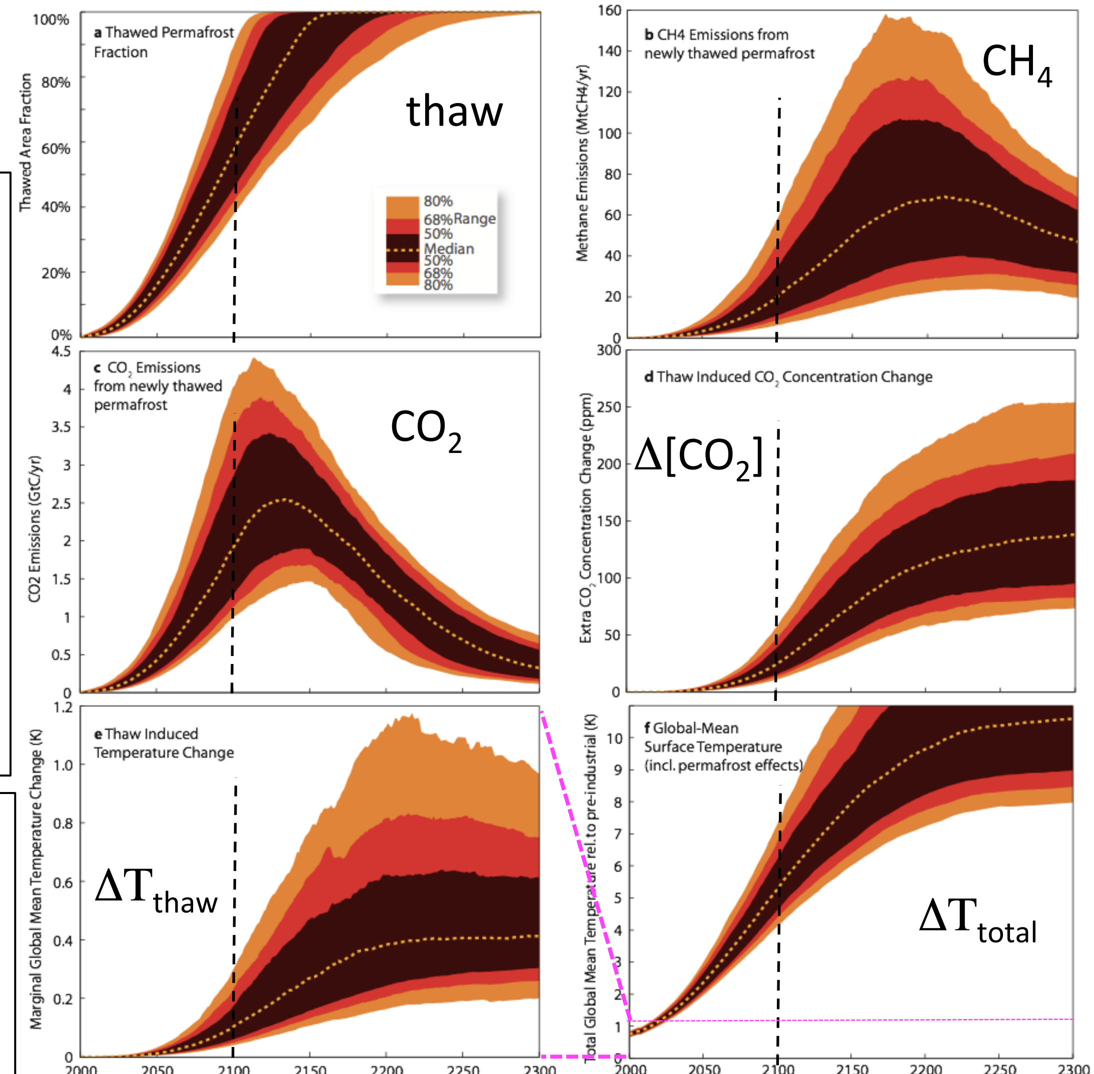
T. Schneider von Deimling[1], M. Meinshausen[1,2], A. Levermann[1,5], V. Huber[1], K. Frieler[1], D. M. Lawrence[3], and V. Brovkin[4,1]

Biogeosciences, 9, 649–665, 2012



uncertainty analysis, under RCP8.5 scenario, for model parameters, such as:

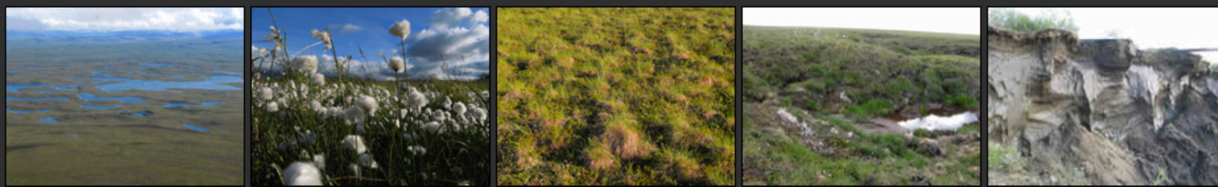
- total SOC and N-S distribution
- fraction of SOC in peat, mineral soil
- anaerobic fraction of SOC
- Q10
- SOC turnover rate
- fraction CH_4 oxidized
- etc.



- most impact is after 2100
- large uncertainties
- impact not 'bomb-like'

Vulnerability of Permafrost Carbon

Research Coordination Network (RCN)



Model-Integration Working Group - Products of the Synthesis

Summary - Dave McGuire, 4 December 2011

- **Product 1**: A retrospective evaluation of thermal and carbon dynamics of extant permafrost-carbon models.

- **Product 2:** State-of-the-art assessment of the vulnerability of permafrost carbon and its effects on the climate system.

- **Product 3:** Synthesis papers on conceptual approaches that should be embraced by coupled permafrost-carbon models.

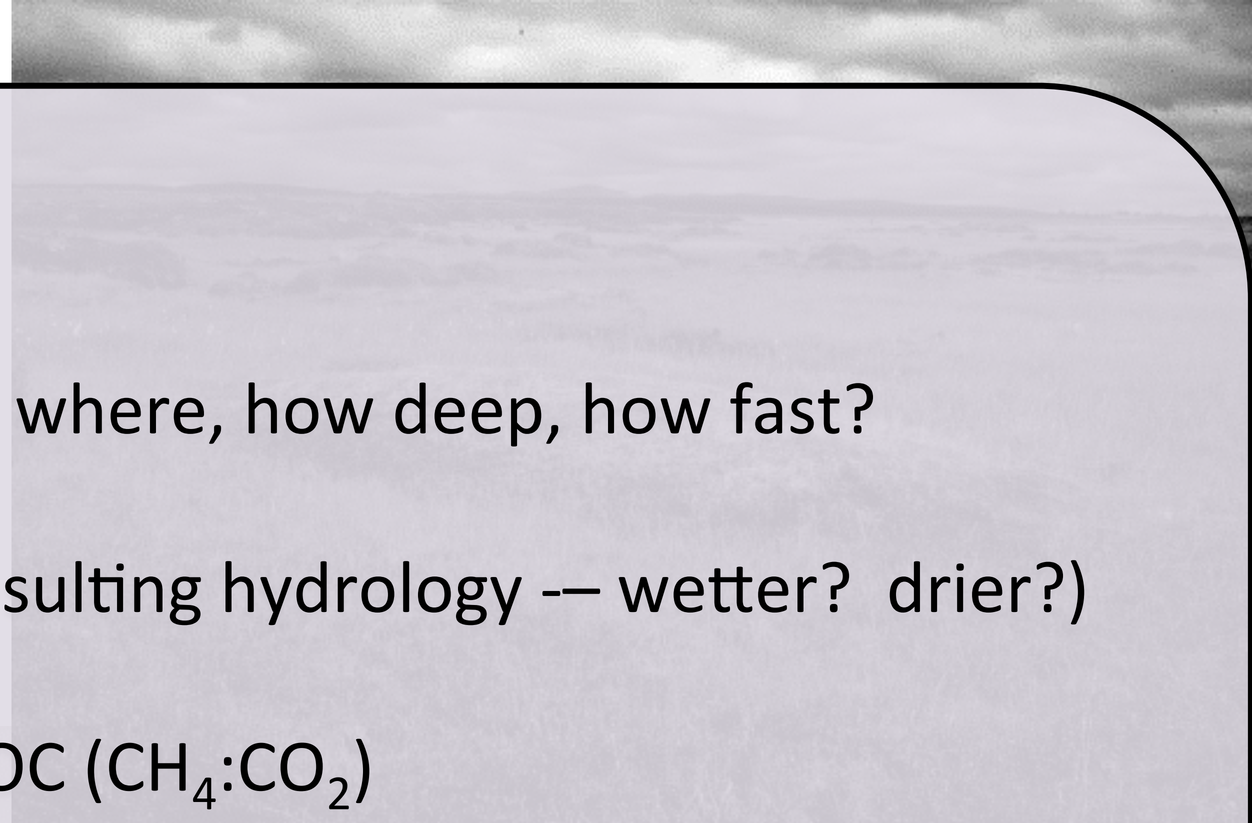
A new, small palsa on Luovdijeäggi palsa mire, western Utsjoki, Finland, July 1999 (height about 60 cm).

Palsa surface in the middle of winter.

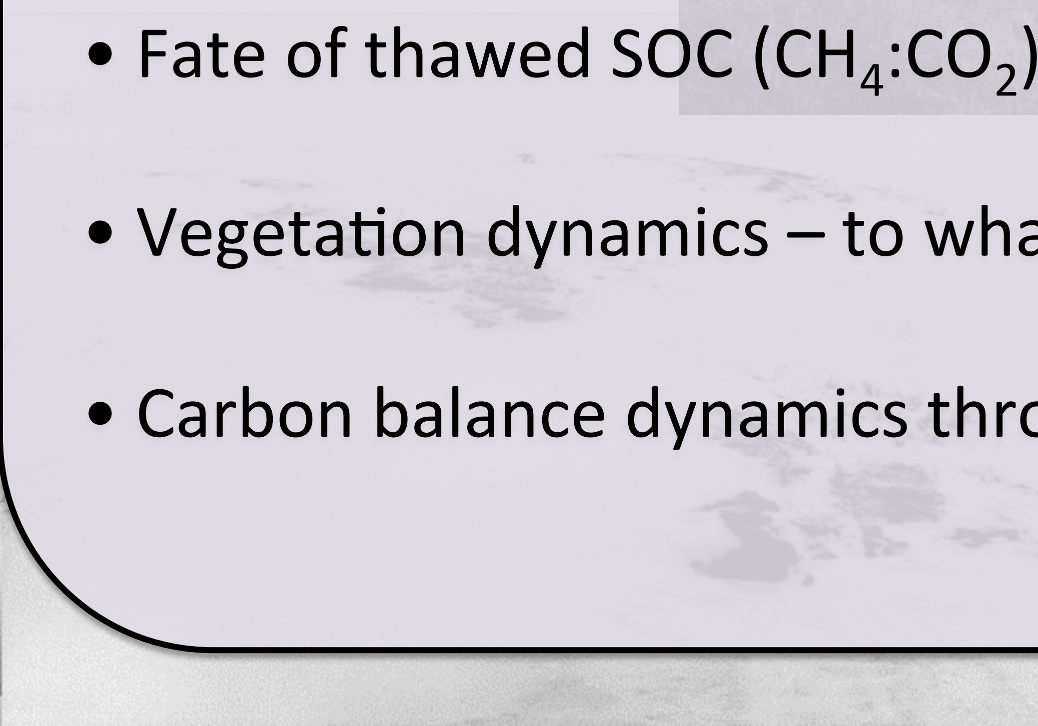
Seppälä M (2003) *Geomorphology* 52:141–148

Permafrost

- Thaw rate: when, where, how deep, how fast?
- Thermokarst? Resulting hydrology -– wetter? drier?)
- Fate of thawed SOC (CH_4:CO_2)
- Vegetation dynamics – to what state? how quickly?
- Carbon balance dynamics through thaw transition?



Palsa surface in the middle of winter.



A new palsa on Luovdijeäggi palsa mire, western Utsjoki, Finland, July 1999.

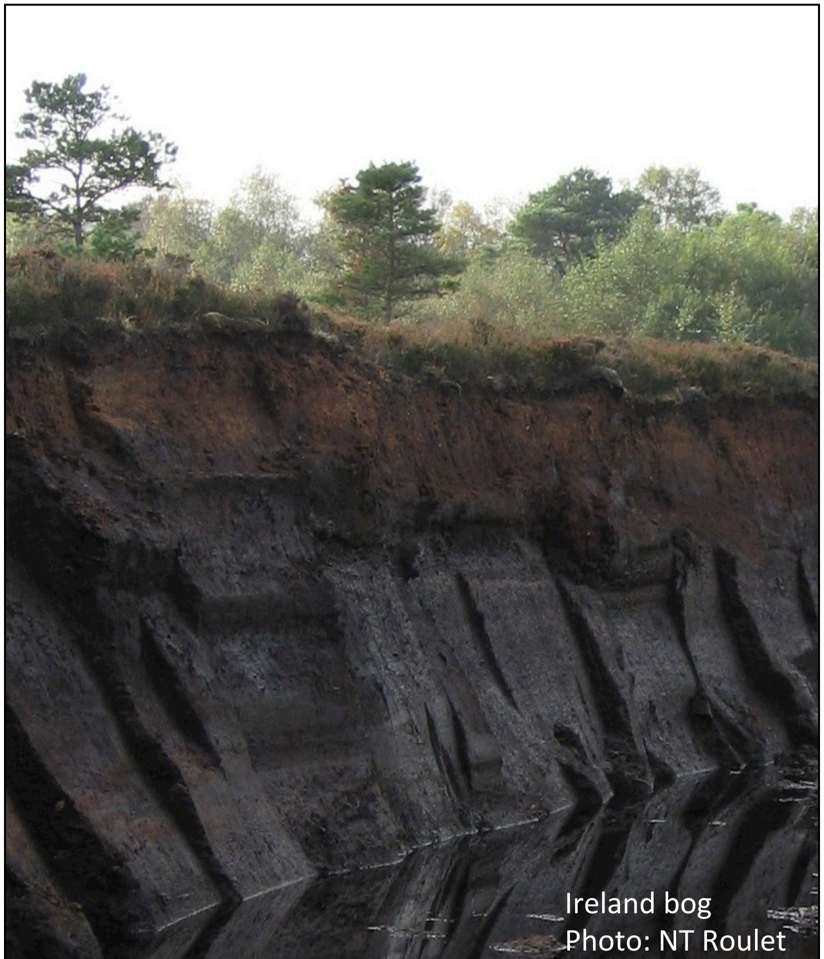
Seppälä M (2003) *Geomorphology* 52:141–148

Peatland characteristic

- thick organic soils

Modeling issues

- thermal & hydraulic properties differ from mineral.
- appropriate soil depth and layering may differ.
- soil profile dynamic over moderate time scales.
- initialization



Frolking, Roulet, Lawrence. 2009. Issues related to incorporating northern peatlands into global climate model, in *Geophys. Monog. 184*, AGU.

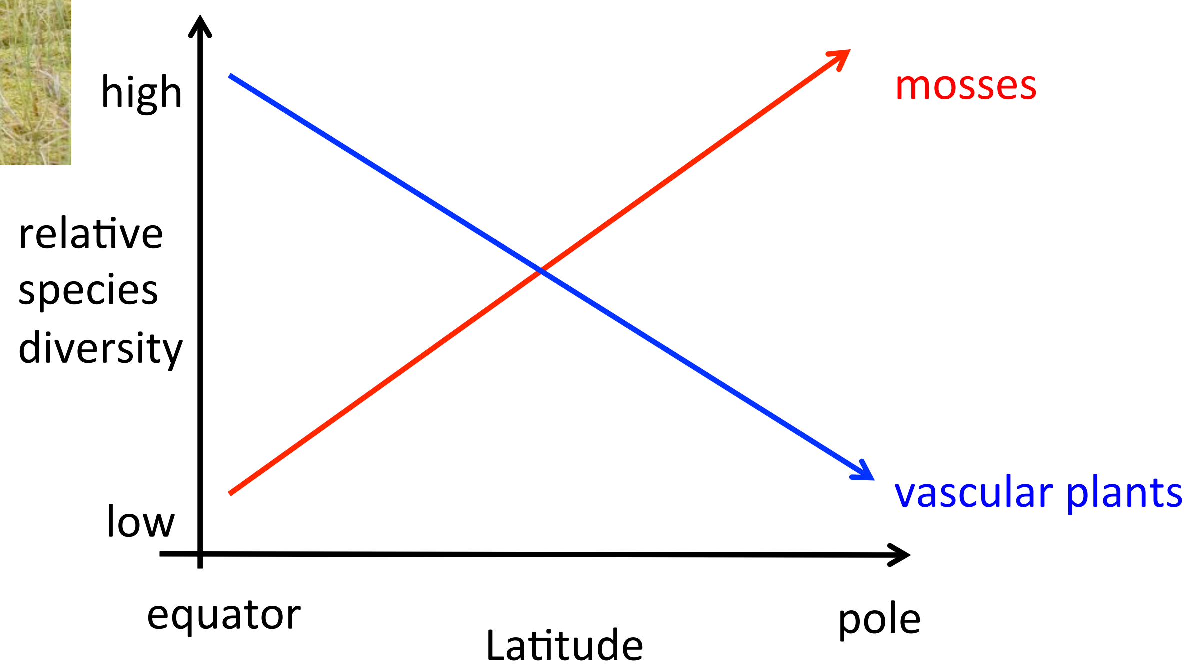
Peatland characteristic

- non-vascular plant cover

Modeling issues

- abundant; different physiology and phenology.
- peat properties relate to overlying vegetation.

permafrost bog near Fairbanks AK
Photo: Miriam Jones



Frolking et al. 2009.

Peatland characteristic

- disturbance characteristics

Modeling issues

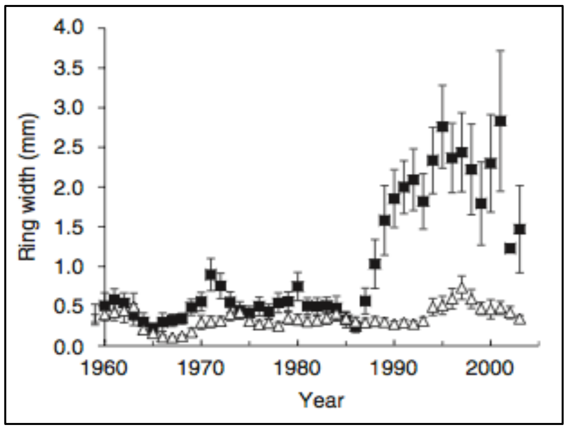
- new parameters for peatland fires & recovery.
- thermokarst dynamics in permafrost/peat soils.
- draining for forestry, crops, or peat harvesting.

Nature Climate Change

Received 10 Mar 2011 | Accepted 29 Sep 2011 | Published xx xxx 2011 DOI: 10.1038/ncomms1523

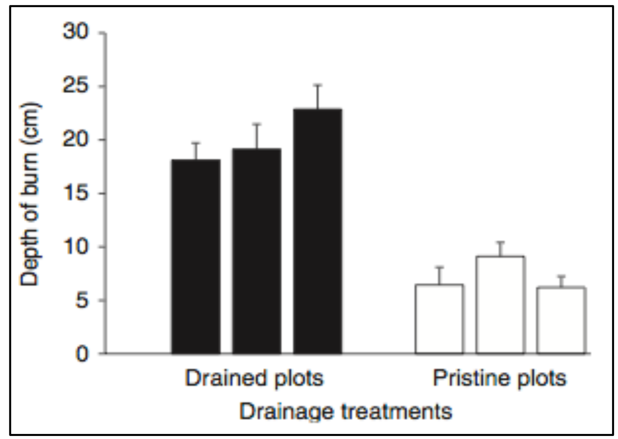
Experimental drying intensifies burning and carbon losses in a northern peatland

M.R. Turetsky[1], W.F. Donahue[2] & B.W. Benscoter[3]



■ drained

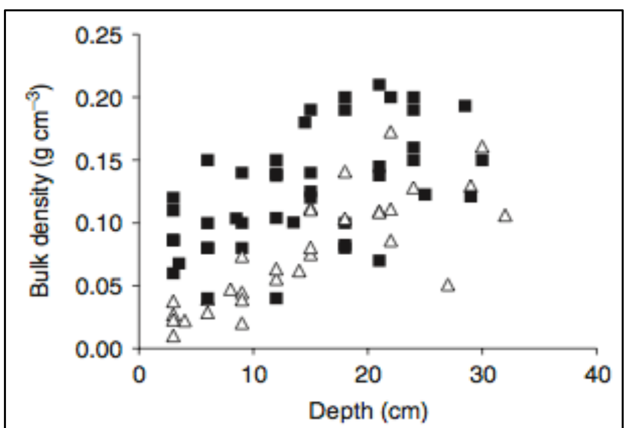
△ undrained



increased tree productivity & C accumulation

+

increased peat bulk density



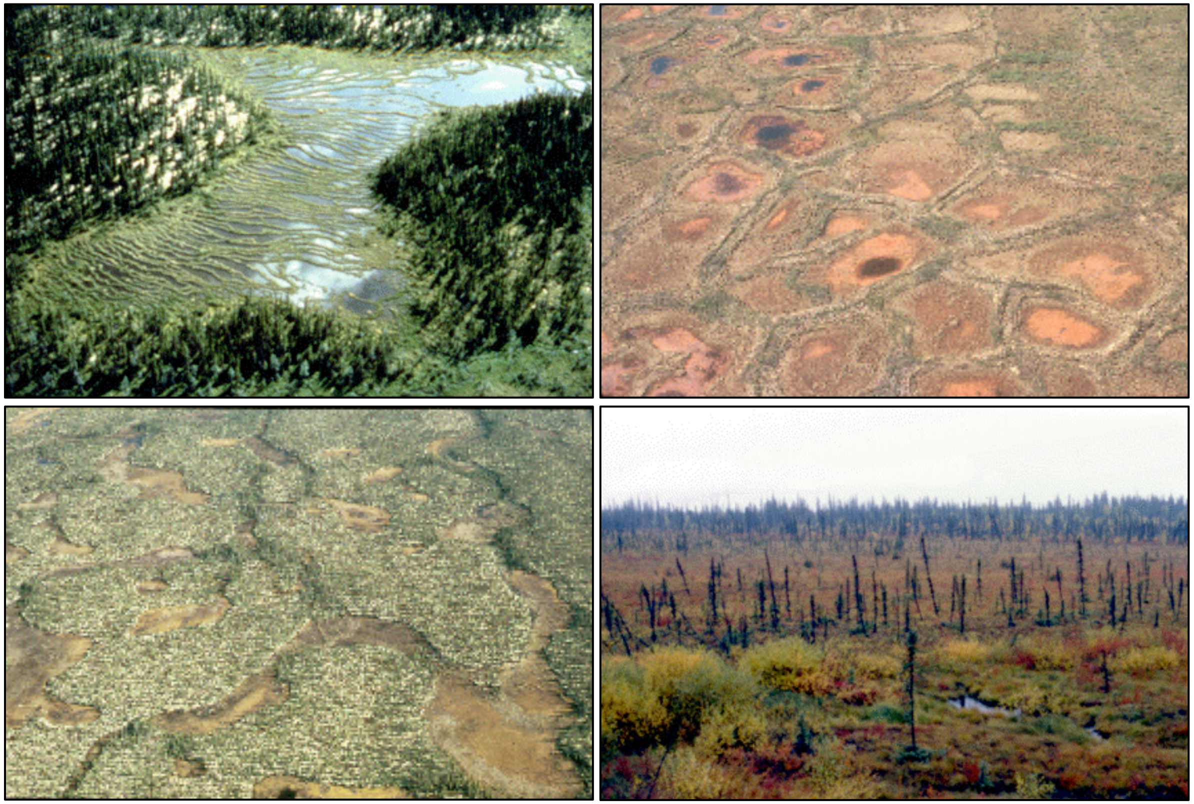
more intense fire burning deeper into peat

Peatland characteristic

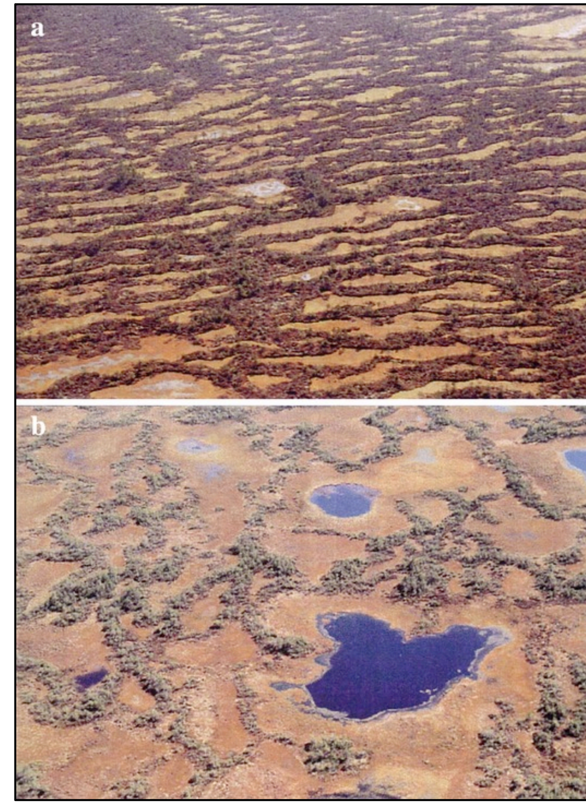
- 1 m – 1 km heterogeneity

Modeling issues

- microtopography, vegetation, and water table.



Photos: http://www.ipcc.ie/wpcanada.html
(*Steve Zoltai, Doyle Wells, Clayton Rubec*)



Siberia (*W. Bleuten and E.D. Lapshina*)

Quebec (*M. Poulin*)

Peatland characteristic

- anaerobic biogeochemistry

Modeling issues

- C and N cycle in different ways at different rates.
- 'subtle hydrology of shallow water tables.' *(NT Roulet)*

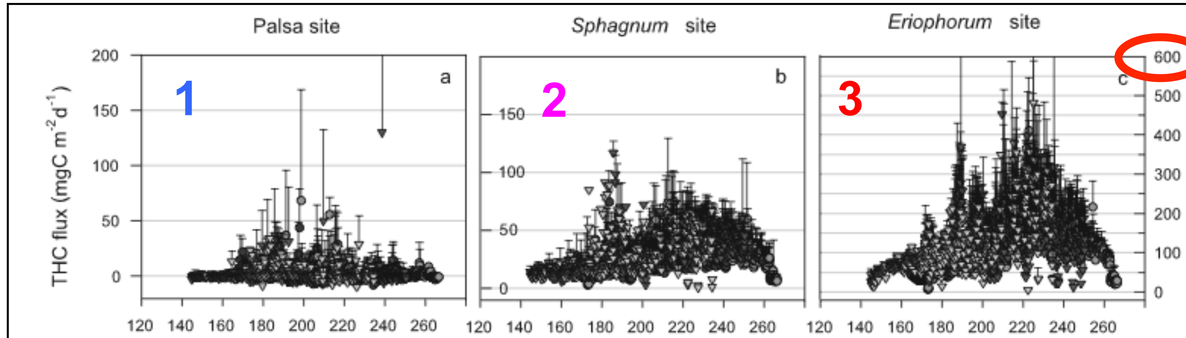
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, G03026, doi:10.1029/2008JG000703, 2008

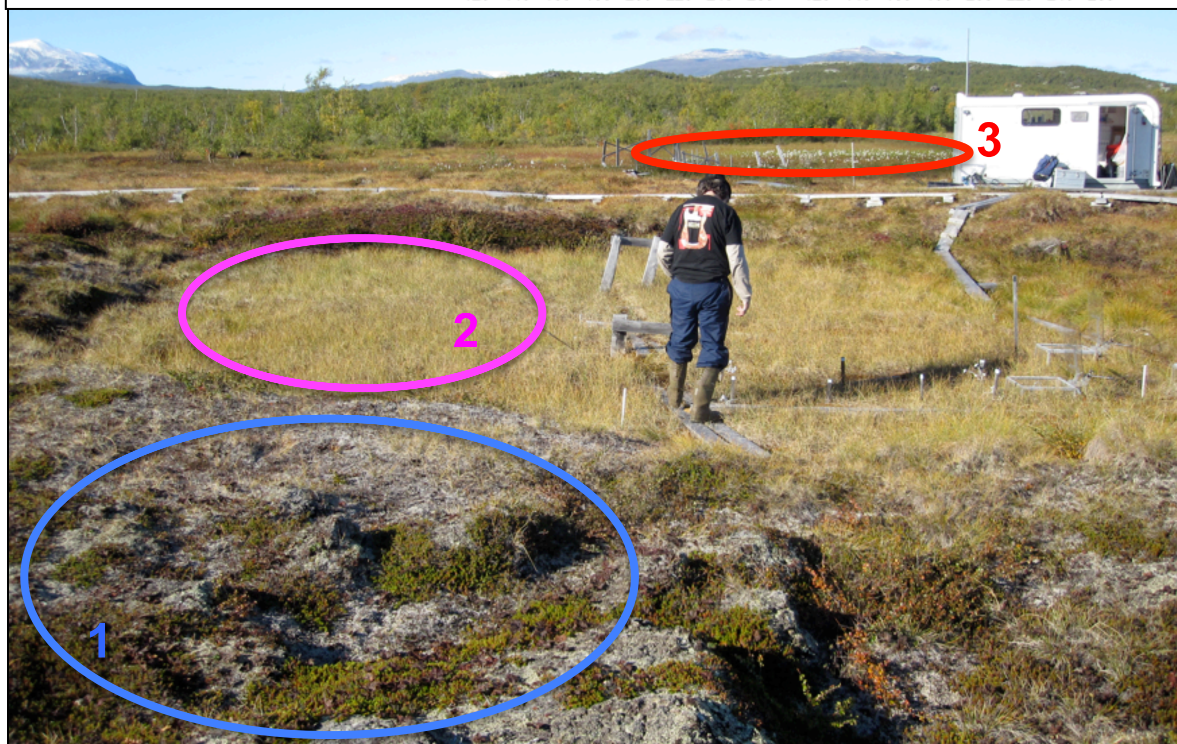
Click Here for Full Article

Total hydrocarbon flux dynamics at a subarctic mire in northern Sweden

Kristina Bäckstrand,[1] Patrick M. Crill,[1] Mikhail Mastepanov,[2] Torben R. Christensen,[2] and David Bastviken[1]

Stordalen Mire, Sweden





Biogeosciences, 8, 1925–1953, 2011
www.biogeosciences.net/8/1925/2011/
doi:10.5194/bg-8-1925-2011
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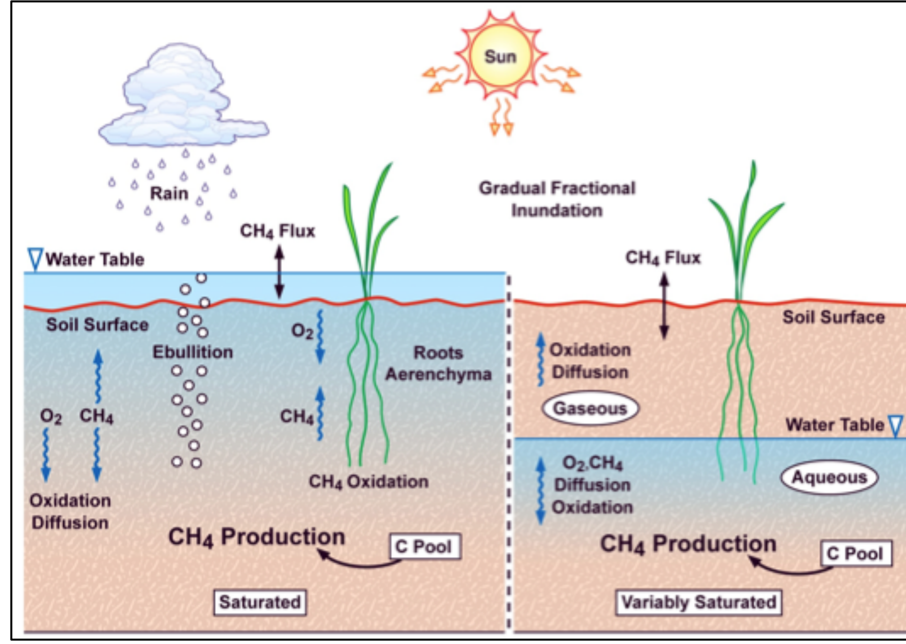
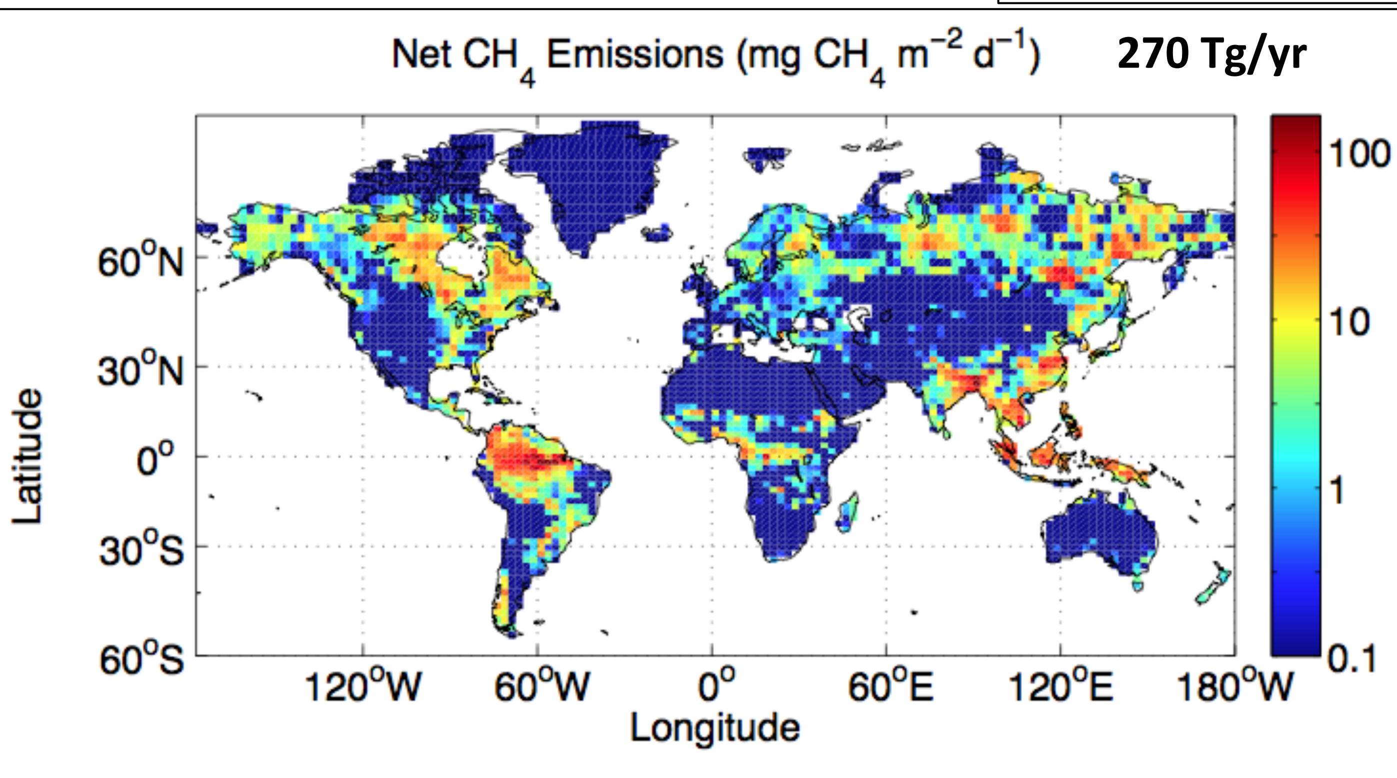
Biogeosciences

Barriers to predicting changes in global terrestrial methane fluxes: analyses using CLM4Me, a methane biogeochemistry model integrated in CESM

W. J. Riley[1], Z. M. Subin[1], D. M. Lawrence[2], S. C. Swenson[2], M. S. Torn[1], L. Meng[3], N. M. Mahowald[4], and P. Hess[3]

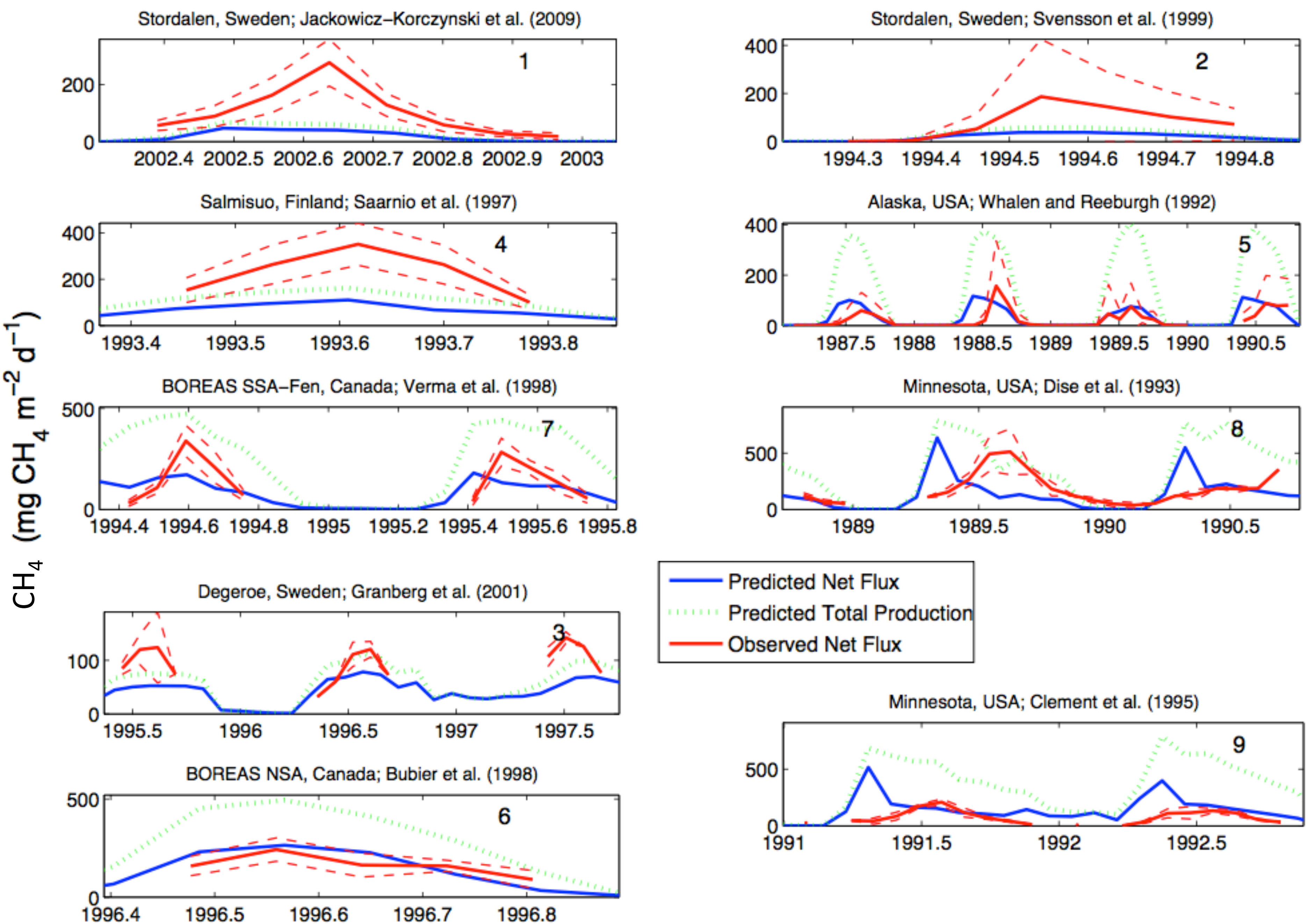




70 Tg/yr

50

160



Stordalen, Sweden; Jackowicz-Korczynski et al. (2009)
Stordalen, Sweden; Svensson et al. (1999)
Salmisuo, Finland; Saarnio et al. (1997)
Alaska, USA; Whalen and Reeburgh (1992)
BOREAS SSA-Fen, Canada; Verma et al. (1998)
Minnesota, USA; Dise et al. (1993)
Degeroe, Sweden; Granberg et al. (2001)
BOREAS NSA, Canada; Bubier et al. (1998)
Minnesota, USA; Clement et al. (1995)
CH_4 (mg CH_4 m^{-2} d^{-1})
Predicted Net Flux
Predicted Total Production
Observed Net Flux

http://arve.epfl.ch/research/wetchimp/overview.php

WETCHIMP Overview page

WETland and Wetland **CH_4 I**nter-comparison of **M**odels **P**roject - WETCHIMP

WETCHIMP is designed to compare global and regional-scale models.

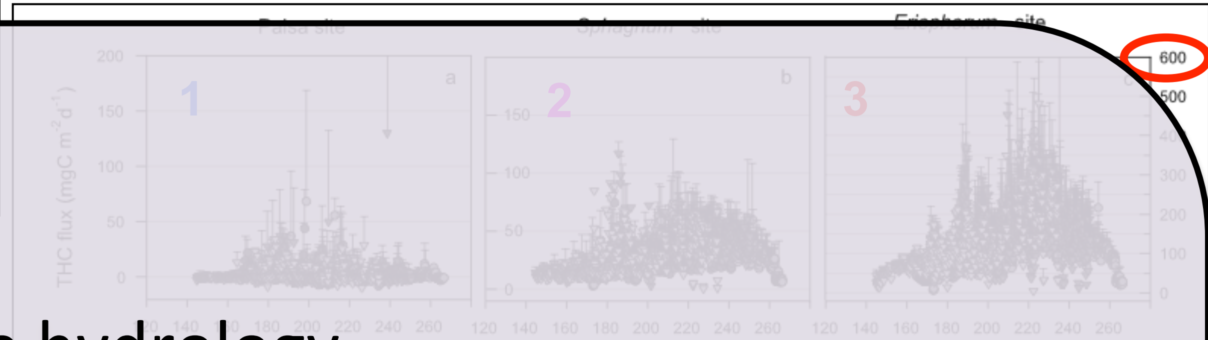
Proposed Simulations

#	Experiment	Climate
1	Equilibrium	1901 – 1931 (repeated)
2	Transient	1932 – 1992 then 1993 – 2004
3	Optimized	User–defined
4	Atmospheric [CO_2] sensitivity	1901 –1931 (repeated)
5	Temperature sensitivity	1901 – 1931 with globally uniformally increased air temperature (repeated)
6	Moisture sensitivity	1901 – 1931 with globally uniformally increased precipitation (repeated)

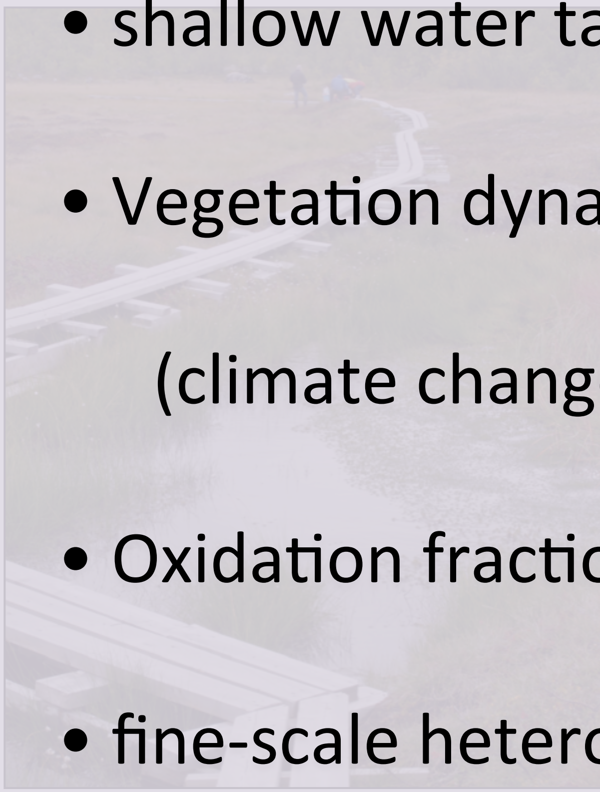
All other boundary conditions are assumed identical with the present climate.

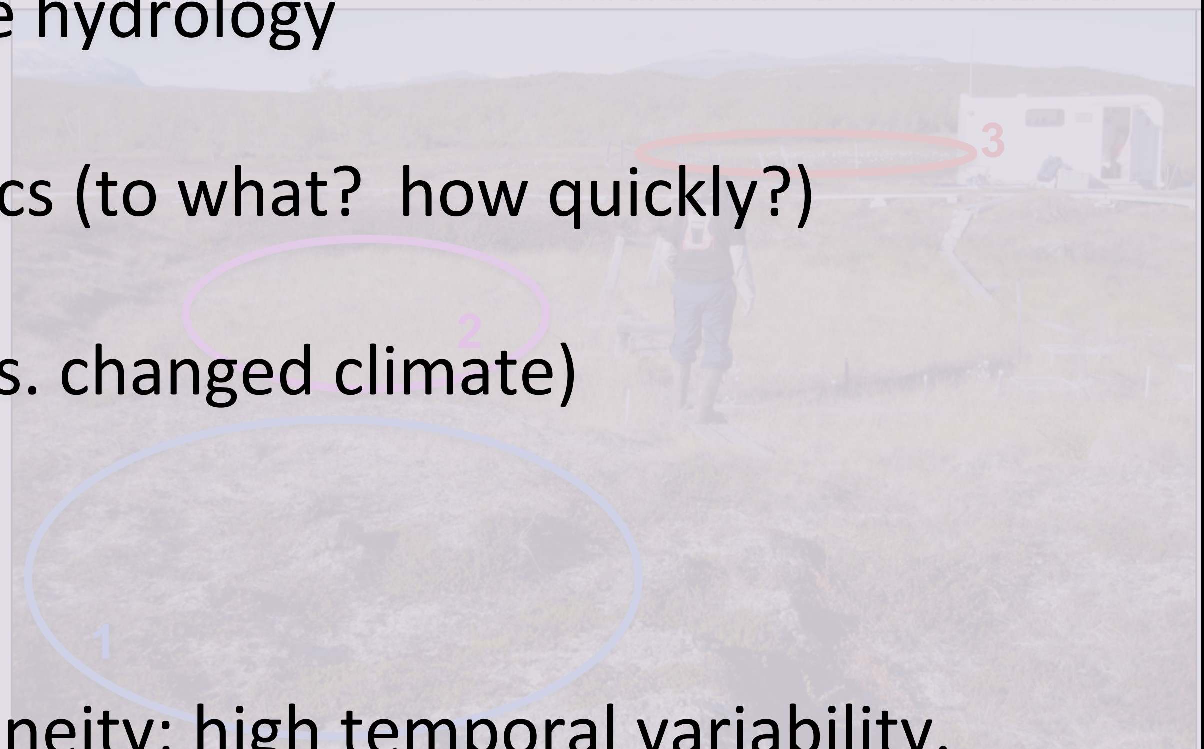
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, G03026, doi:10.1029/2008JG000703, 2008

Methane



Stordalen Mire, Sweden





- shallow water table hydrology
- Vegetation dynamics (to what? how quickly?)

    (climate change vs. changed climate)

- Oxidation fraction
- fine-scale heterogeneity; high temporal variability.

Common disturbances affecting soil organic carbon in northern high latitudes

drying lakes

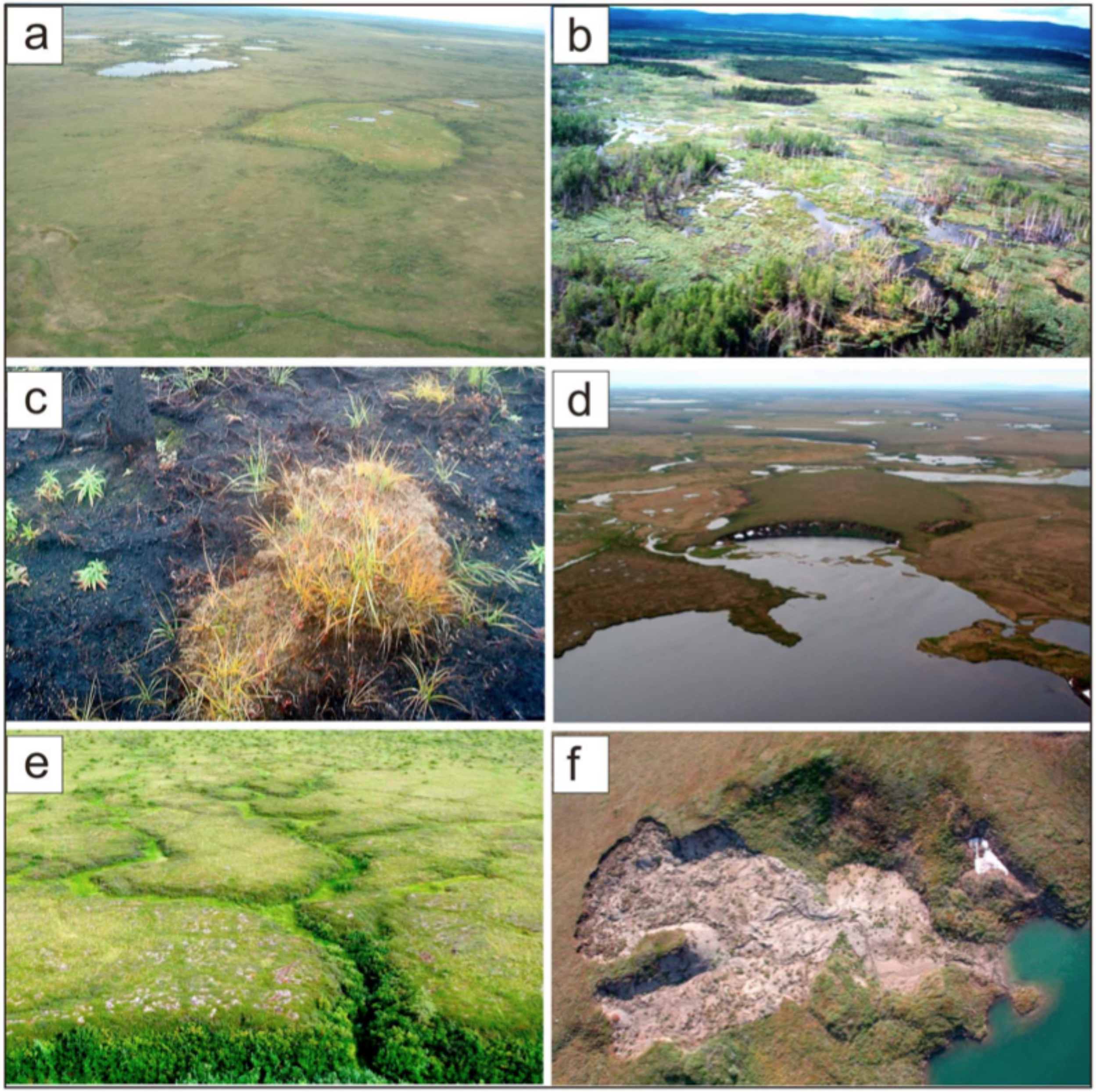
thermokarst fens and bogs

fires – burned and unburned surface mosaic

thermokarst lakes

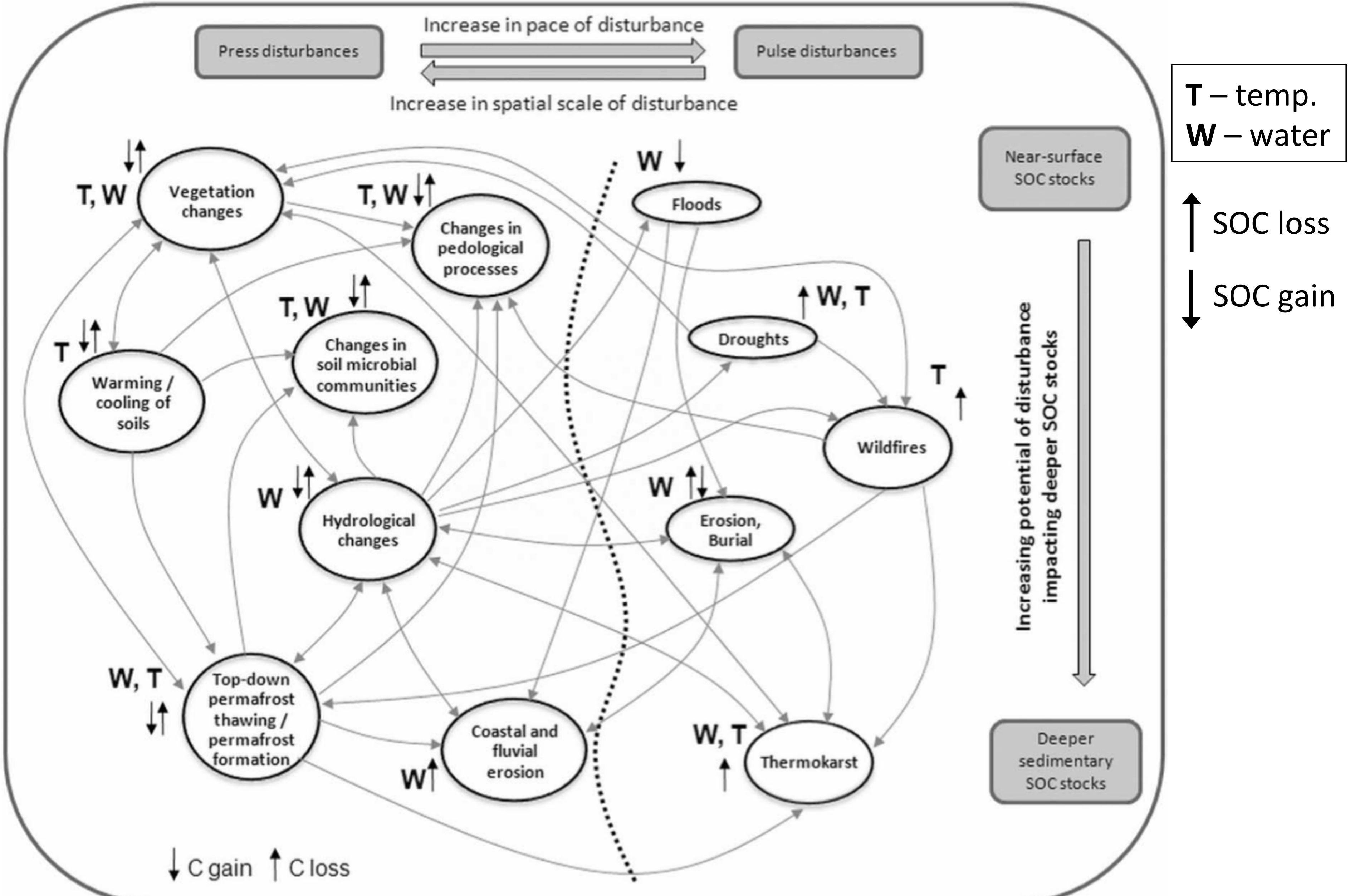
thermoerosional gullies

thaw slump due to glacial thermokarst



Grosse et al. (2011-*JGR*) Vulnerability of high-latitude soil organic carbon in North America to disturbance

Disturbance processes affecting soil carbon

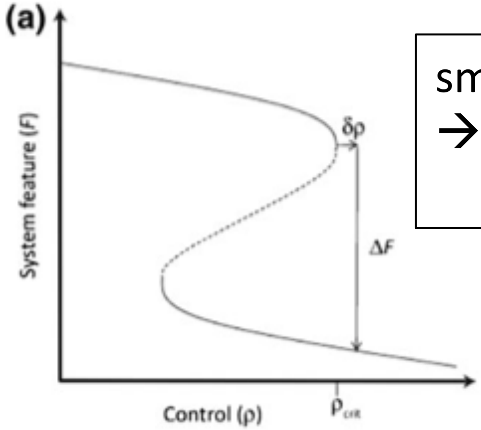


Grosse et al. (2011-*JGR*) Vulnerability of high-latitude soil organic carbon in North America to disturbance

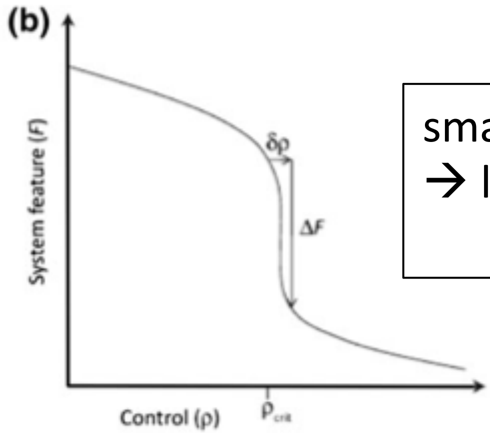
AMBIO (2012) 41:10–22
DOI 10.1007/s13280-011-0221-x

Arctic Climate Tipping Points

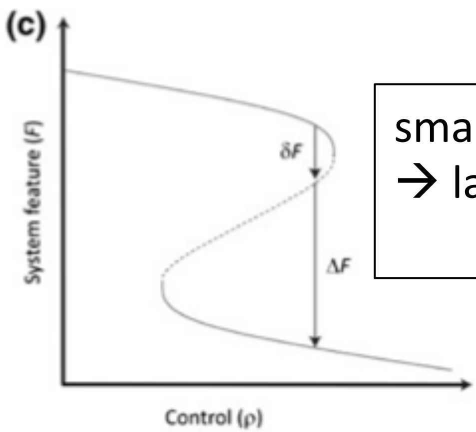
Timothy M. Lenton



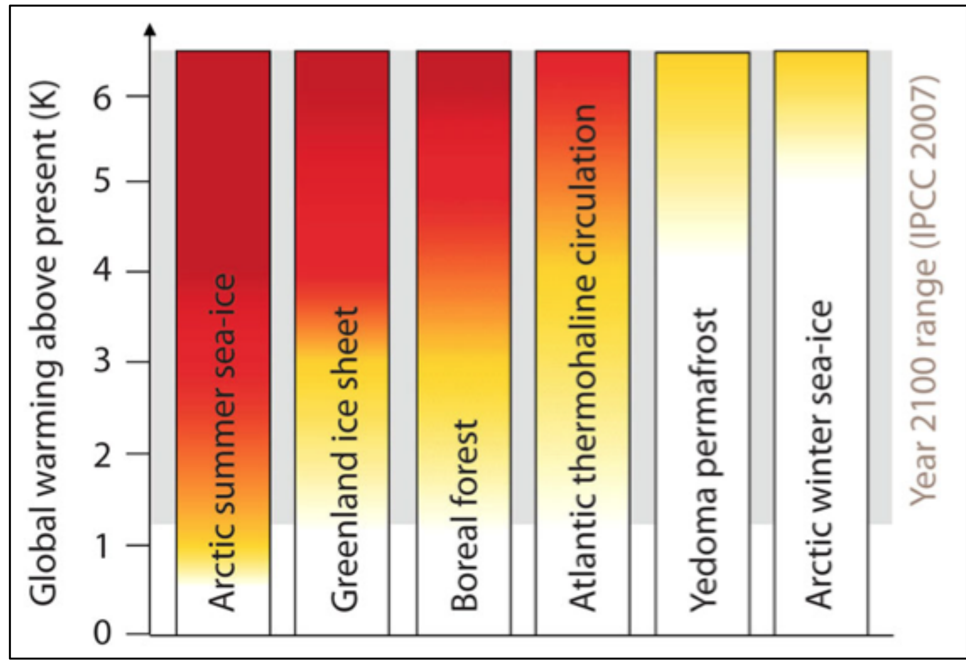
small change in forcing
→ large change in state
(irreversible)



small change in forcing
→ large change in state
(reversible)

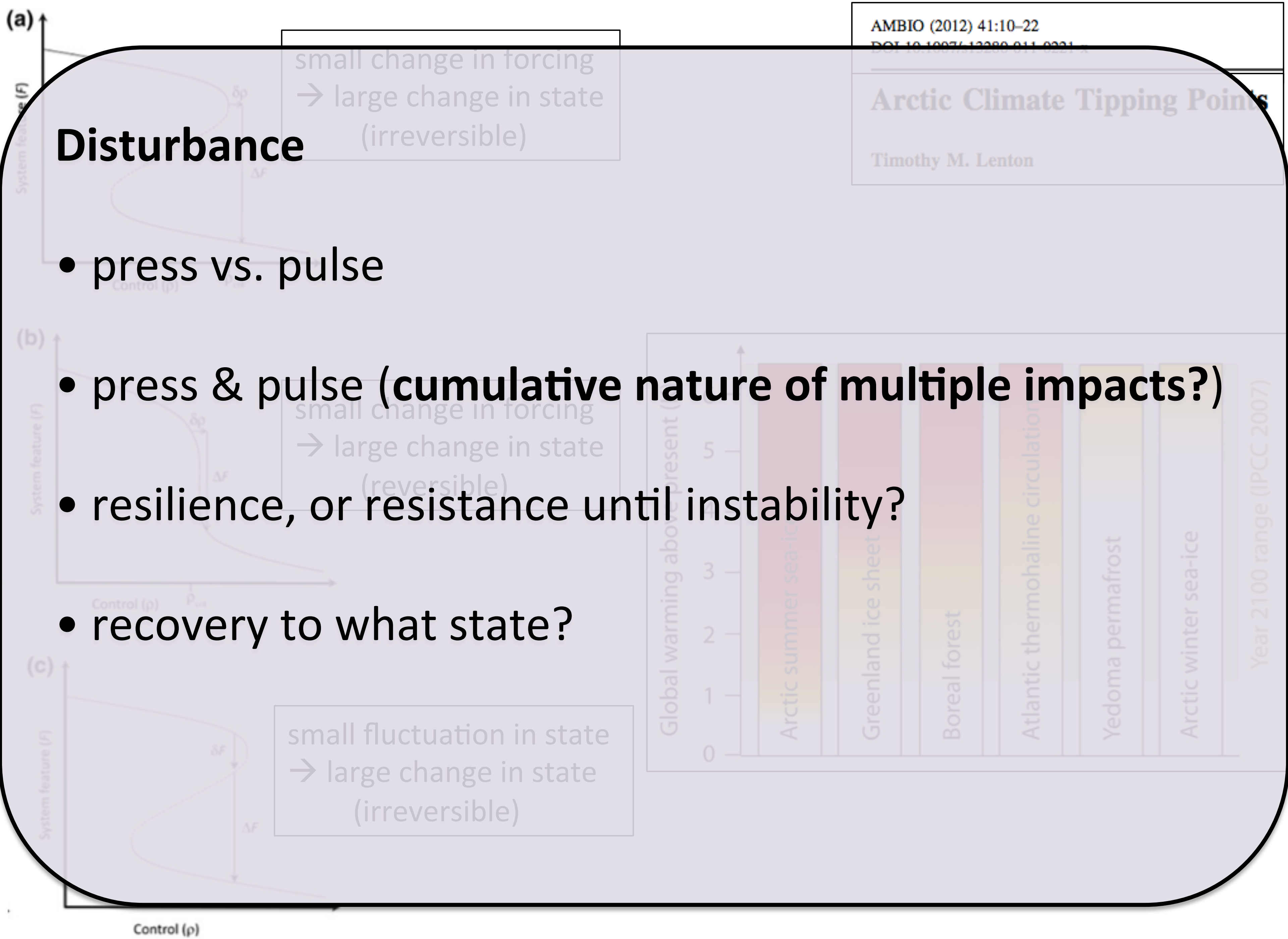


small fluctuation in state
→ large change in state
(irreversible)



Disturbance

- press vs. pulse
- press & pulse (**cumulative nature of multiple impacts?**)
- resilience, or resistance until instability?
- recovery to what state?



GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 23, GB3015, doi:10.1029/2008GB003413, 2009

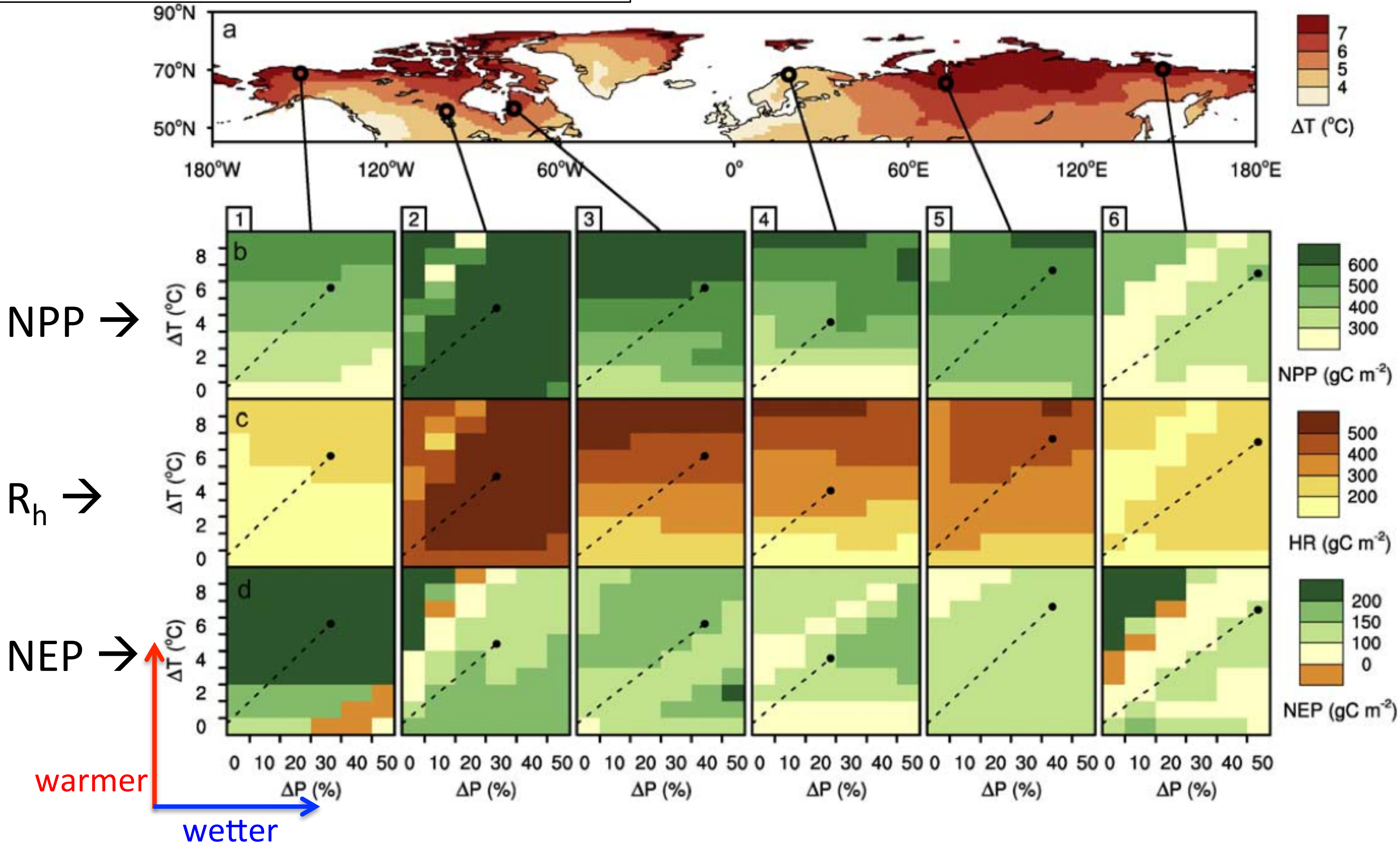
Click Here for Full Article

Integrating peatlands and permafrost into a dynamic global vegetation model:
2. Evaluation and sensitivity of vegetation and carbon cycle processes

R. Wania,[1,2] I. Ross,[3,4] and I. C. Prentice[5]

LPJ-WHy – 21st century climate change leads to increased CO_2 sink

ECHAM5 SRES-A2; 380 & 780 ppmv CO_2



GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 25, GB3018, doi:10.1029/2010GB003813, 2011

Is the northern high-latitude land-based CO_2 sink weakening?

D. J. Hayes,[1] A. D. McGuire,[2] D. W. Kicklighter,[3] K. R. Gurney,[4,5] T. J. Burnside,[1] and J. M. Melillo[3]

TEM – late-20th century global change leads to decreased CO_2 sink

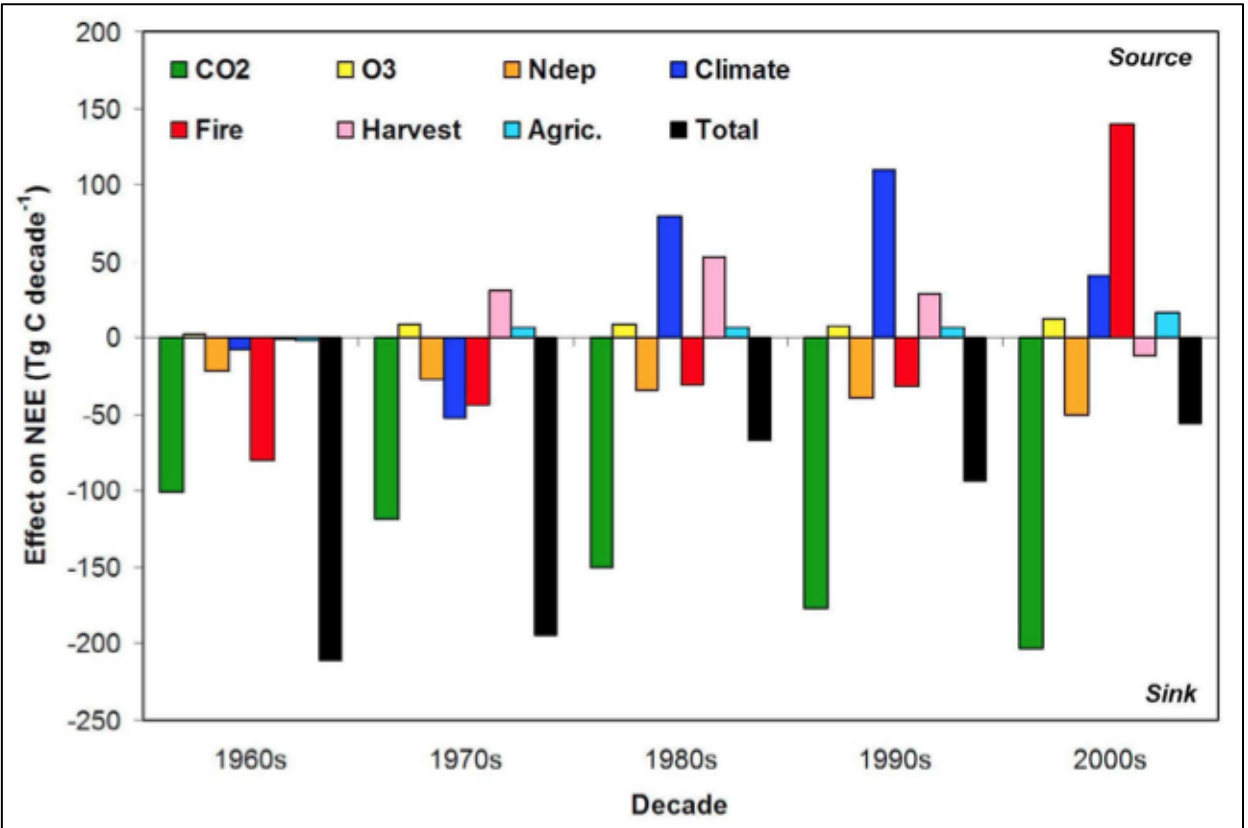


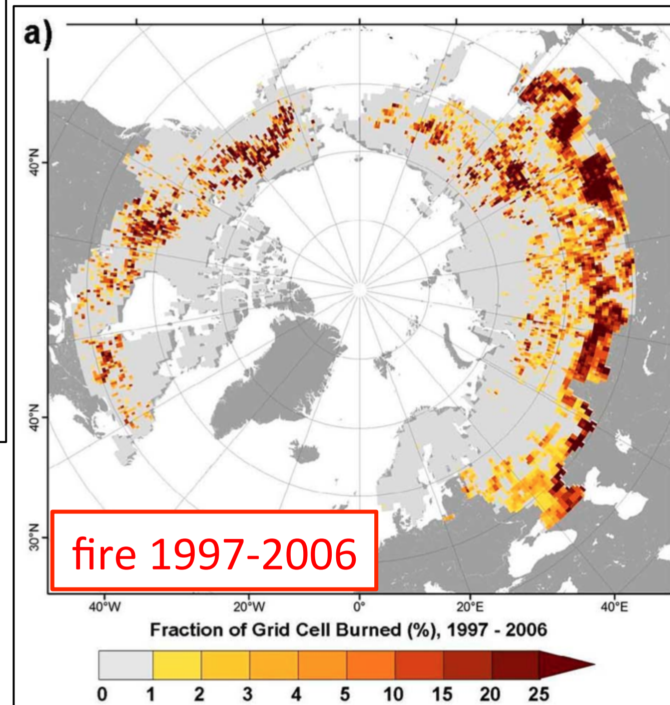
Figure 3. Total and individual average annual effects (Tg C yr^{-1}) of temporal variability in atmospheric [CO_2], tropospheric O_3 levels, N deposition rates, climate, fire, forest harvest, and agricultural establishment and abandonment on NEE for each decade since the 1960s across the northern high-latitude study area (the BONA, BOEU, and BOAS regions combined).

Net CO_2 flux trends 1960-2005

fire

climate

CO_2 fert.



PNAS

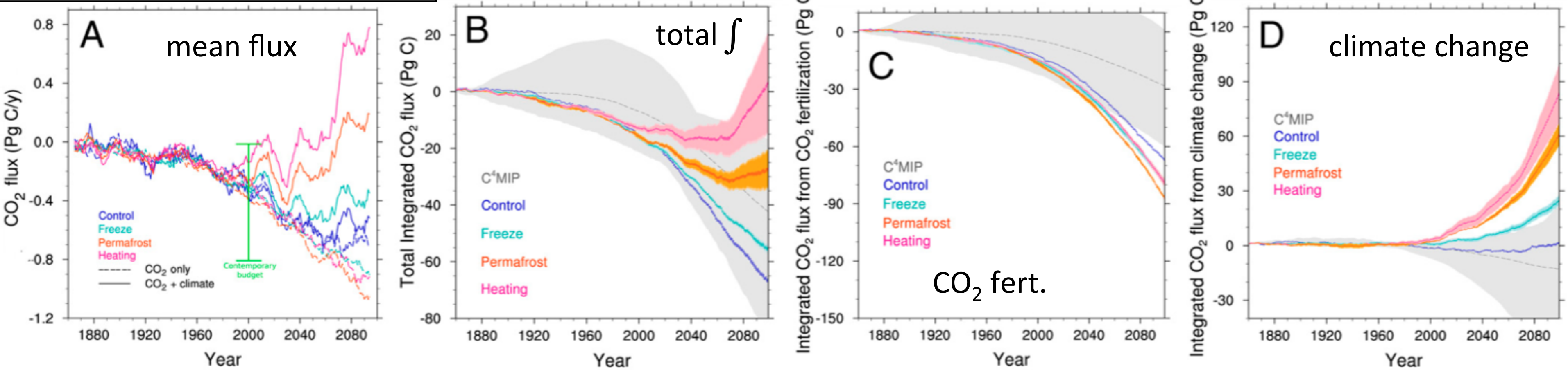
Permafrost carbon-climate feedbacks accelerate global warming

Charles D. Koven[a,b,1], Bruno Ringeval[a], Pierre Friedlingstein[c], Philippe Ciais[a], Patricia Cadule[a], Dmitry Khvorostyanov[d], Gerhard Krinner[e], and Charles Tarnocai[f]

www.pnas.org/cgi/doi/10.1073/pnas.1103910108

Control – soil carbon is vertically resolved
Freeze – seasonally frozen soil, no SOC in permafrost
Permafrost –permafrost carbon and soil organic insulation
Heating – inclusion of microbial metabolic heat production

ORCHIDEE – north of 60°N



Tellus (2011), 63B, 165–180
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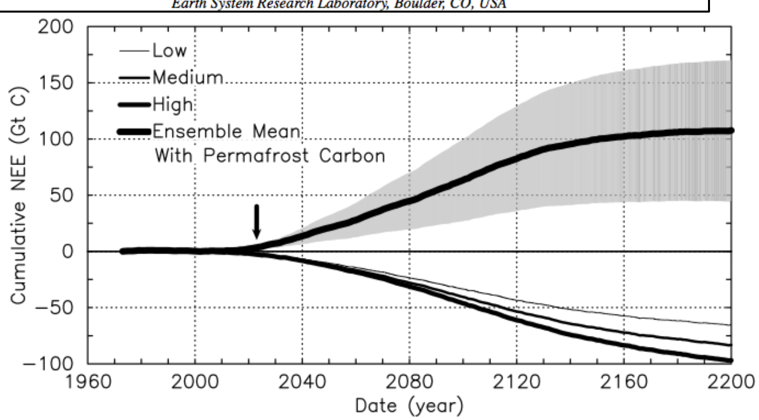
TELLUS

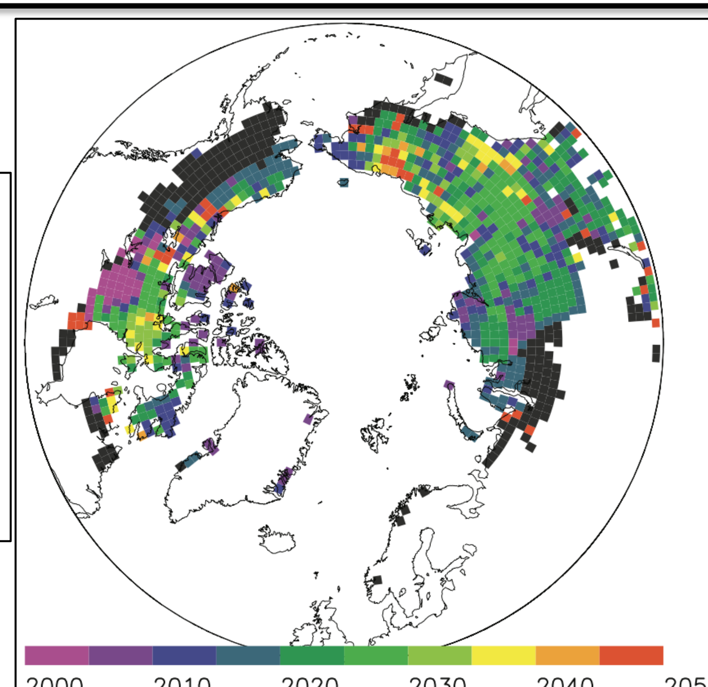
Amount and timing of permafrost carbon release in response to climate warming

By KEVIN SCHAEFER[1]*, TINGJUN ZHANG[1], LORI BRUHWILER[2] and ANDREW P. BARRETT[1], [1]National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, CO 80309, USA; [2]National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Boulder, CO, USA



SiB-CASA

Timing of transition to positive permafrost carbon feedback



Biogeosciences Discuss., 9, 4543–4594, 2012
www.biogeosciences-discuss.net/9/4543/2012/
doi:10.5194/bgd-9-4543-2012
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Biogeosciences Discussions

This discussion paper is/has been under review for the journal Biogeosciences (BG).
Please refer to the corresponding final paper in BG if available.

An assessment of the carbon balance of arctic tundra: comparisons among observations, process models, and atmospheric inversions

A. D. McGuire[1], T. R. Christensen[2,3], D. Hayes[4], A. Heroult[2], E. Euskirchen[5], Y. Yi[6], J. S. Kimball[6], C. Koven[7], P. Lafleur[8], P. A. Miller[2], W. Oechel[9], P. Peylin[10], and M. Williams[11]

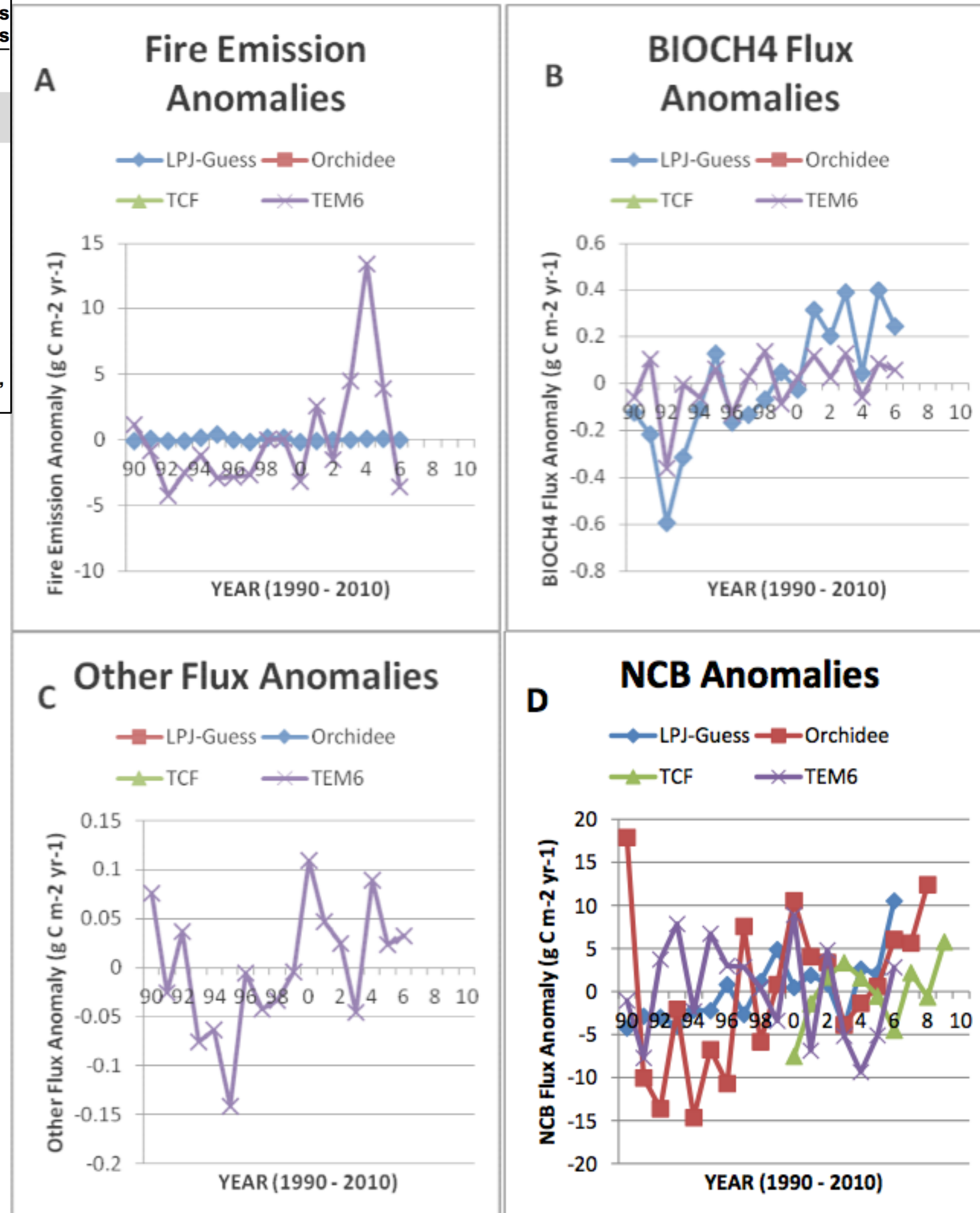
Comparisons among Orchidee, LPJ-Guess WHyMe, TCF, and TEM of inter-annual variability between 1990 and 2010 for

A. anomalies of fire emissions;

B. biogenic CH_4 emissions;

C. harvest & DOC export;

D. net carbon balance (NCB).



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Atmospheric inversions

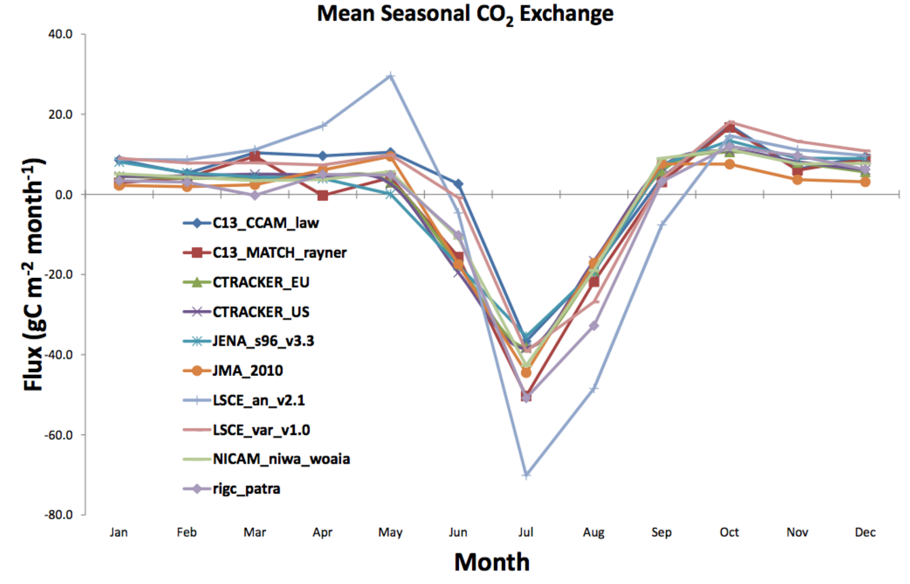

Fig. 7. Comparison among inversion model estimates of the mean net monthly exchange of CO_2 between arctic tundra and the atmosphere.

seasonal cycle

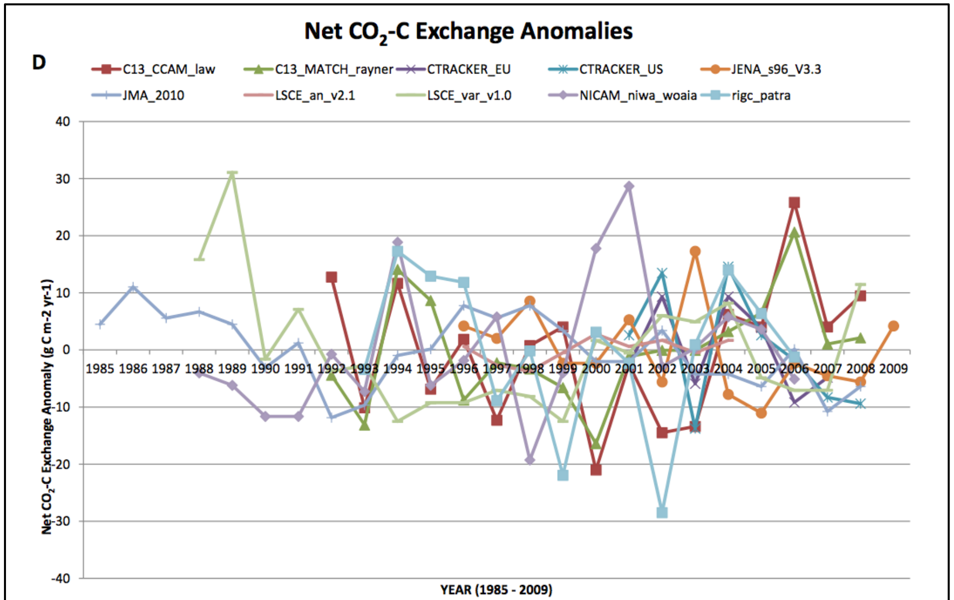

Fig. 8. Comparison among inversion model estimates of the interannual variability between 1985 and 2009 for anomalies of the net annual exchange of CO_2 between arctic tundra and the atmosphere.

interannual variability

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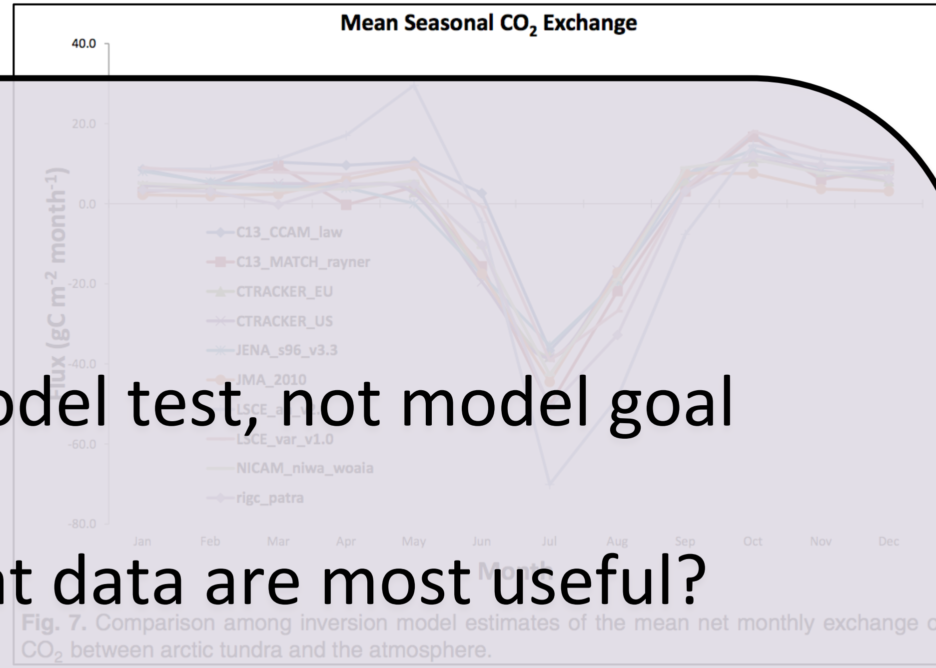
Biogeosciences Discussions



Modeling goals

- interannual variability – model test, not model goal
- 10-100+ year changes: what data are most useful?
  - flux towers – records are too short
  - manipulations – changed climate vs. climate change
  - space-for-time – changed climate v. climate change

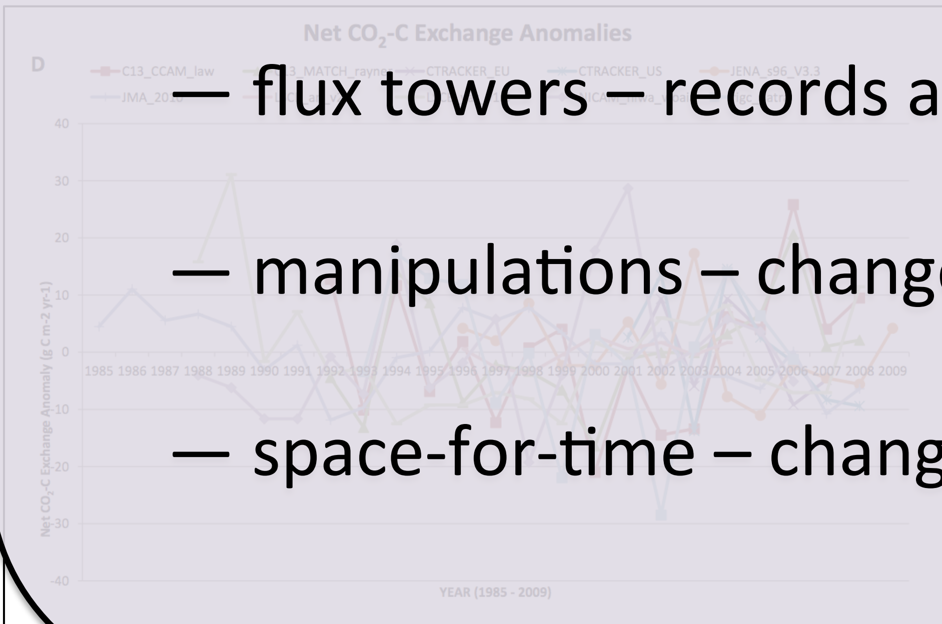


Fig. 8. Comparison among inversion model estimates of the interannual variability between 1985 and 2009 for anomalies of the net annual exchange of CO_2 between arctic tundra and the atmosphere.

‘Size determines an object,

but scale determines art.’

Robert Smithson – Spiral Jetty, Great Salt Lake UT, 1970

‘Size determines an object,

but scale determines art.’

Robert Smithson – Spiral Jetty, Great Salt Lake UT, 1970

multiple scales

relating to

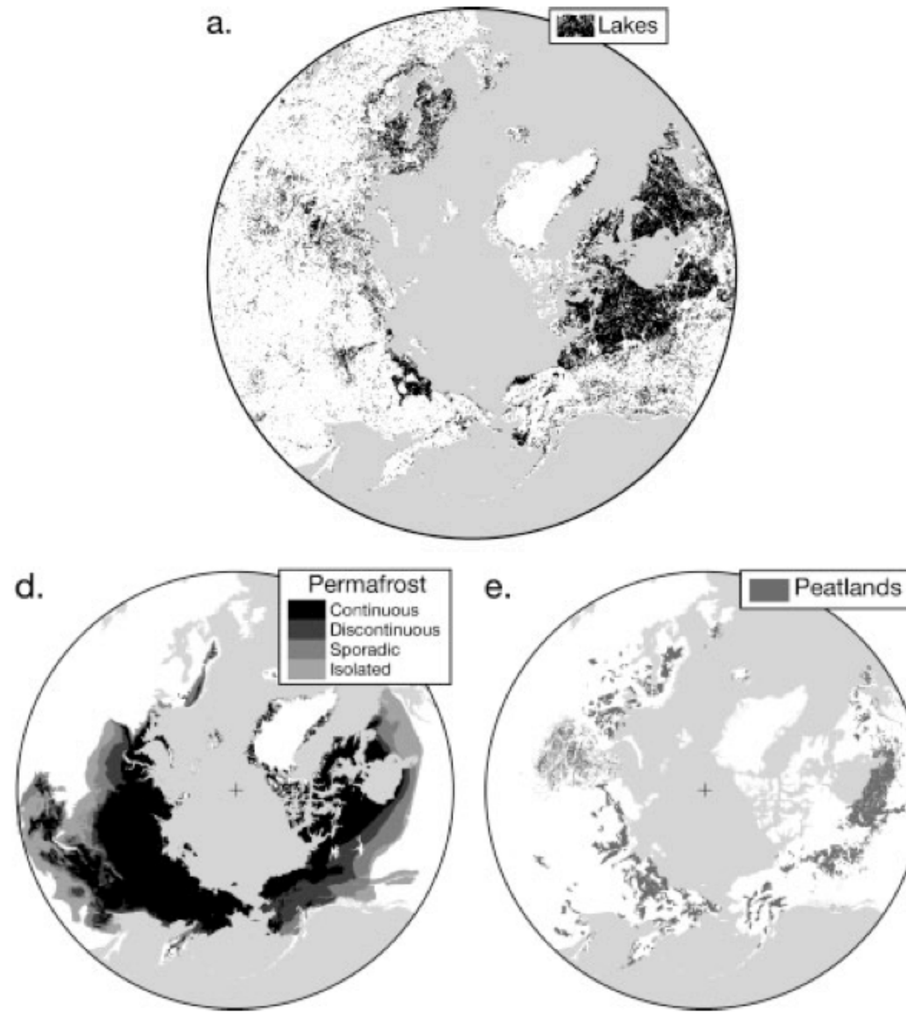
multiple variables

PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. **18**: 201–208 (2007)
Published online 10 April 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/ppp.581

Short Communication

A First Pan-Arctic Assessment of the Influence of Glaciation, Permafrost, Topography and Peatlands on Northern Hemisphere Lake Distribution

Laurence C. Smith, Yongwei Sheng and Glen M. MacDonald*

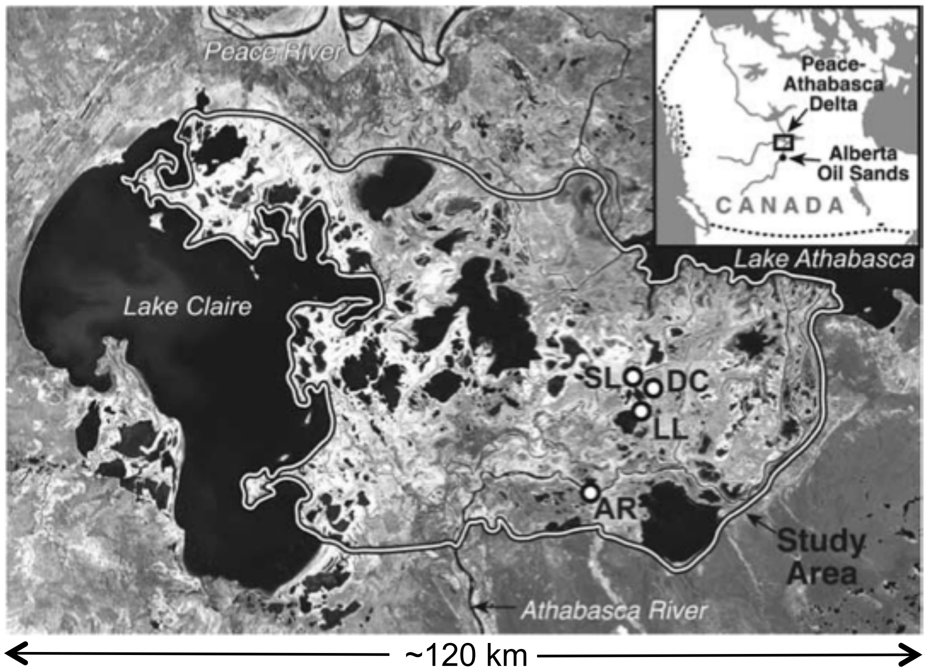


GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L08403, doi:10.1029/2008GL033268, 2008

Click Here for Full Article

Remote sensing of hydrologic recharge in the Peace-Athabasca Delta, Canada

Tamlin M. Pavelsky[1] and Laurence C. Smith[1]



MODIS-derived inundated area differed by nearly 100% in late spring/early summer of 2006 & 2007 due to snow pack and ice dam differences.

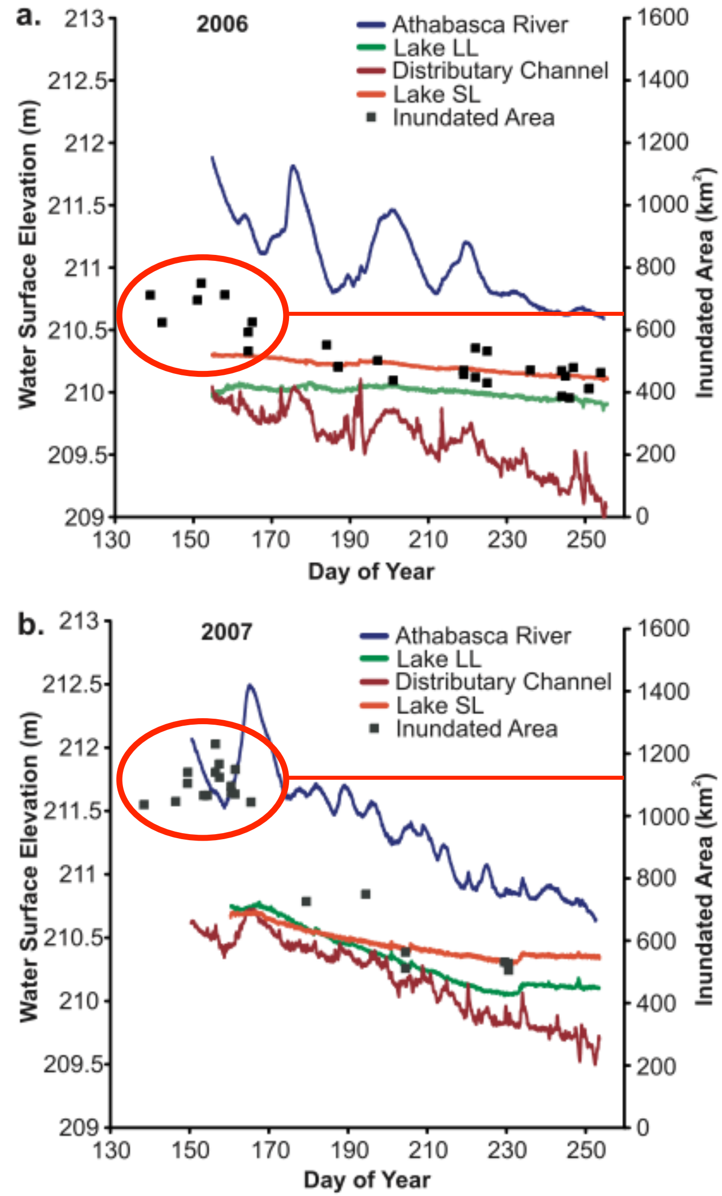
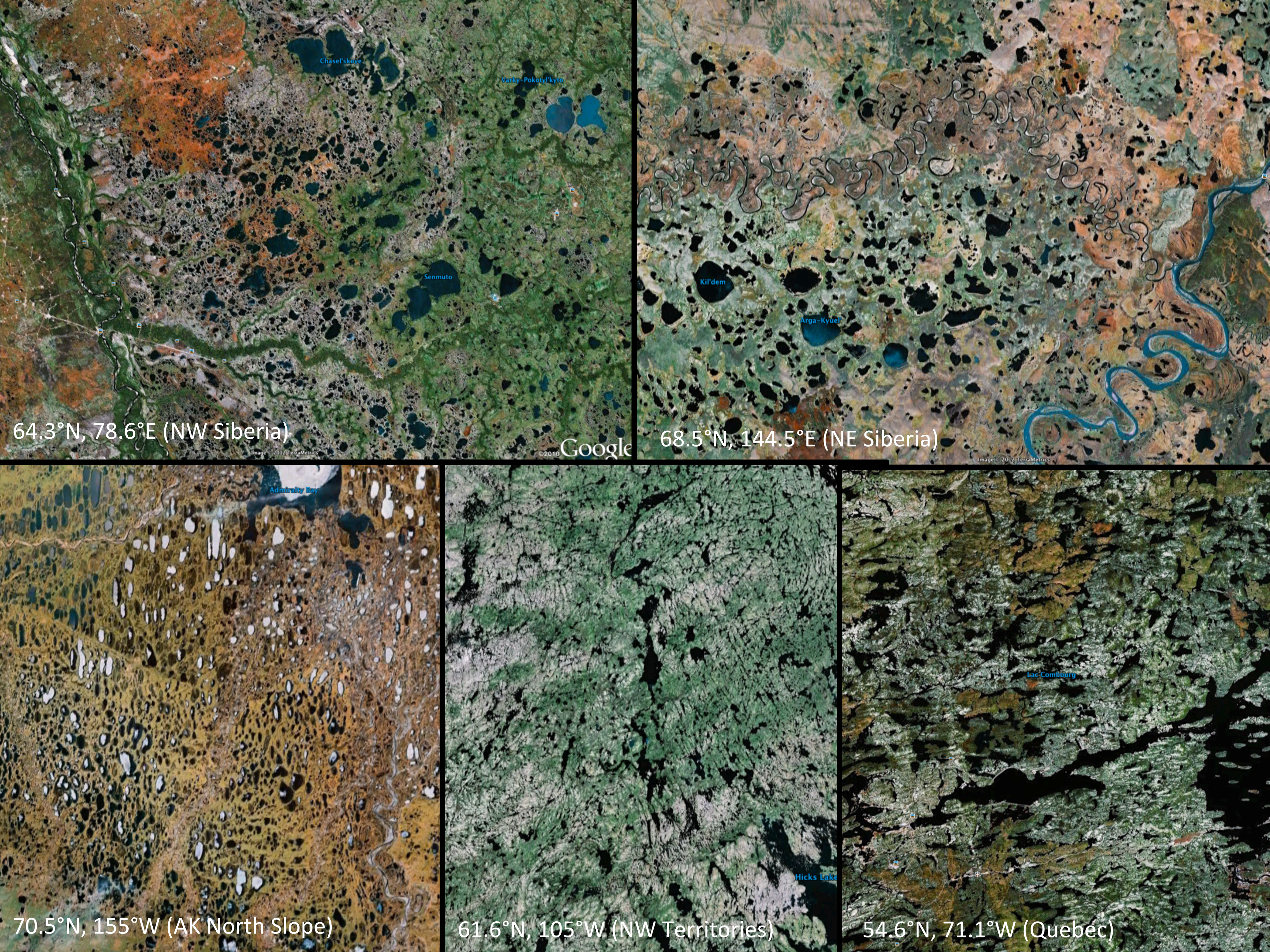


Figure 2. Time series of water surface elevation at four locations within the Peace Athabasca Delta for (a) 2006 and (b) 2007. LL and SL lake water surface elevations in 2006 were not manually surveyed, so their absolute magnitudes in Figure 2a are arbitrary and only relative changes within each time series are considered.


64.3°N, 78.6°E (NW Siberia)
68.5°N, 144.5°E (NE Siberia)
70.5°N, 155°W (AK North Slope)
61.6°N, 105°W (NW Territories)
54.6°N, 71.1°W (Quebec)

Scaling

- overlapping features: SOC, vegetation, permafrost, disturbance, hydrology, topography.
- doesn't look like it will be easy; what's most important?
- may be particularly important for coupling carbon and water cycles.

64.3°N, 78.6°E (NW Siberia)

68.5°N, 144.5°E (NE Siberia)

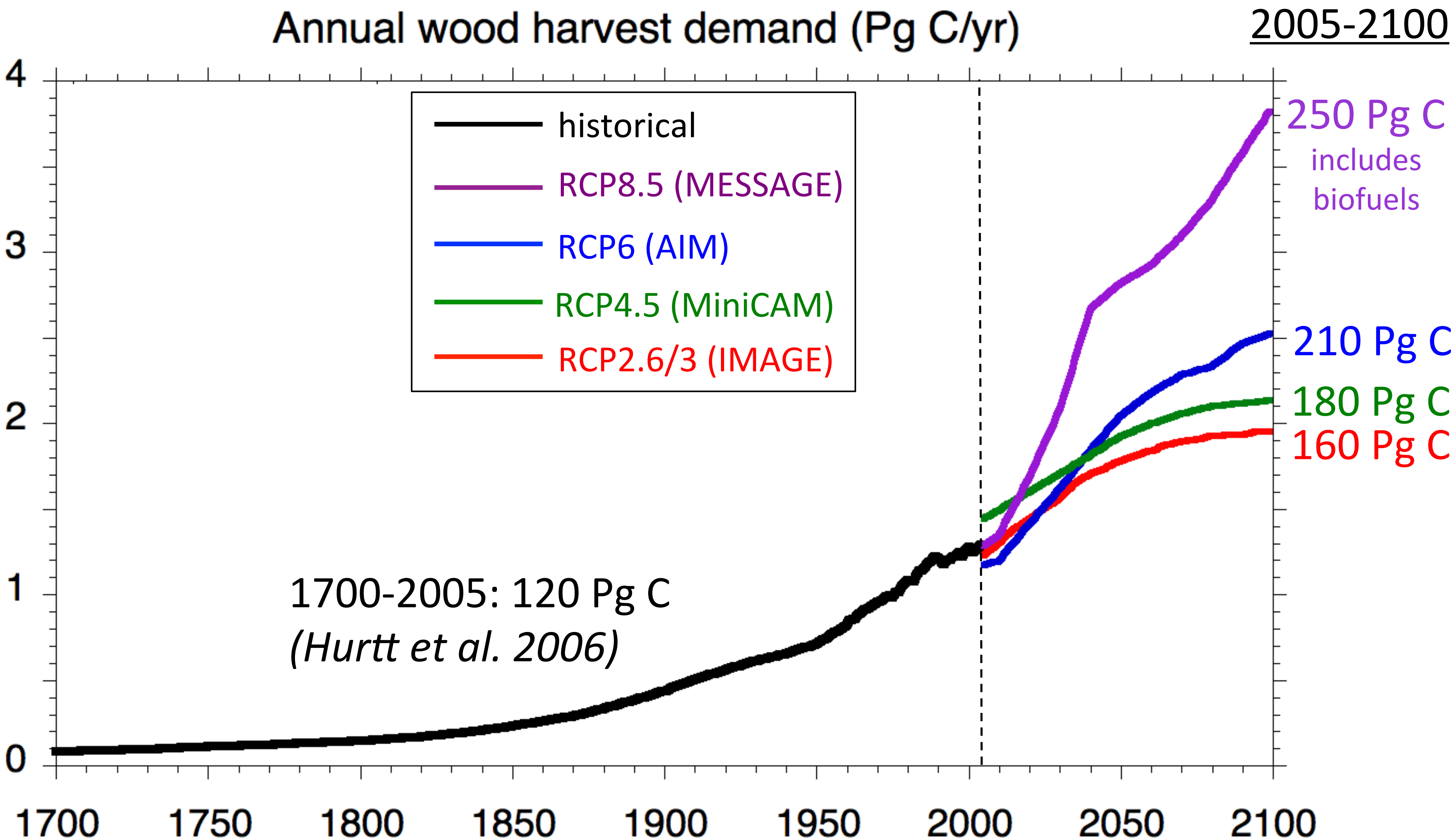
70.5°N, 155°W (AK North Slope)

61.6°N, 105°W (NW Territories)

54.6°N, 71.1°W (Quebec)

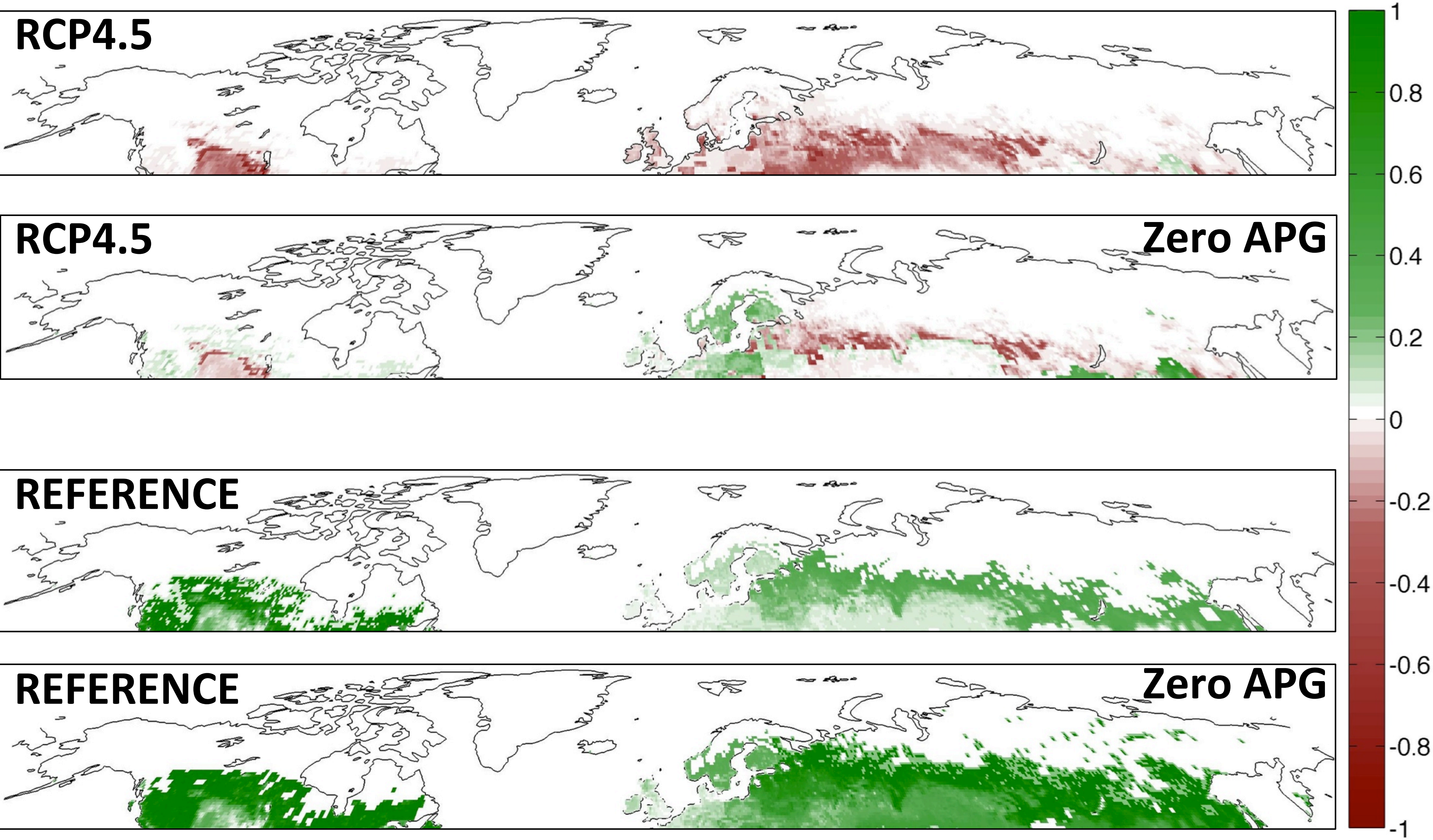
Finally, don't forgot about people

IPCC AR5 wood harvest 1700-2100



Projections for continually increasing rates of wood harvest – impact on boreal forest?

GCAM: 2005-2100 – change in grid cell fraction in cropland



Thomson et al. (2010, *PNAS*)

CONCLUSIONS

- permafrost – moving beyond area/depth of thaw to carbon cycle and vegetation/ecosystem/hydrology impacts.
- shallow water tables, spatial heterogeneity; permafrost, thermokarst, methane.
- multiple, interacting press & pulse disturbances.
- data sets needed to evaluate decadal-centennial modeling.