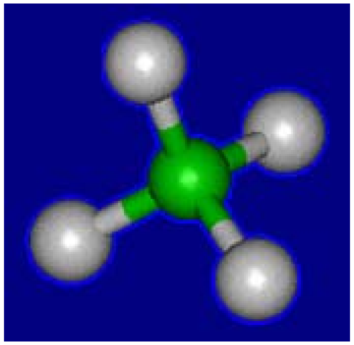
Wetland Sources and Their Contributions to Arctic Methane Emissions

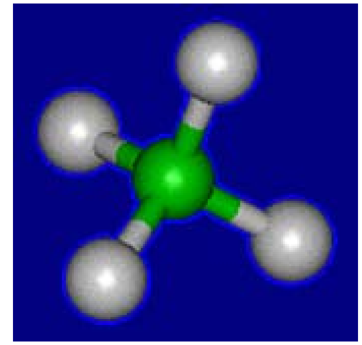
Stordalen Mire

Patrick Crill
Dept of Geological Sciences
Bolin Centre for Climate Research
Stockholm University

patrick.crill @geo.su.se



Methane Formation
generalities



- Metabolic product of methanogenic *Archaea*

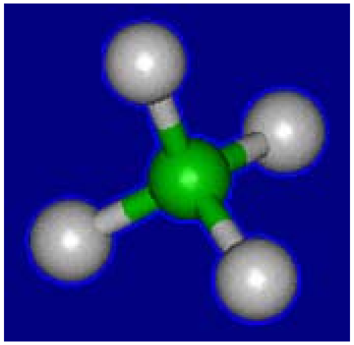
- The main substrates are acetate or $CO_2 + H_2$:

$$CH_3COOH \rightarrow CH_4 + CO_2$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

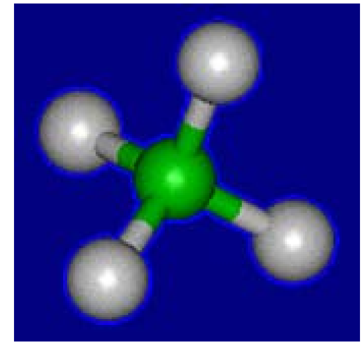
(There are a few “non-competitive” subtrates (demethylation of osmotic regulators, e.g. glycine betaine, trimethylamine, DMSP))

- Formed at low Eh: < -200mV
  (very low O_2, SO_4^{2-} and NO_3^- concentrations)

➡ Methanogenesis is strictly an **ANAEROBIC** process



Methane oxidation



- Catalyzed by methanotrophic or methylotrophic bacteria and archaea

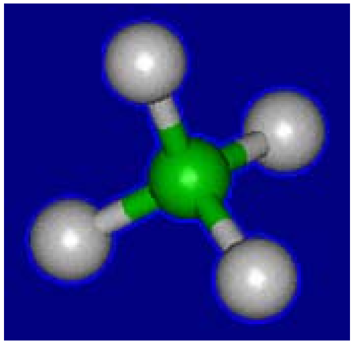
- The main substrates are CH_4 and O_2:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Methane oxidation is mostly an AEROBIC process

(marine sediments, metalliferous and hypersaline environments are the exceptions)

Some Points about Tropospheric CH_4



1. Its mixing ratio is increasing in troposphere, with a rate that appears to have become variable in recent years.

2. The reason for the increasing trend is not clearly established, but both natural and anthropogenic sources appear to be important.

3. Its mixing ratio is larger by 5 – 10% in NH compared to SH.

4. Its seasonality is similar to that of CO_2.

5. Its principal removal mechanism from the troposphere is chemical decomposition by OH attack. Its lifetime is thought to be 8 to 11 years.

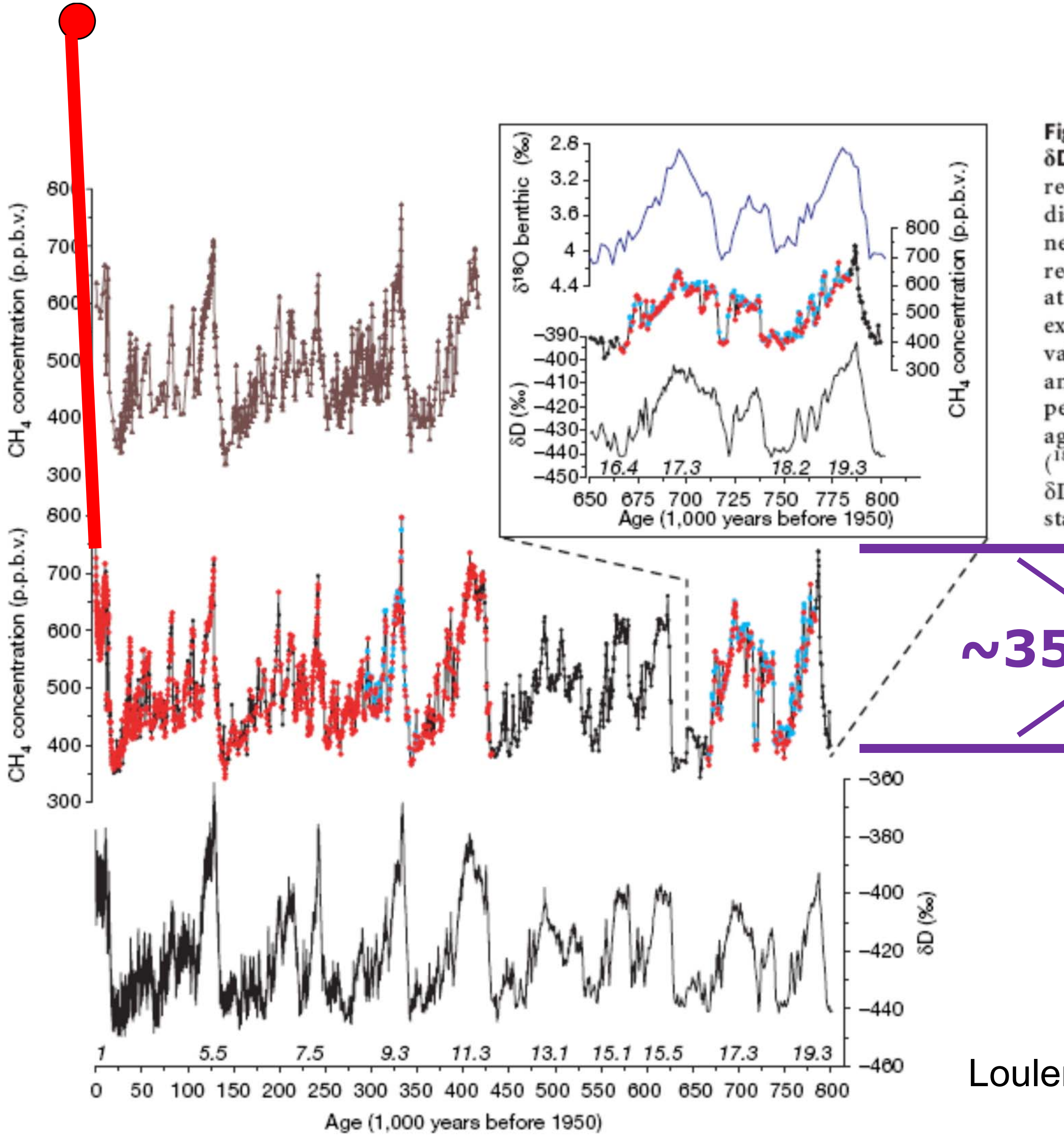
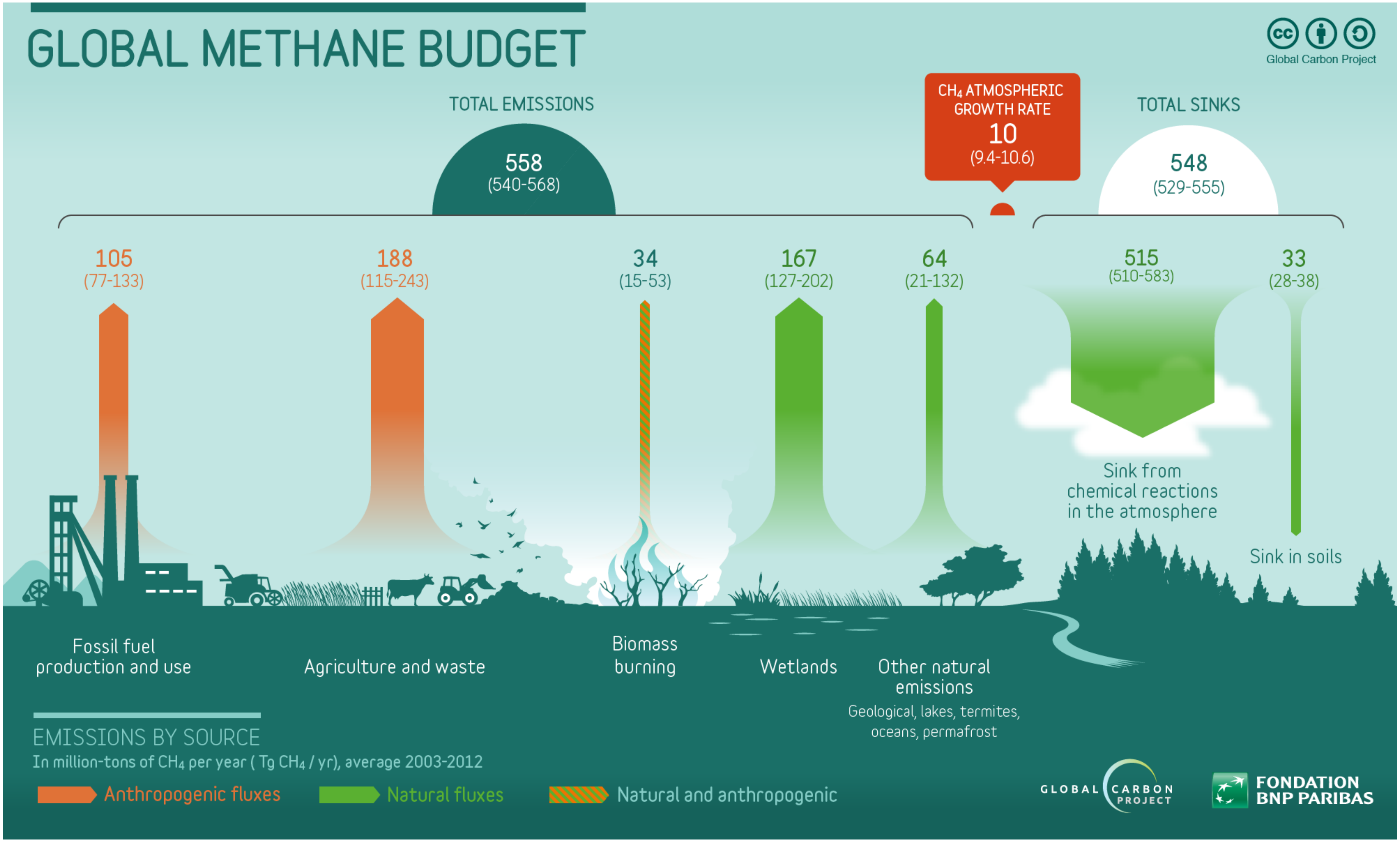


Figure 1 | Methane records and EPICA/Dome C δD. Bottom to top: δD record[9]; EDC methane record (previously published data[2], black diamonds; new data from LGGE, red diamonds; new data from Bern, blue dots); Vostok methane record[1]. Marine Isotope Stage numbering is given at the bottom of each interglacial. Insert: expanded view of the bottom section of EDC: δD values[9] (black line), CH_4 (black line) from EDC and stack benthic $\delta^{18}O$ values (blue line)[19] for the period from MIS 16 to 20.2, on their respective age scales. $\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard}] - 1$, where standard is vPDB; $\delta D = [(D/H)_{sample}/(D/H)_{standard}] - 1$ where standard is SMOW.

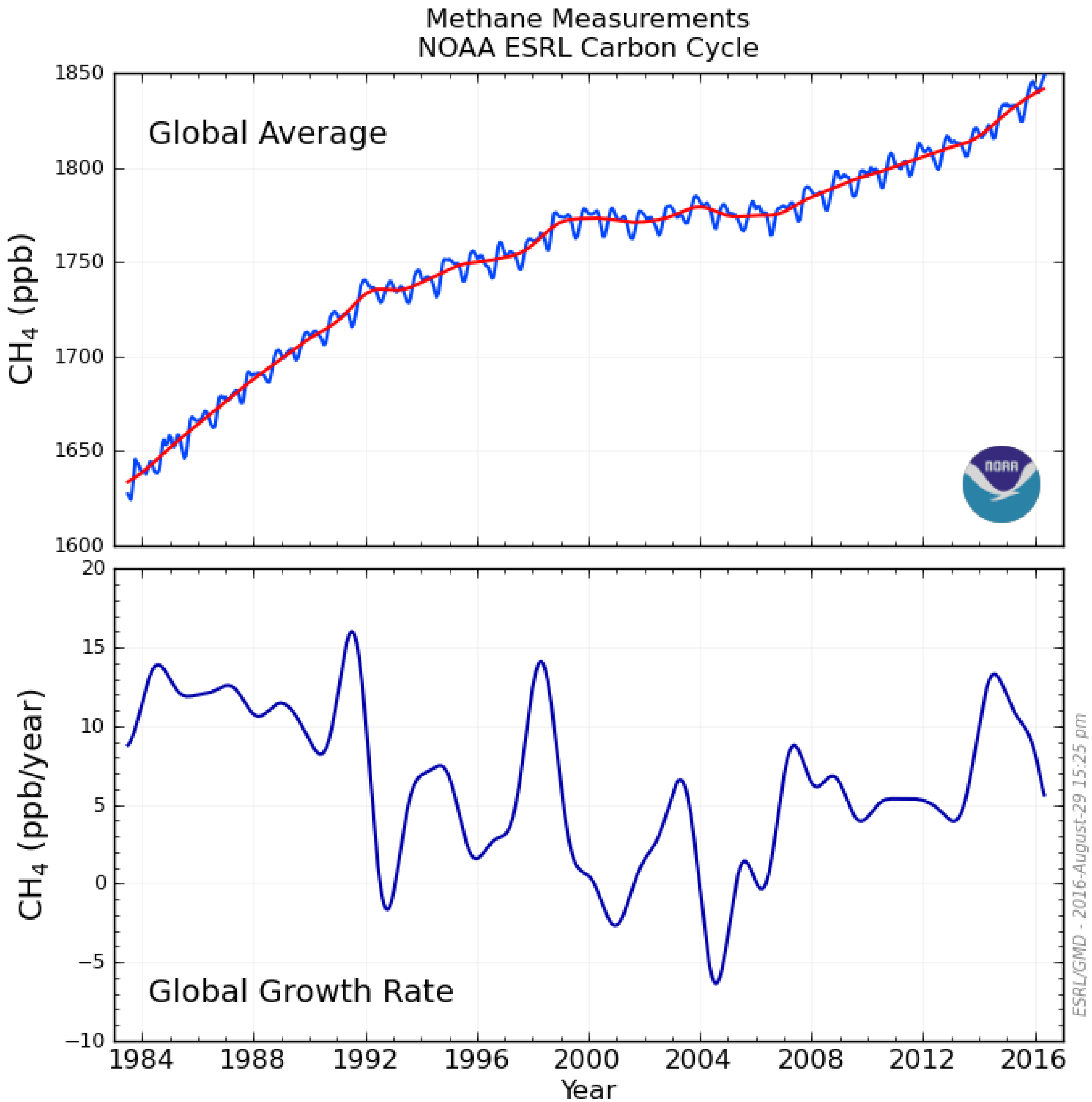
~350 ppb ≈ 975 Tg

Loulergue et al. Nature, 2008

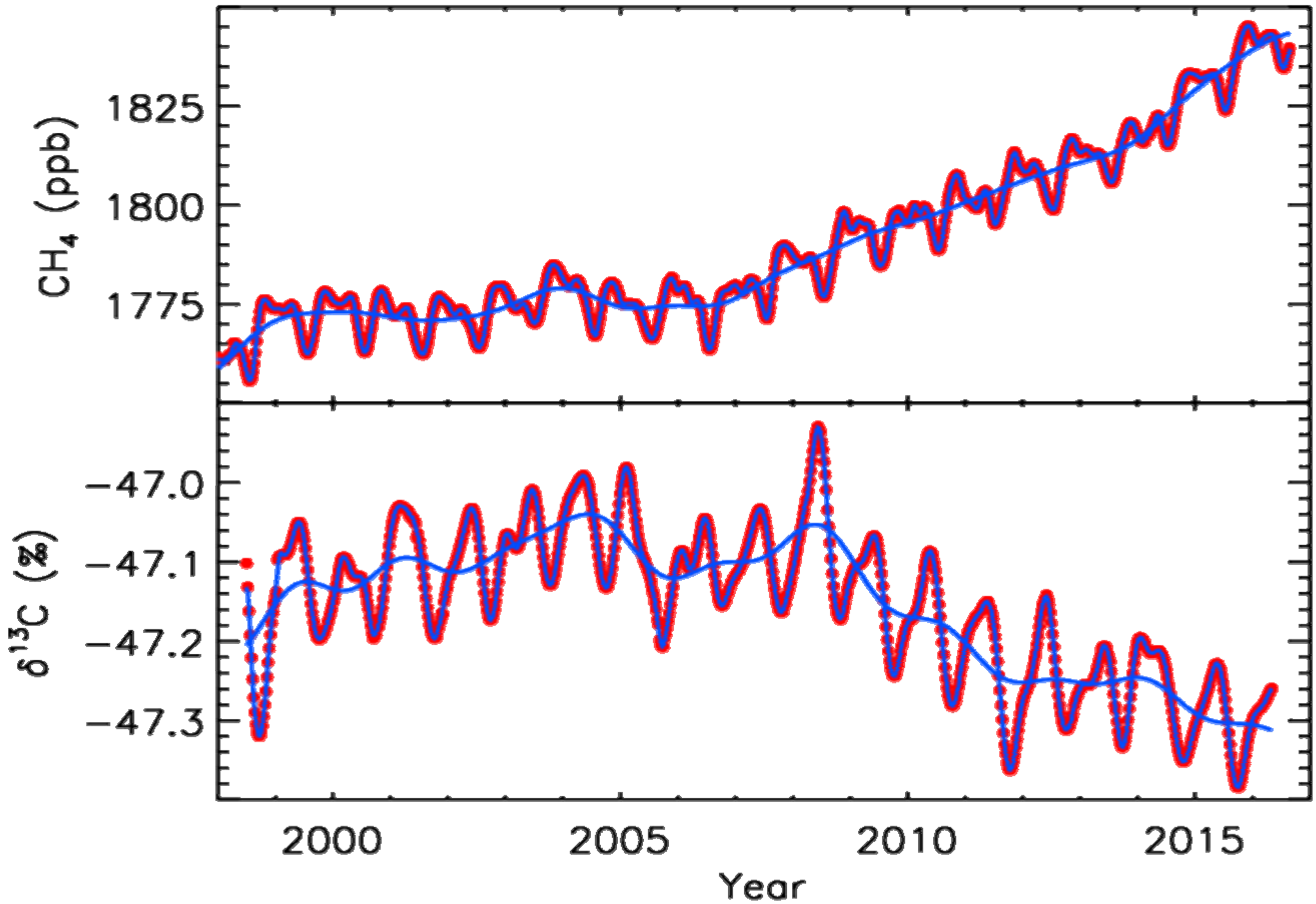
Global Methane Budget 2003-2012



http://www.globalcarbonatlas.org

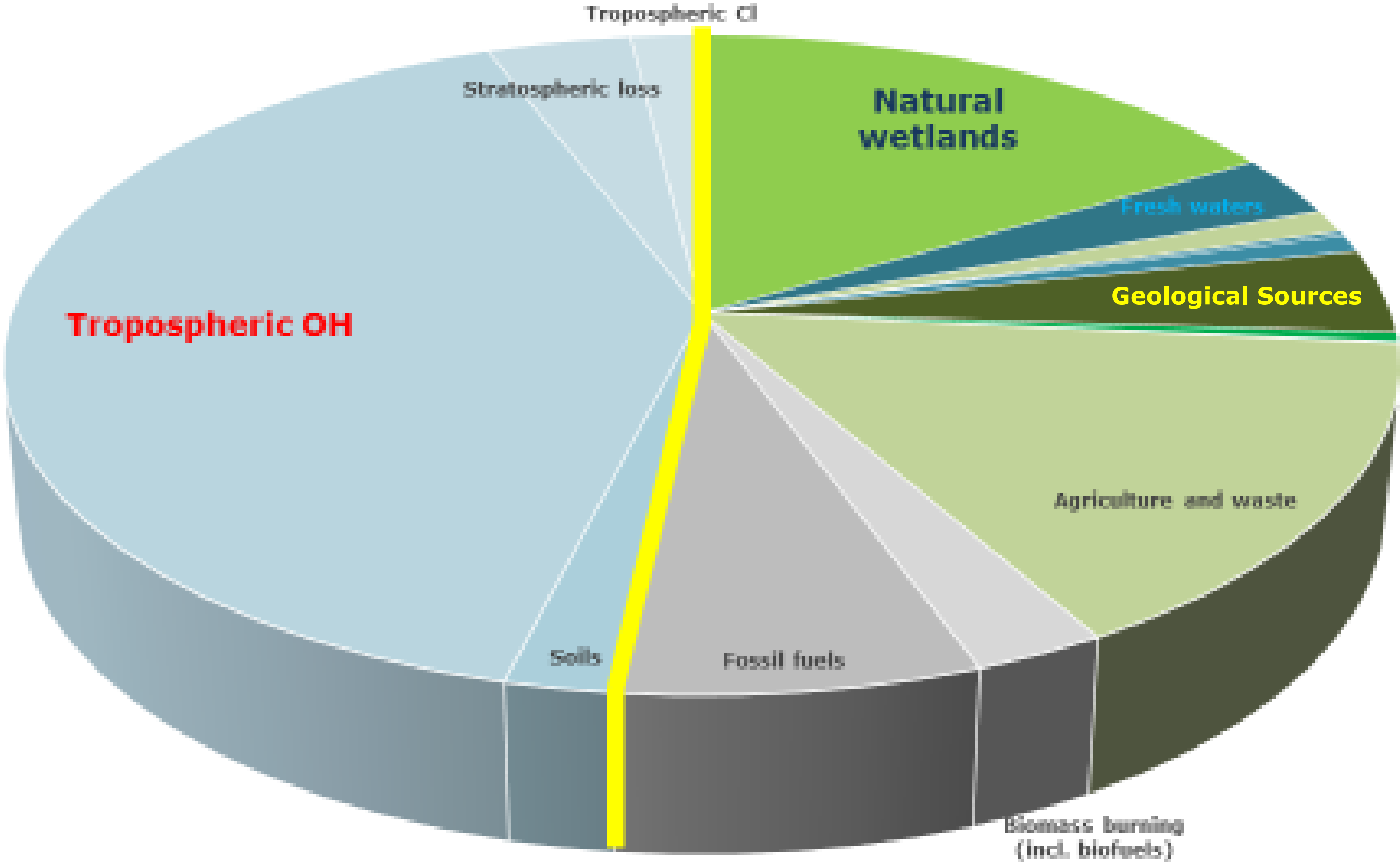


Top: Global average atmospheric methane mixing ratios (blue line) determined using measurements from the Carbon Cycle cooperative air sampling network. The red line represents the long-term trend. Bottom: Global average growth rate for methane. Contact: Dr. Ed Dlugokencky, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6228, ed.dlugokencky@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

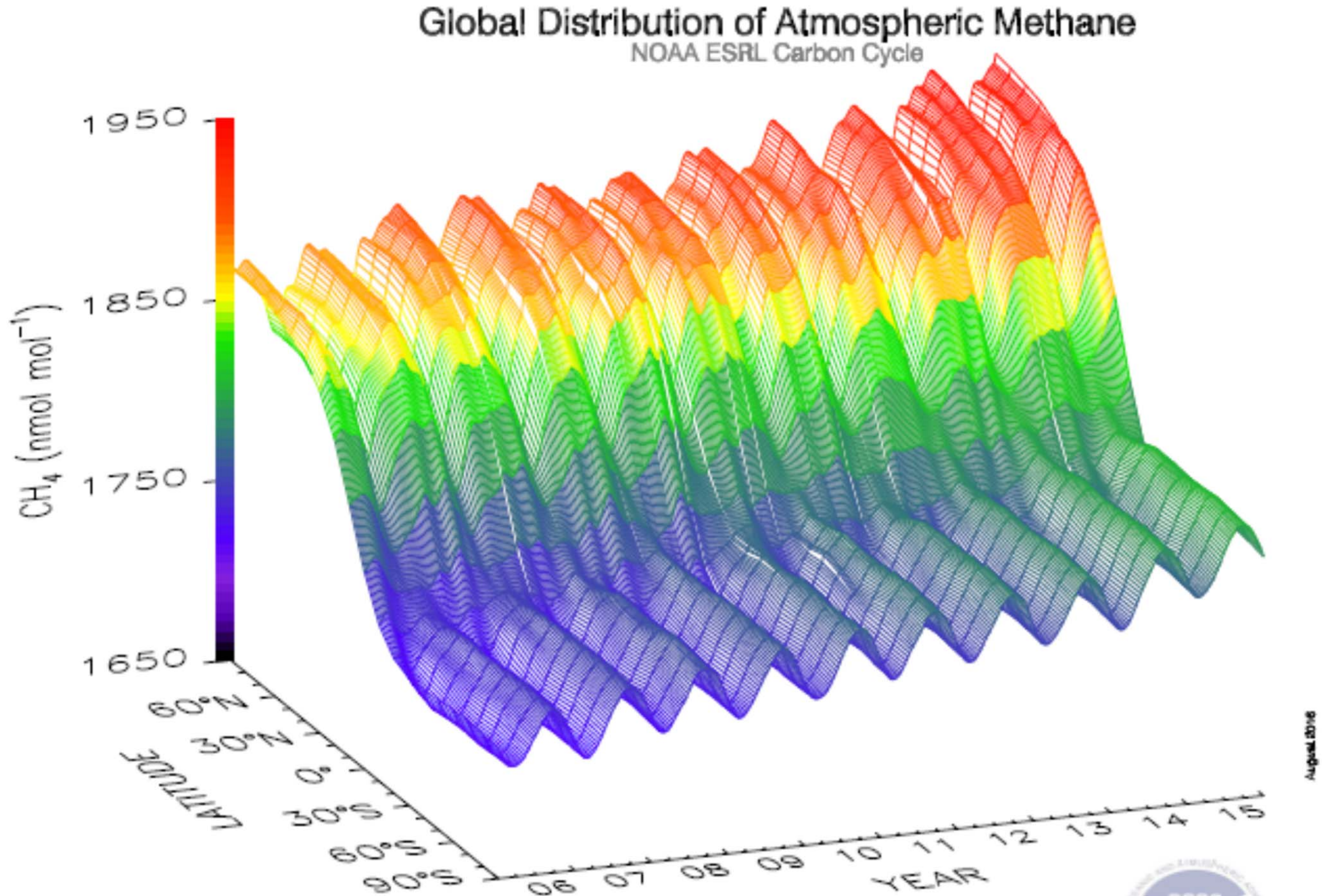


Provided by: Michel, White CU INSTAAR; Dlugokencky NOAA ESRL

Kirschke Bottom Up Methane Budget



Kirschke et al 2013



Three-dimensional representation of the latitudinal distribution of atmospheric methane in the marine boundary layer. Data from the Carbon Cycle cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Contact: Dr. Ed Dlugokencky, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6228, ed.dlugokencky@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

Global Carbon Pools

Global Vegetation C — **650 Pg**

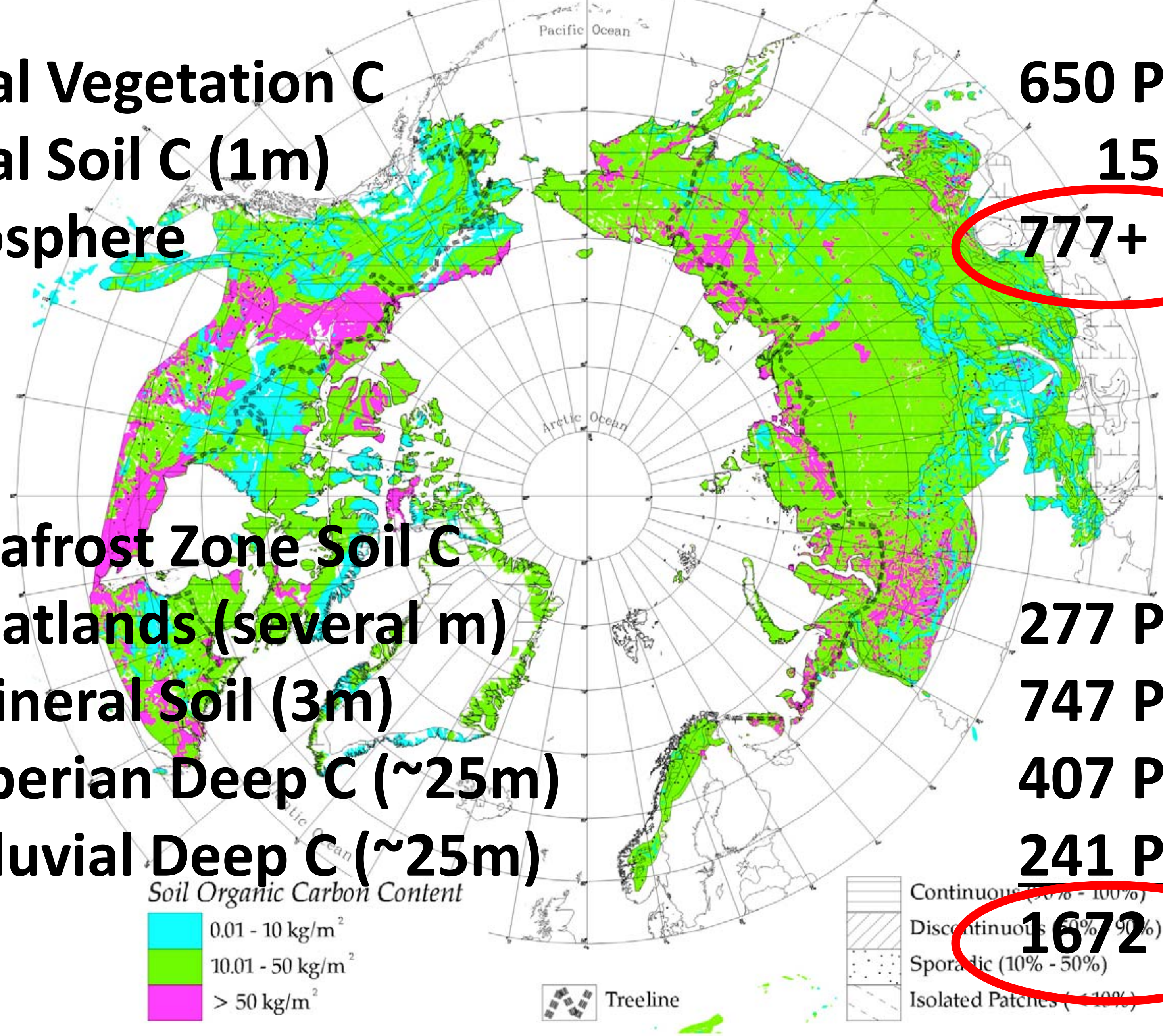
Global Soil C (1m) — **1500 Pg**

Atmosphere — **777+ Pg**

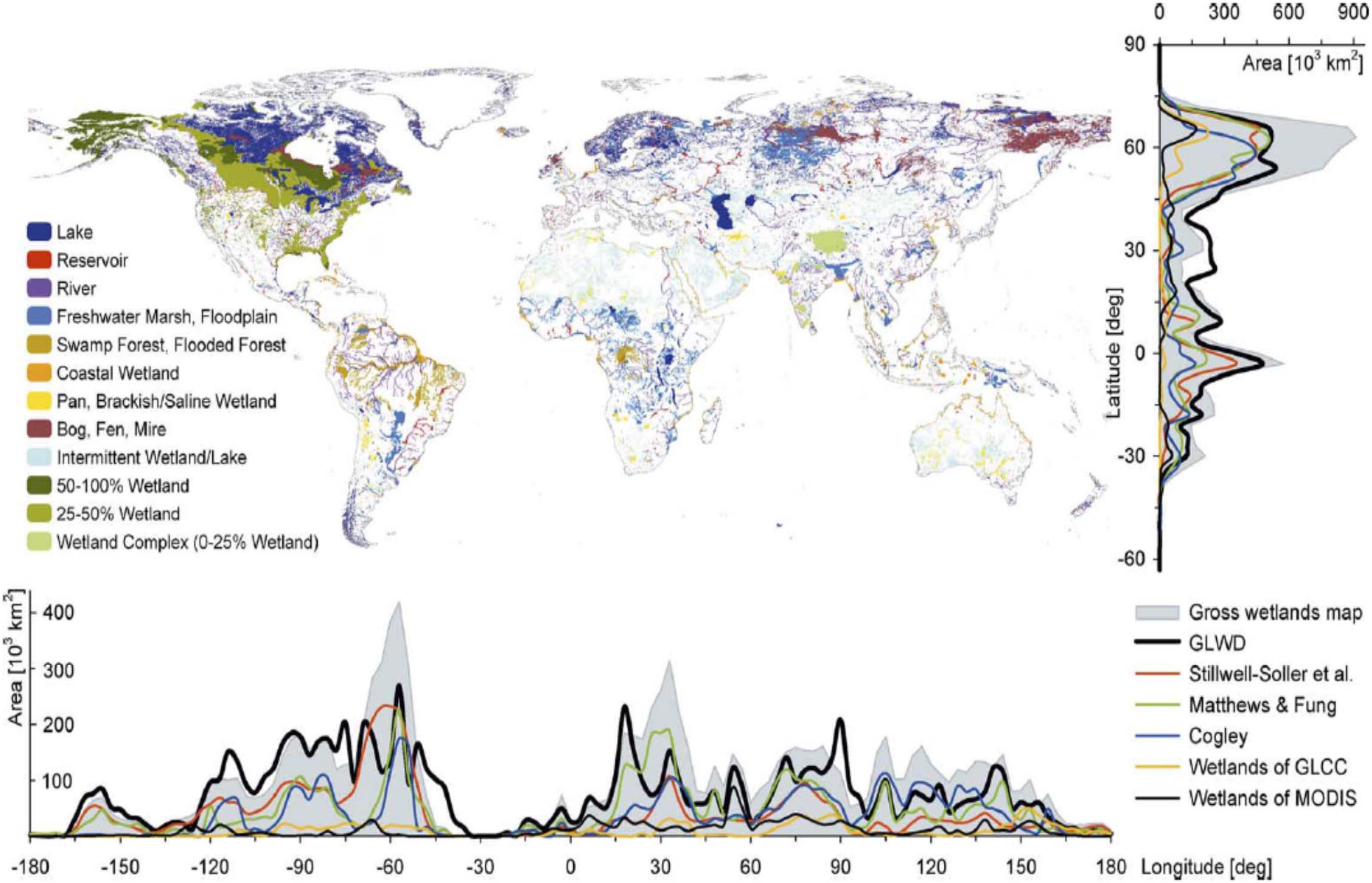
Permafrost Zone Soil C

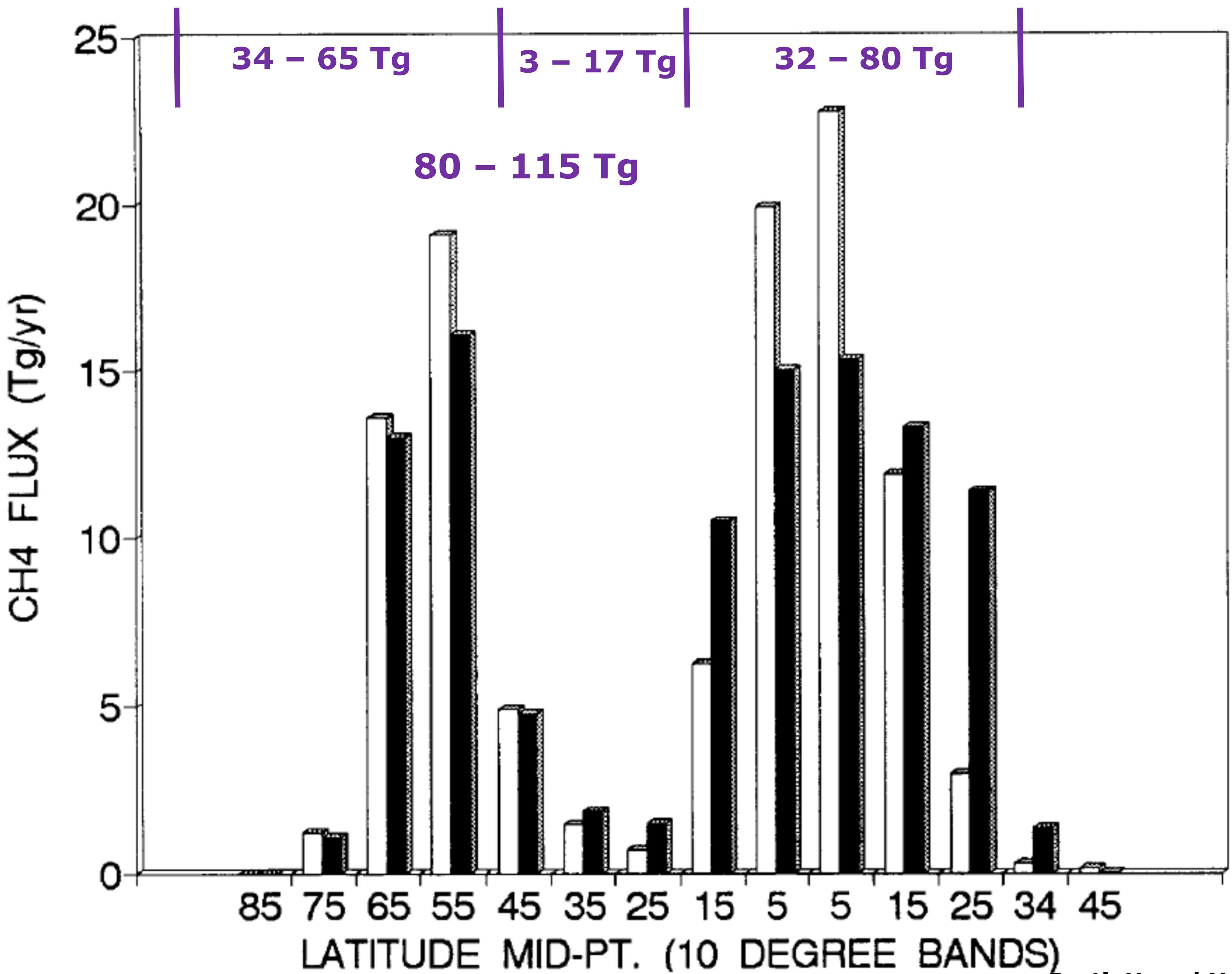
- **Peatlands (several m)** — **277 Pg**
- **Mineral Soil (3m)** — **747 Pg**
- **Siberian Deep C (~25m)** — **407 Pg**
- **Alluvial Deep C (~25m)** — **241 Pg**

1672 Pg

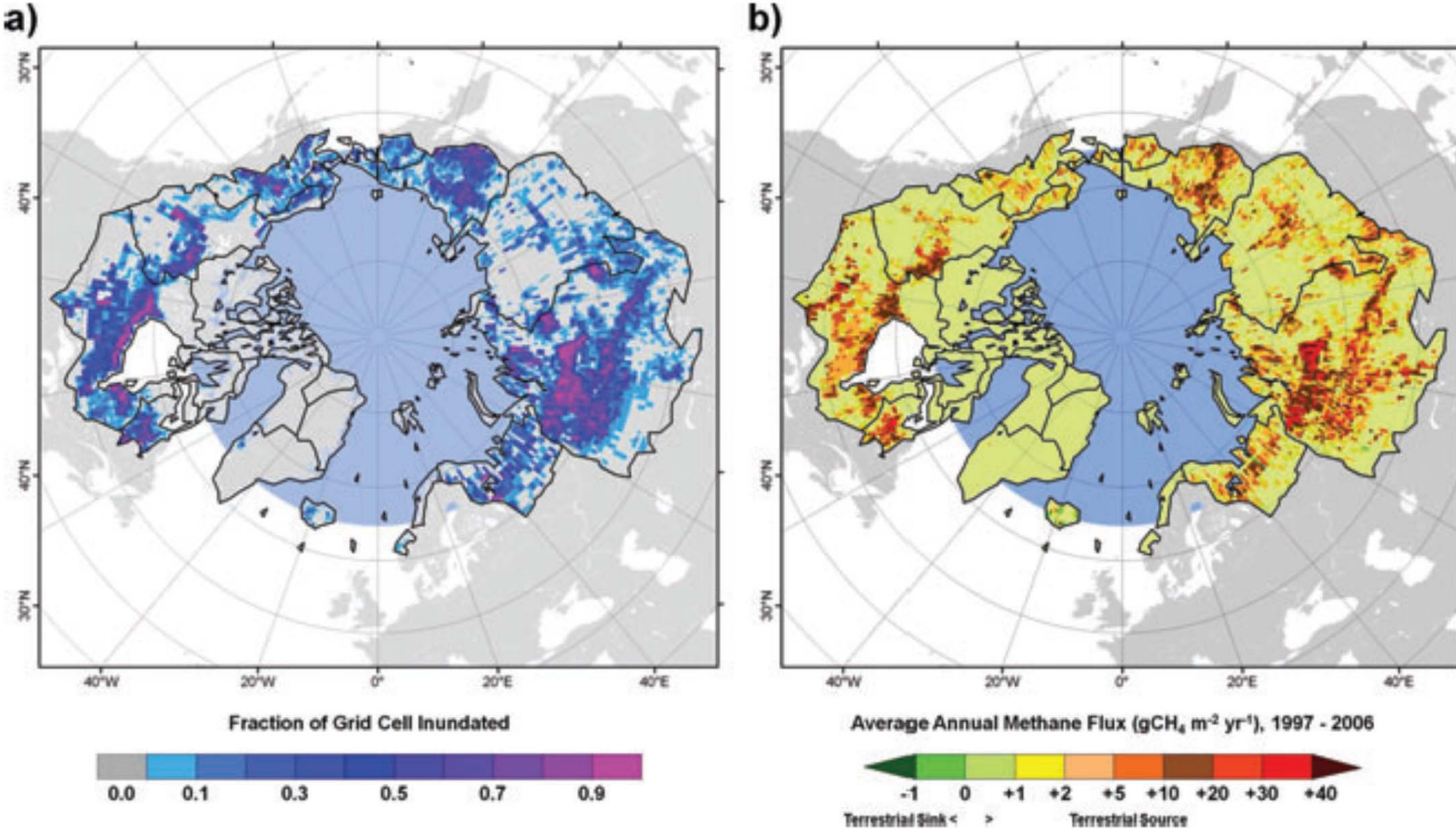


[Jobaggy 2000, Field et al. 2007, Zimov et al. 2006, Tarnocai et al. 2009, Schuur et al. 2008]


Lake
Reservoir
River
Freshwater Marsh, Floodplain
Swamp Forest, Flooded Forest
Coastal Wetland
Pan, Brackish/Saline Wetland
Bog, Fen, Mire
Intermittent Wetland/Lake
50-100% Wetland
25-50% Wetland
Wetland Complex (0-25% Wetland)
0
300
600
900
Area [10^3 km^2]
90
60
30
0
-30
-60
Latitude [deg]
400
300
200
100
Area [10^3 km^2]
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
Longitude [deg]
Gross wetlands map
GLWD
Stillwell-Soller et al.
Matthews & Fung
Cogley
Wetlands of GLCC
Wetlands of MODIS

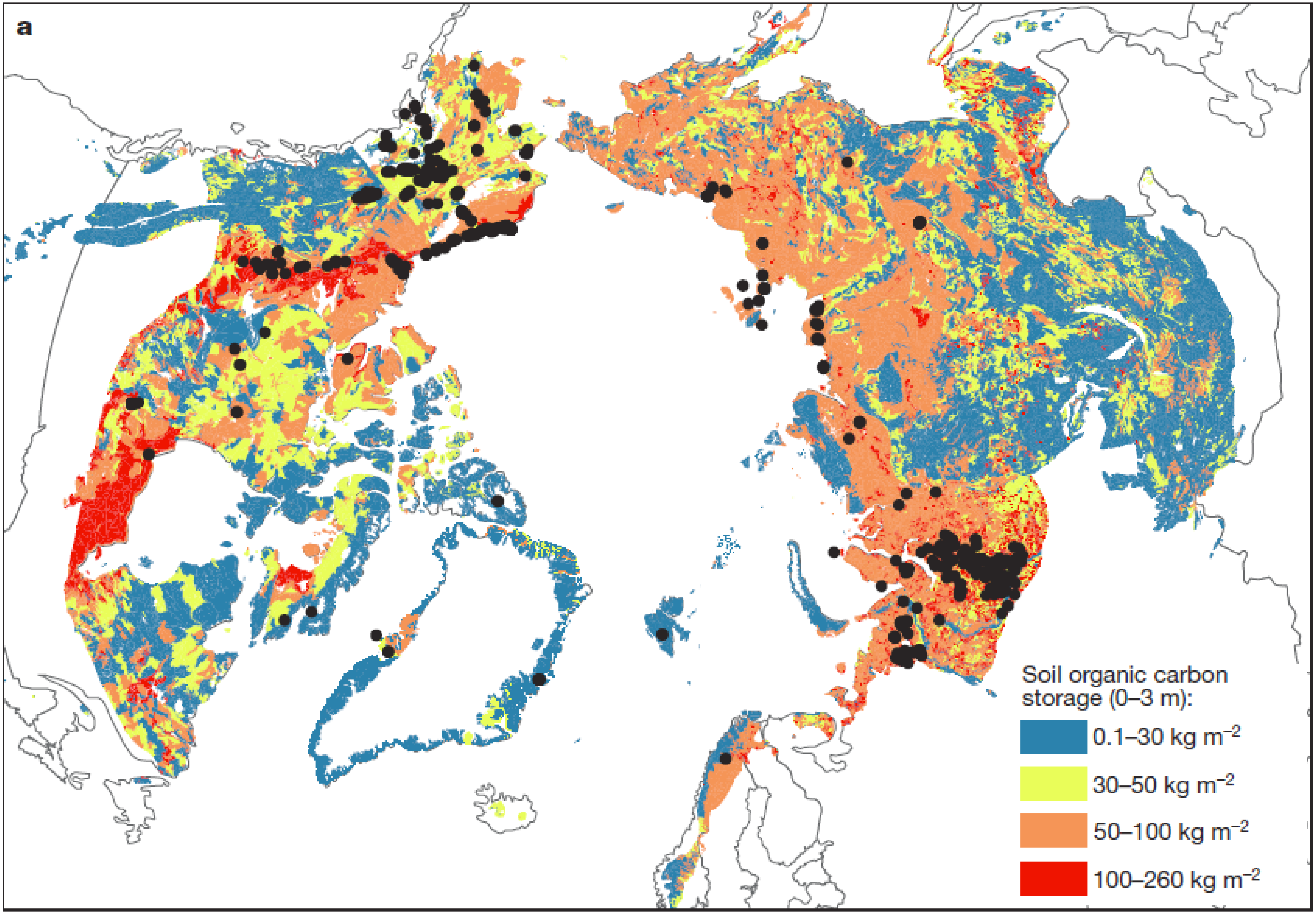


Bartlett and Harriss 1993



Terrestrial areas of the Arctic were a net source of 41.5 Tg CH_4 yr^{-1} that increased by 0.6 Tg CH_4 yr^{-1} during the decade of analysis (1997-2006).

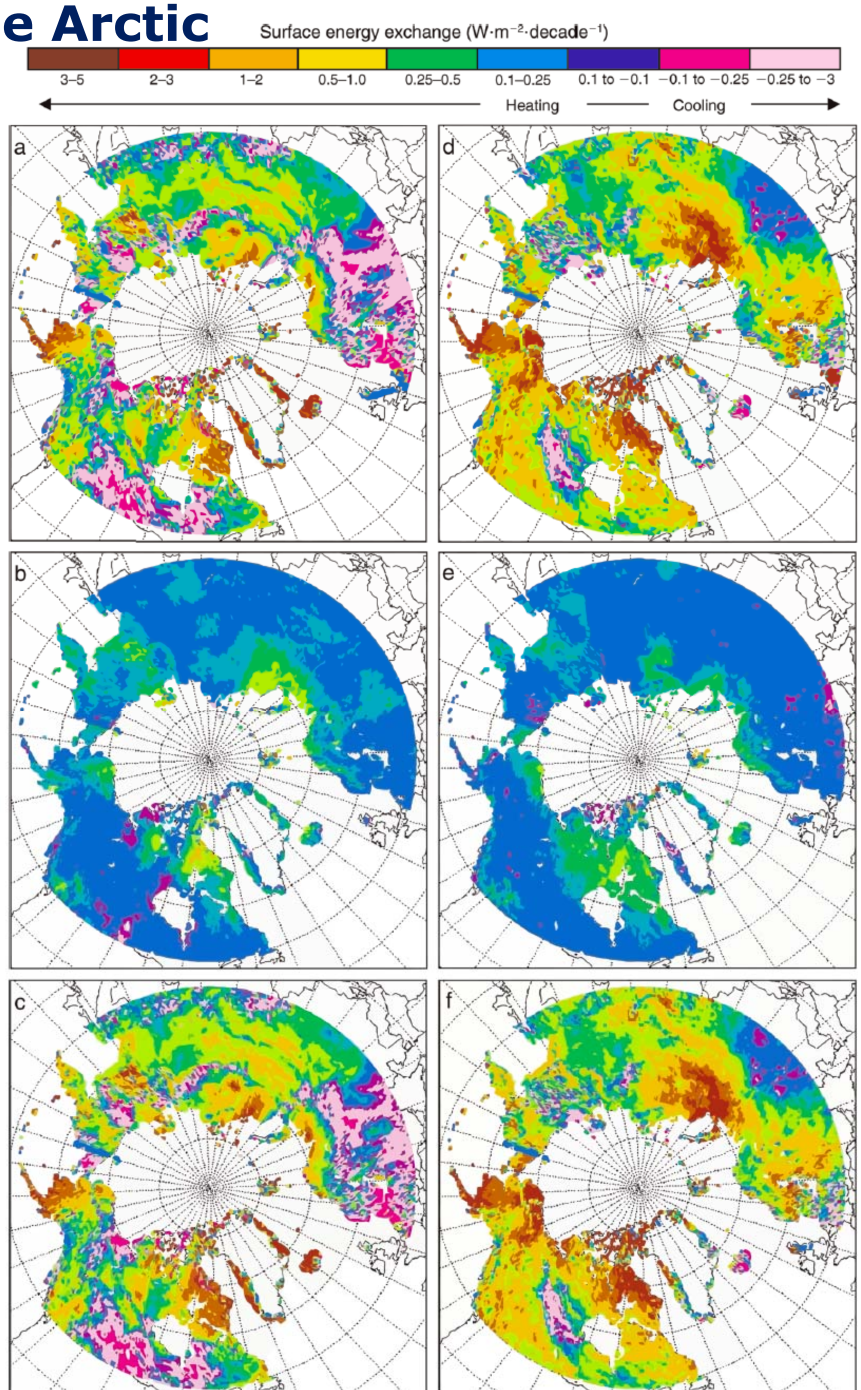
McGuire et al. 2010



Hugelius et al. 2013; Schuur et al. 2015

Shifting Trends in the Arctic

1910-1940 **1970-2000**



Timing of snowmelt

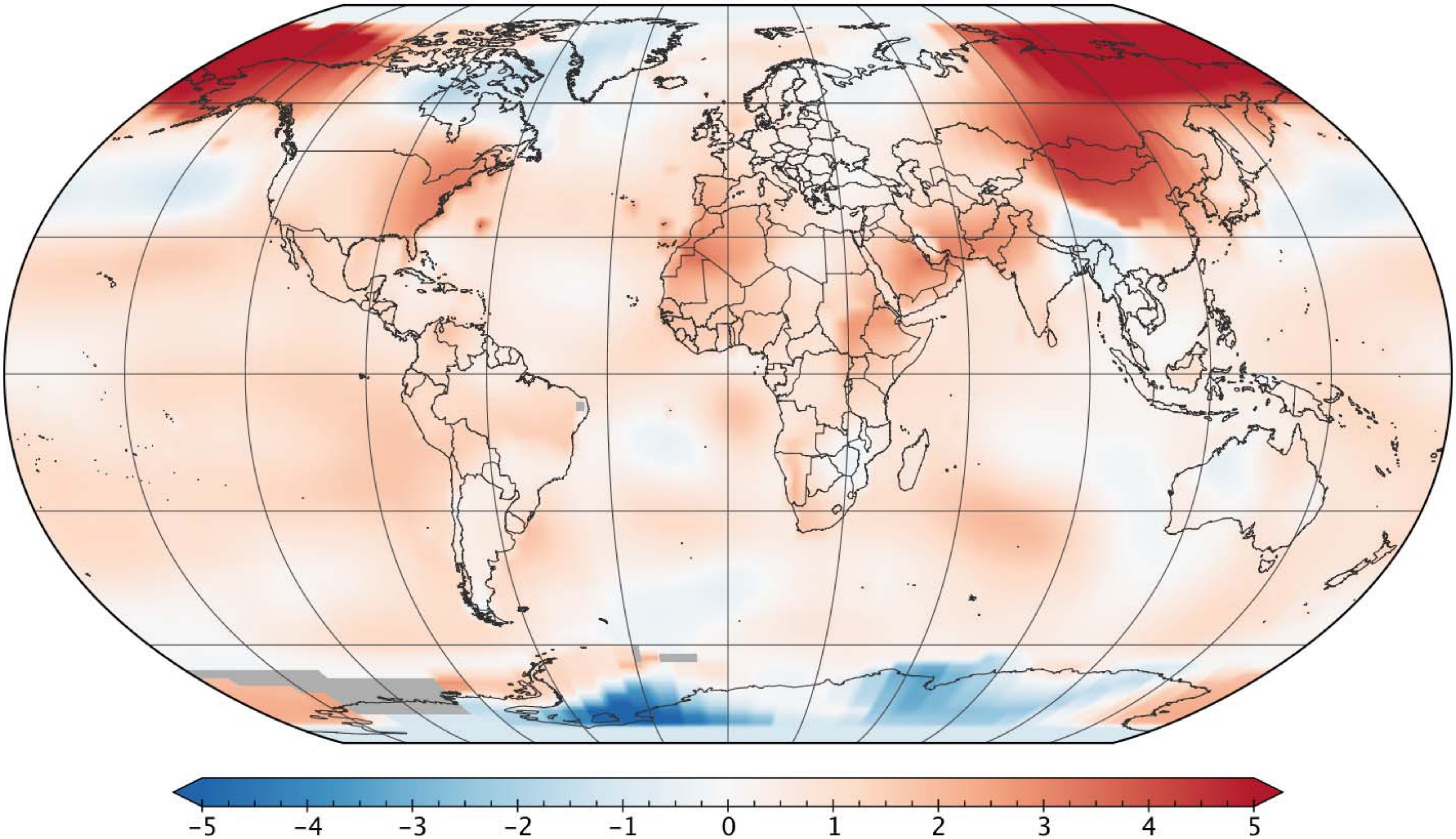
Timing of snow return

Surface energy flux due to snow cover

Euskirchen etal. 2007 in Hinzman et al. Ecol Appl 2013

GISTEMP LOTI Anomaly (°C)

April 2017



Base Period: 1951-1980

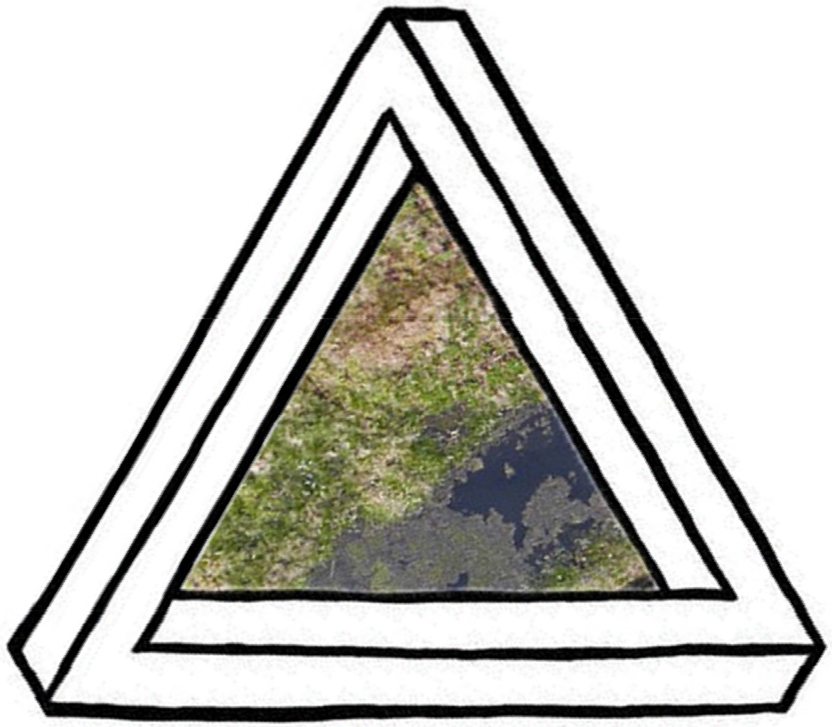
Data Min = −5.7, Max = 7.5, Mean = 0.9

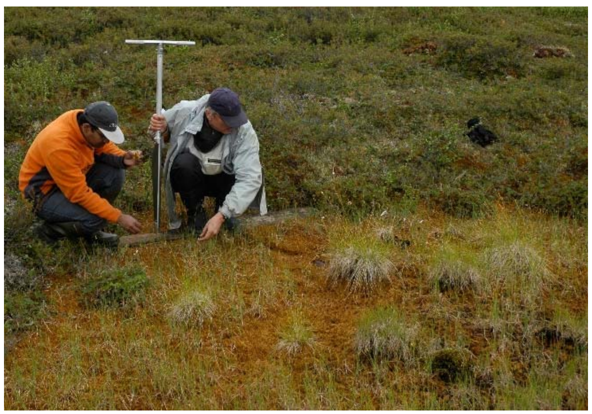
NASA/GISS/GISTEMP

Drained or Dry Peatlands and Permafrost

Palsa, Heath
Drains to Local Hydrology
Woody Plants and Shrubs

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$





$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

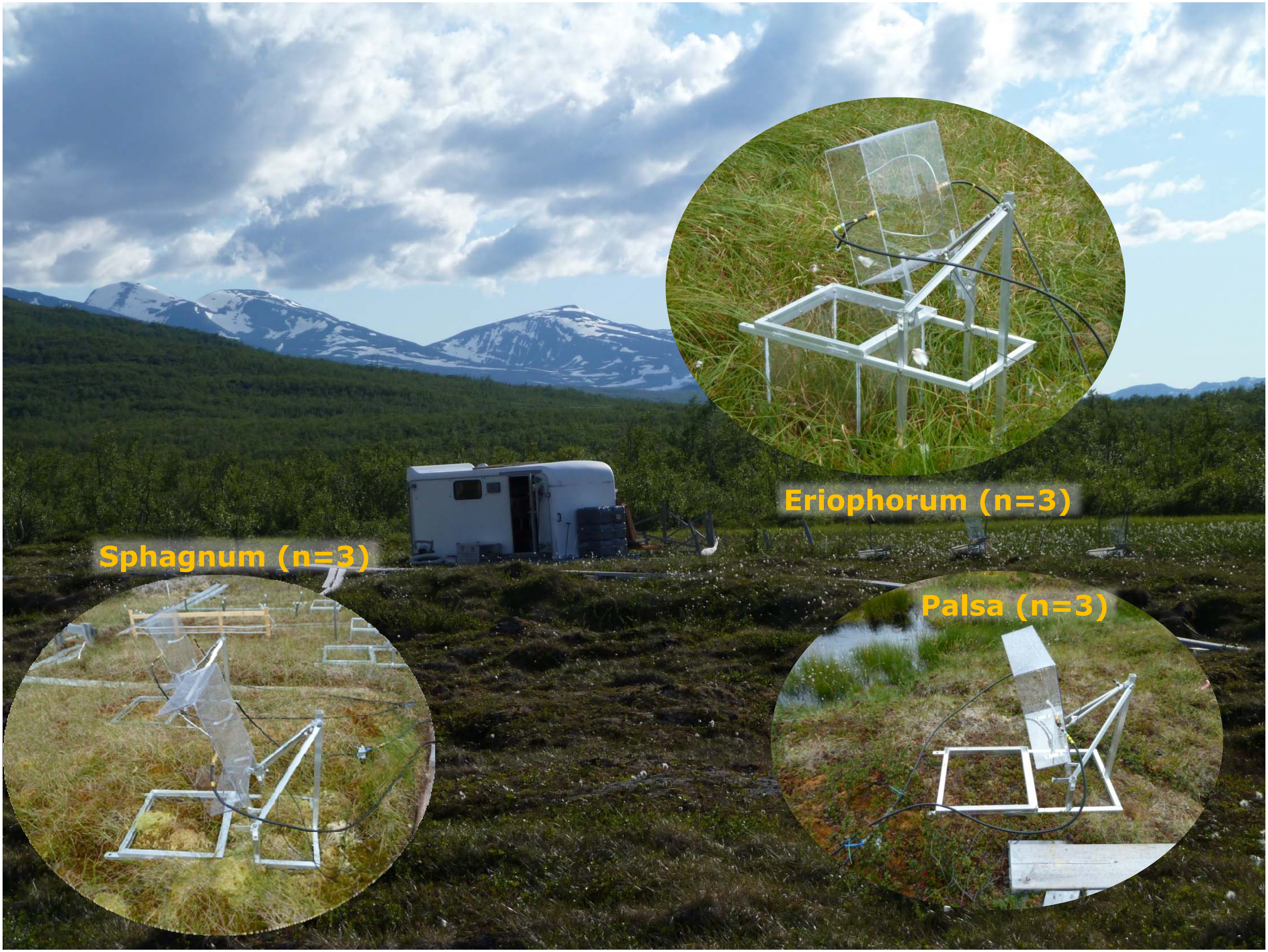
Wet Peat or C_{org} Accumulating

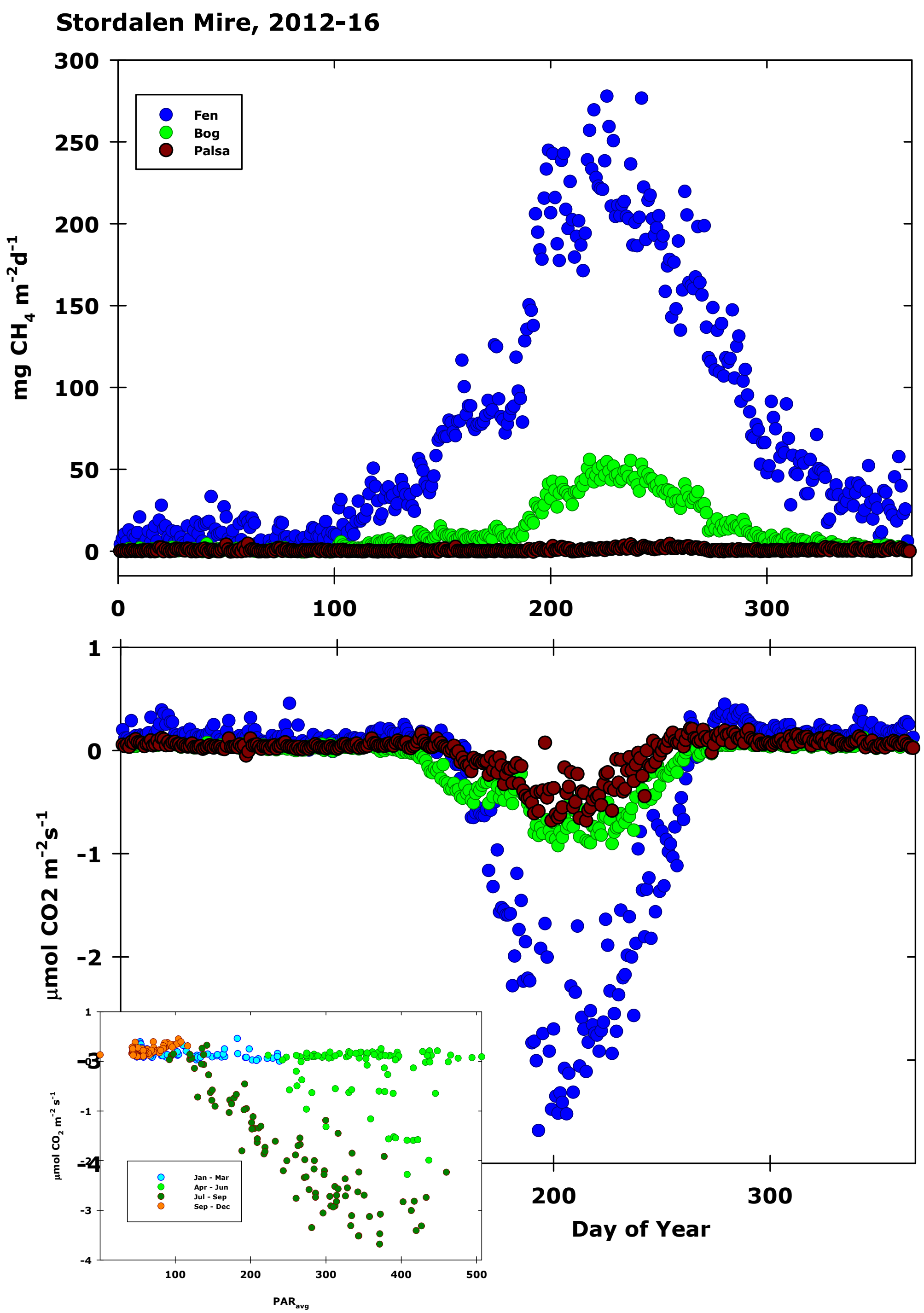
Bogs, Sediments
Ombrotrophic
Perched above Regional Hydrology
Lower Rates of Production

$$CH_3COOH \rightarrow CH_4 + CO_2$$

Very Wet Productive Systems

Fens, Swamps, Littoral
Minerotrophic
Linked to Regional Hydrology
Significant Annual Production


Eriophorum (n=3)
Sphagnum (n=3)
Palsa (n=3)



Methane

Accum Fen Fluxes g m^{-2}

	EC	AC
Winter	4.23	4.27
Spring	2.14	1.13
Growing	20.67	21.48

R. Conrad / FEMS Microbiology Ecology 28 (1999) 193–202

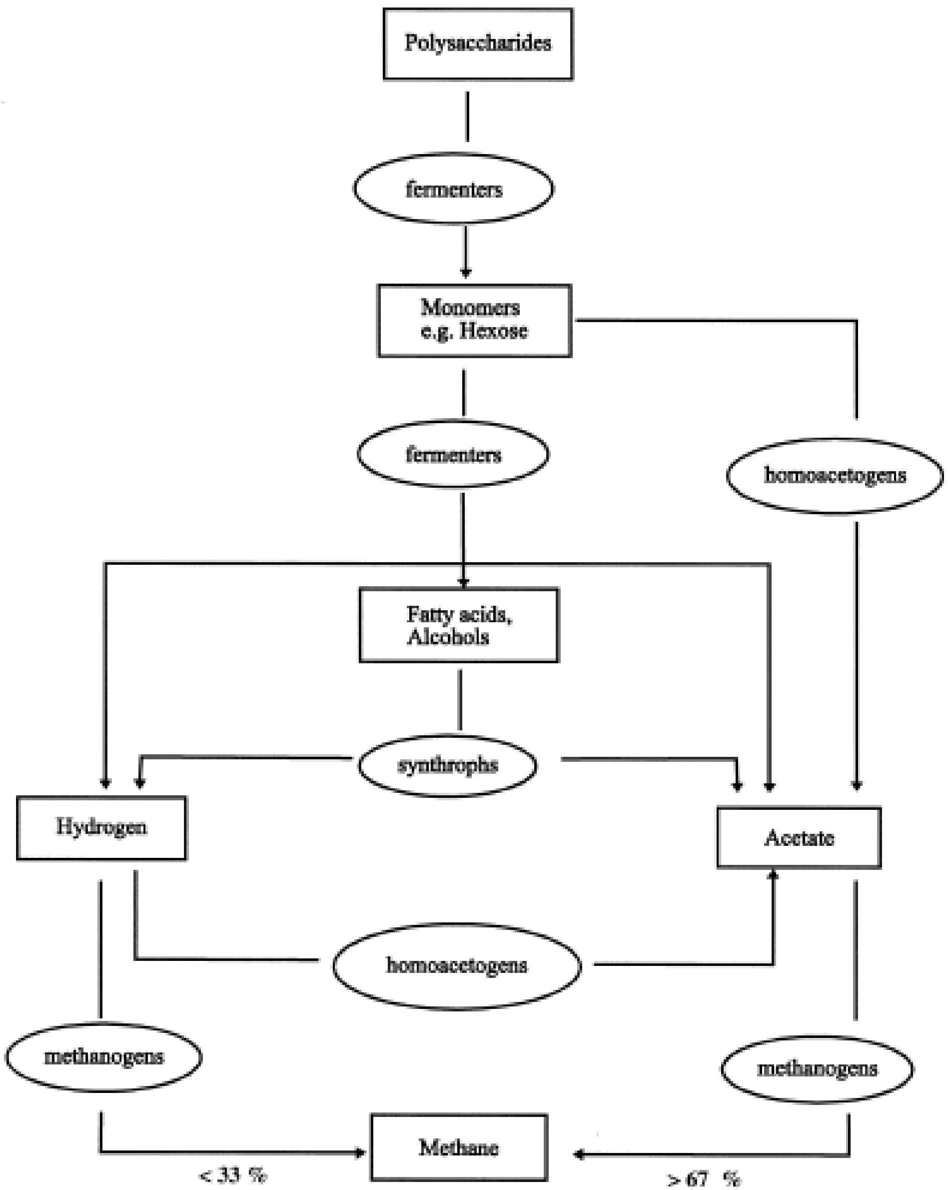


Fig. 1. Pathway of anaerobic degradation of organic matter to methane.

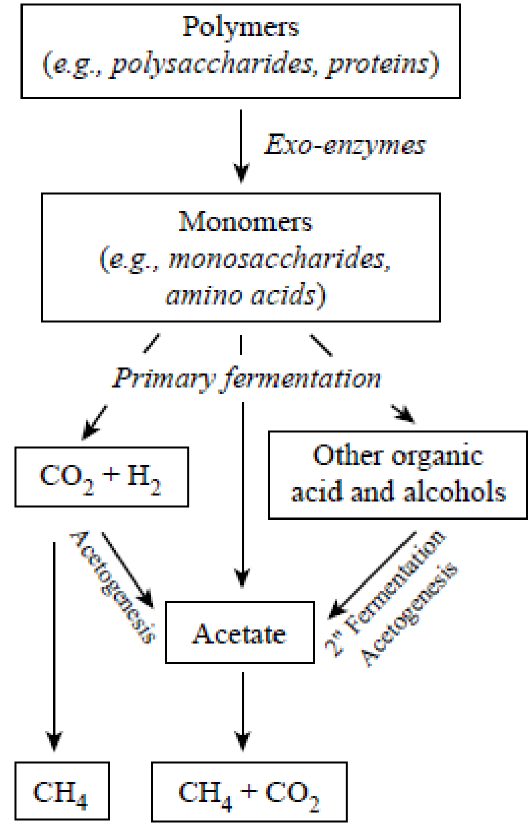


Figure 4 Metabolic scheme for the degradation of complex organic matter, culminating in methanogenesis. Polymers are cleaved via extracellular or cell-surface associated enzymes to monomers that are fermented to organic products, H_2 and CO_2. Methane is formed primarily from the oxidation of H_2 coupled to CO_2 reduction or by the fermentation of acetate. Acetate is formed by primary fermentation, acetogenesis from H_2/CO_2, and from secondary fermentation of primary fermentation products.

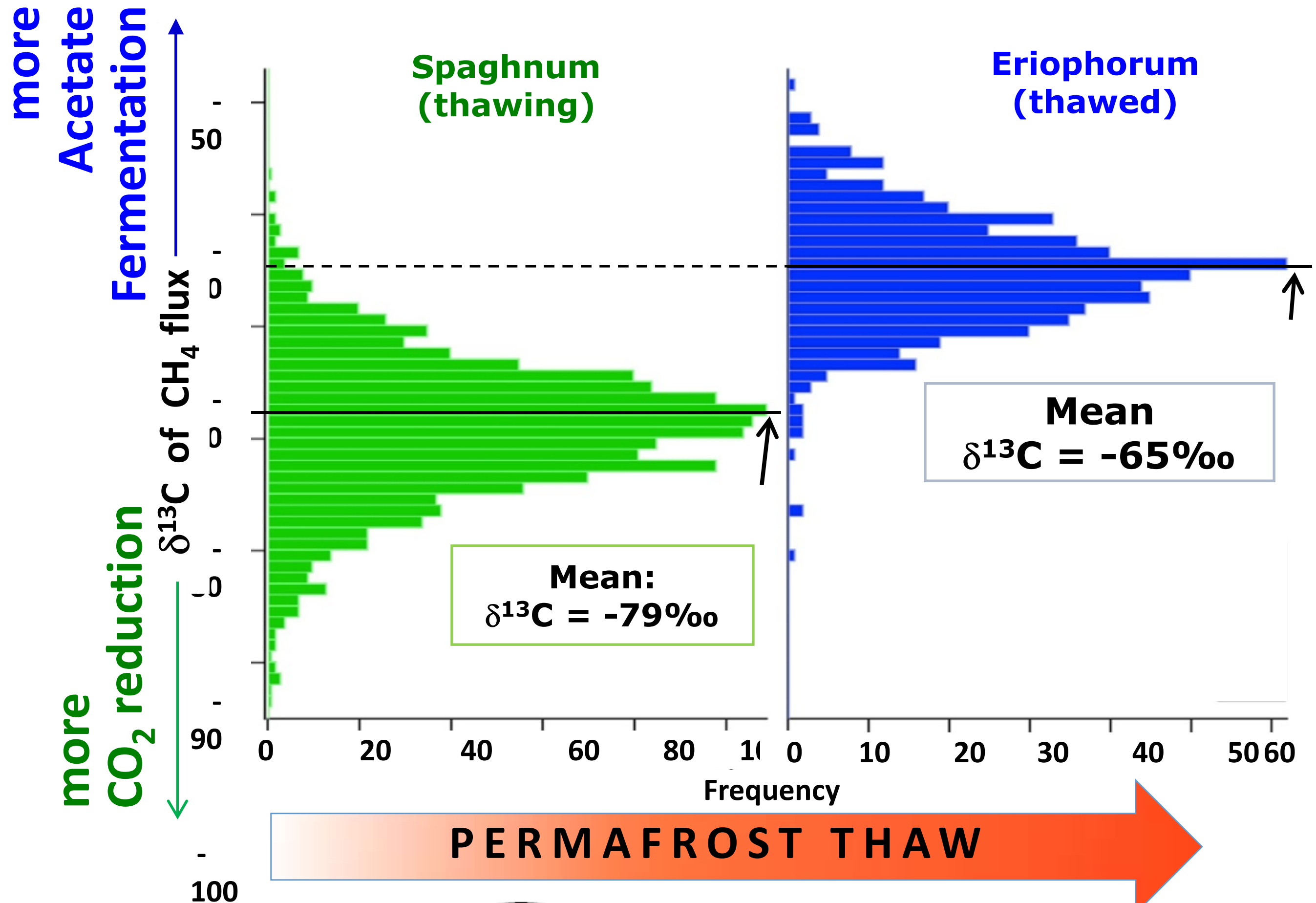
Megonigal et al. 2004

Genome-centric analysis
of whole community
carbon metabolism

across the thaw gradient
and by depth

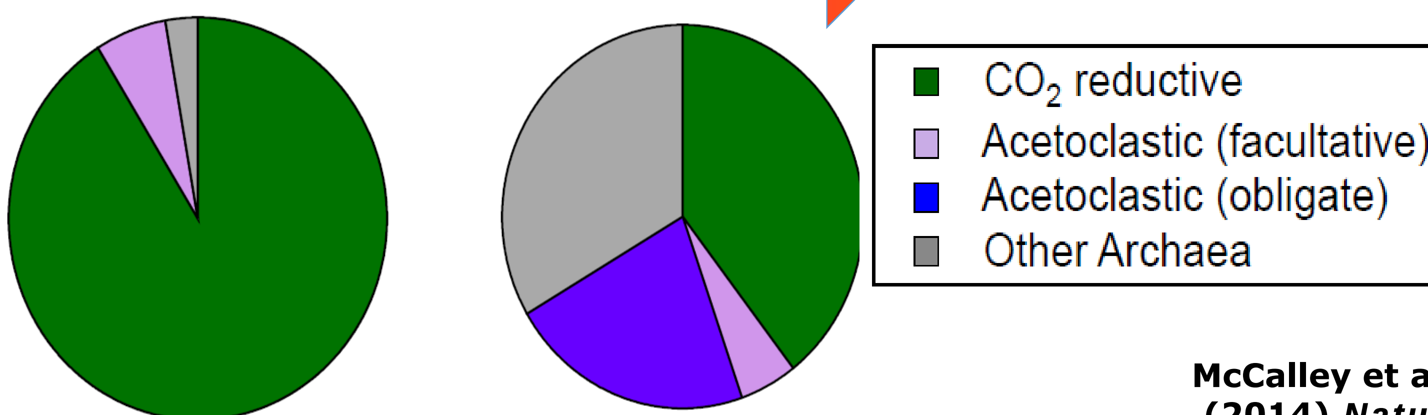
Ben Woodcroft
2017, in prep

Thaw shifts methane **isotopically heavier…**



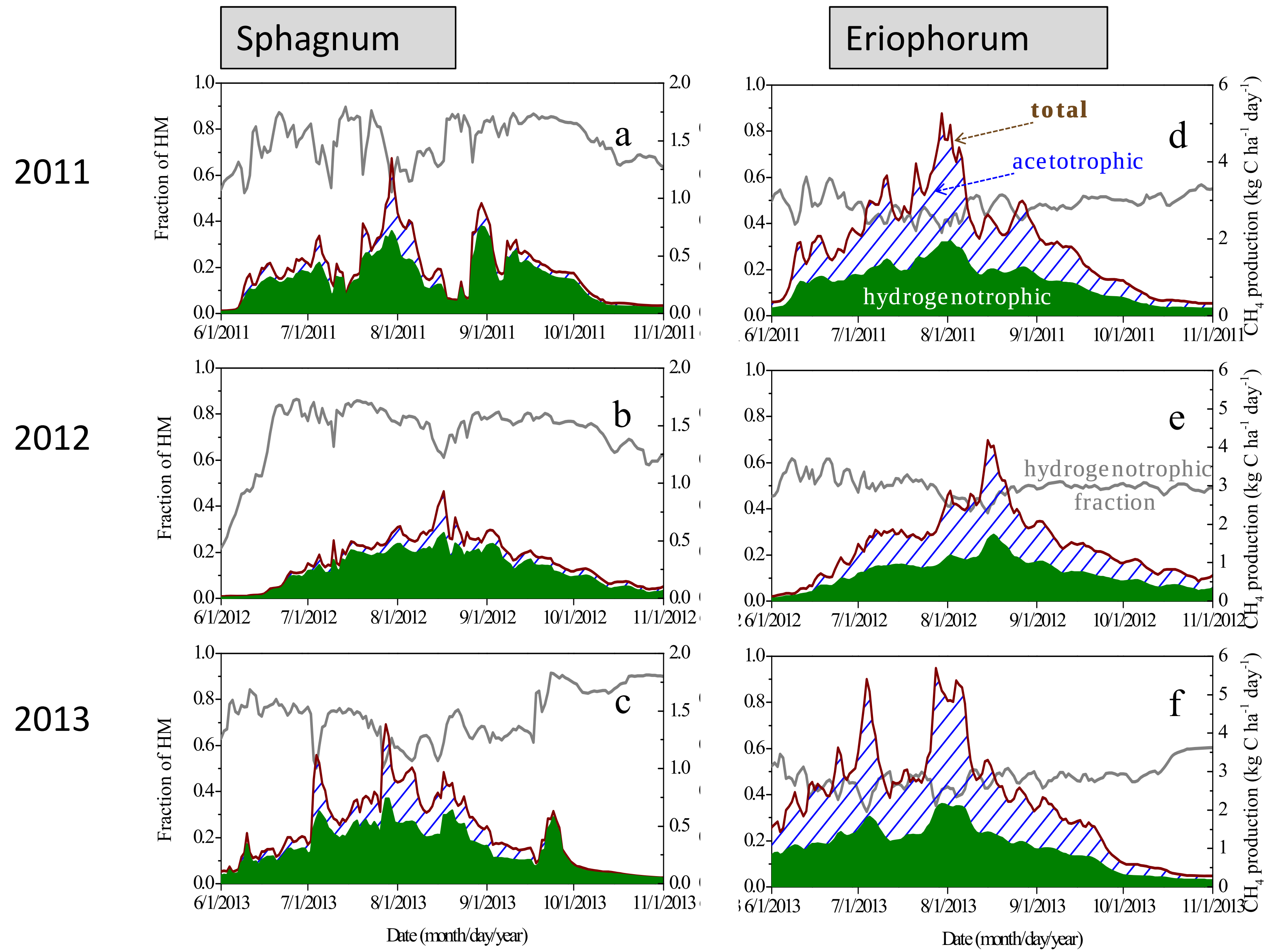
Concordant responses of **isotope geochemistry** and **microbial communities**

… and archaeal communities from CO_2 reductive towards acetoclastic clades



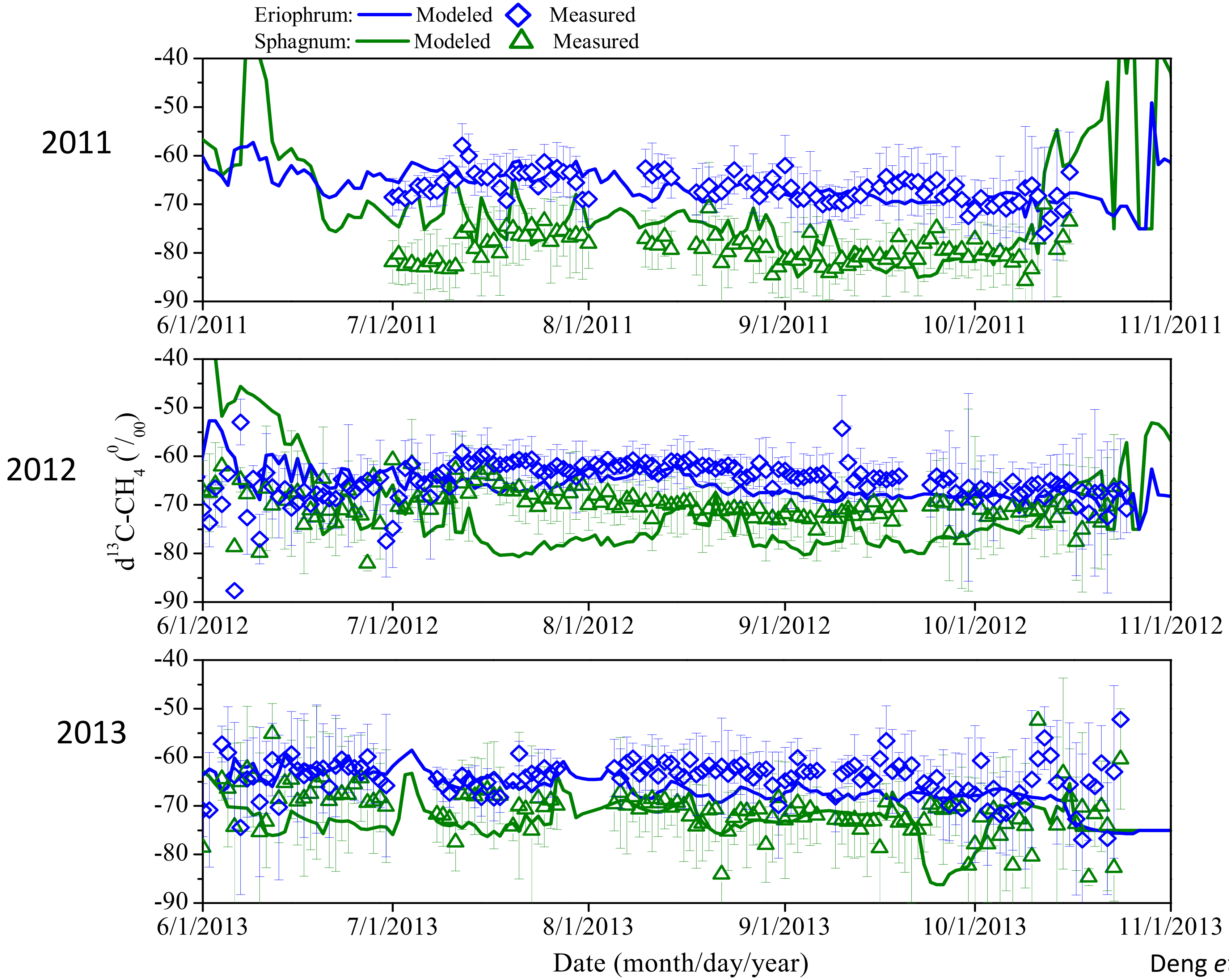
McCalley et al., (2014) *Nature*

Simulated daily CH_4 production partitioned into hydrogenotrophic & acetotrophic production



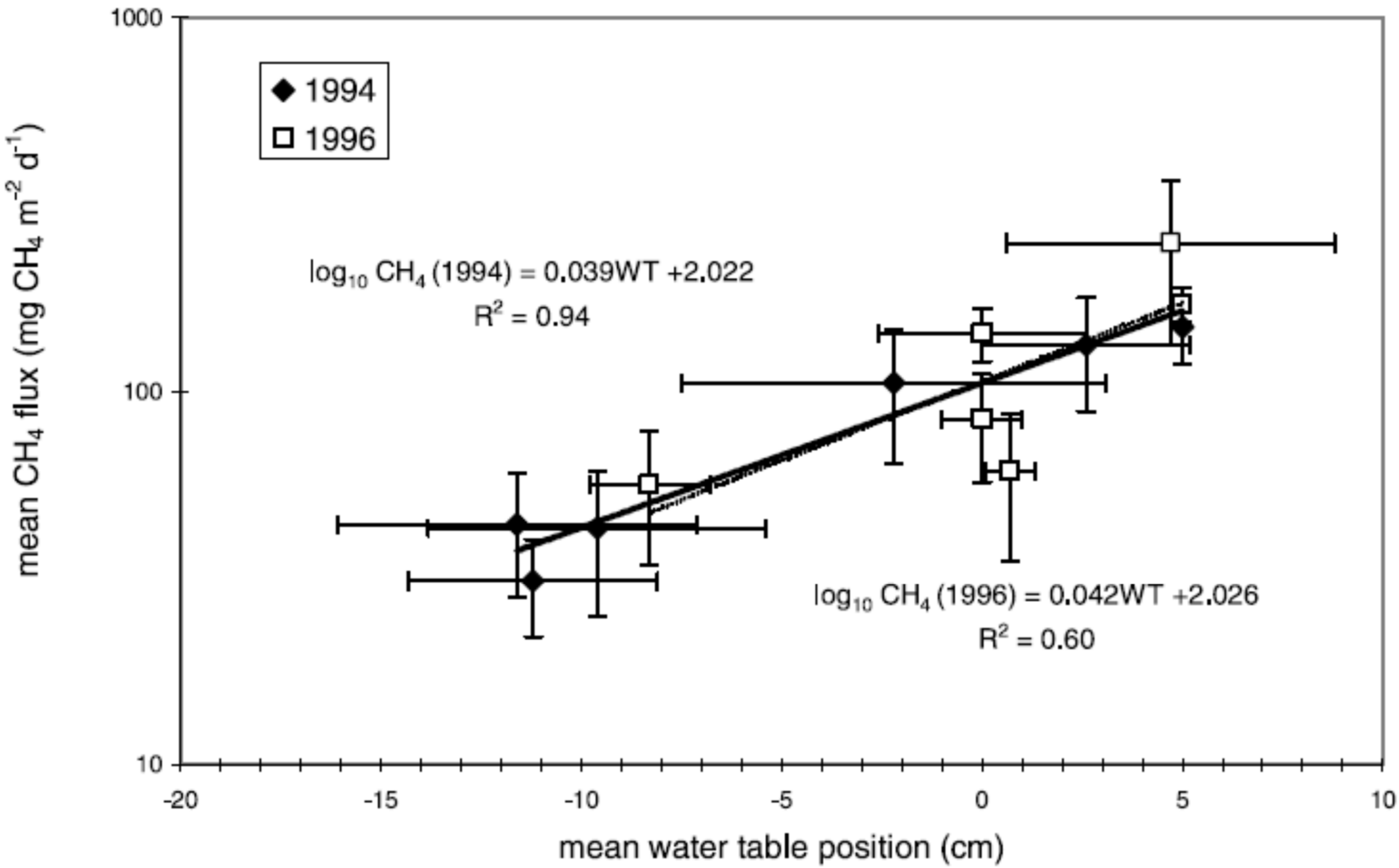
Deng *et al*. JAMES, 2017

Simulated and observed δ^{13}C of daily CH_4 fluxes



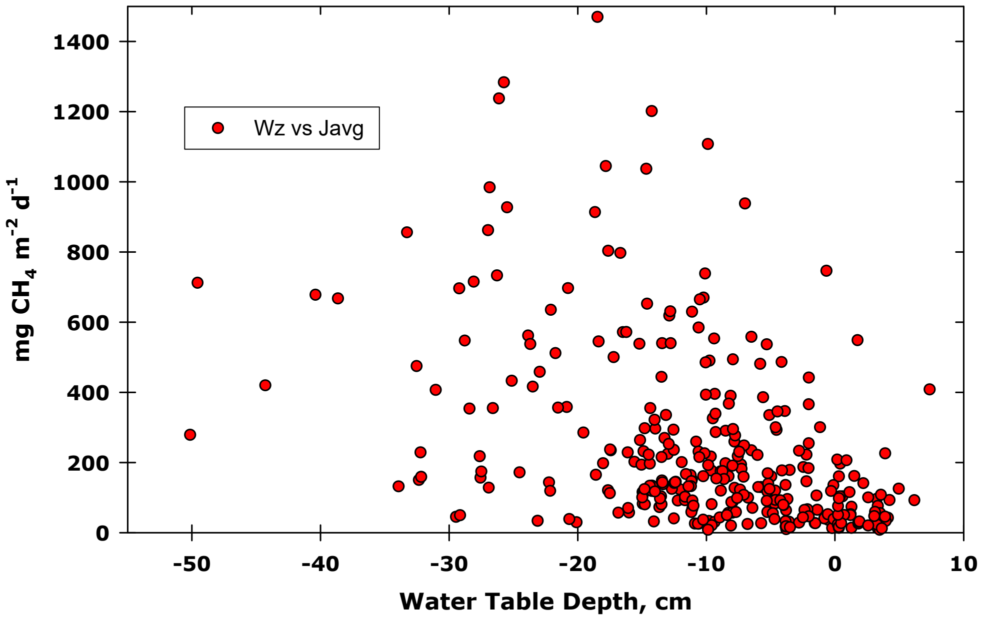
Deng *et al*. JAMES, 2017

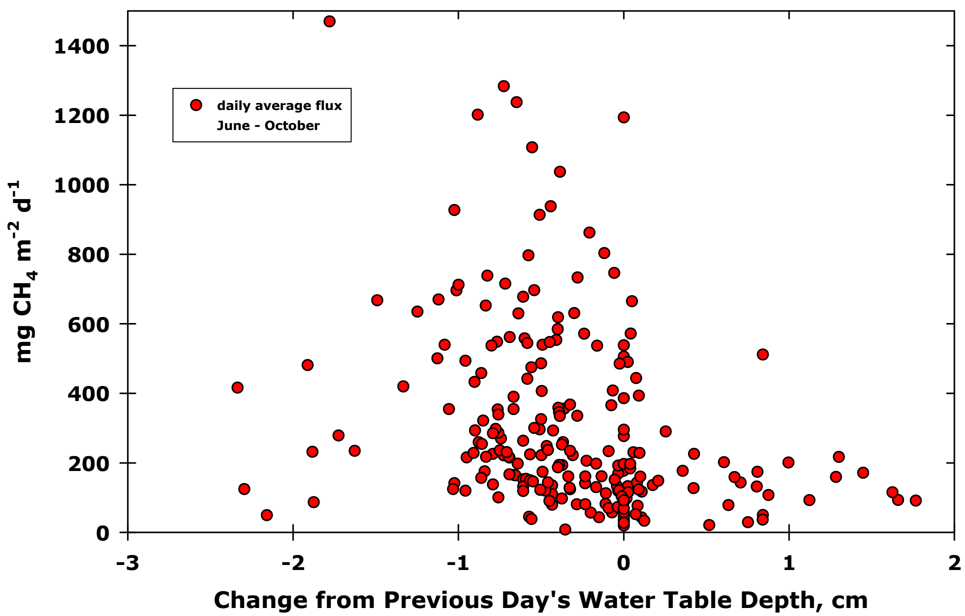
Hydrology affects CH_4 flux from Wetlands



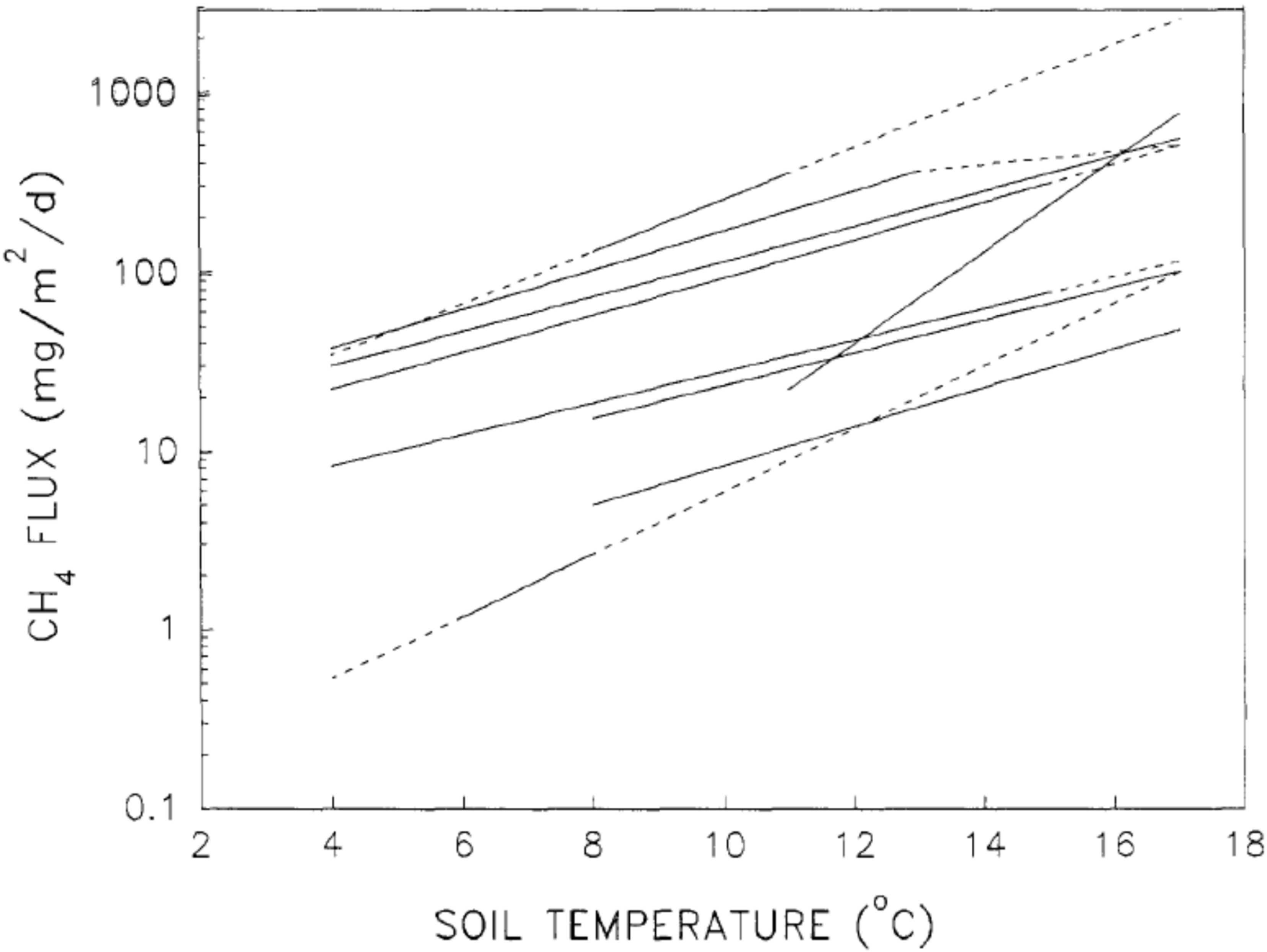
Bubier et al. 2005

Though not always in the way you expect



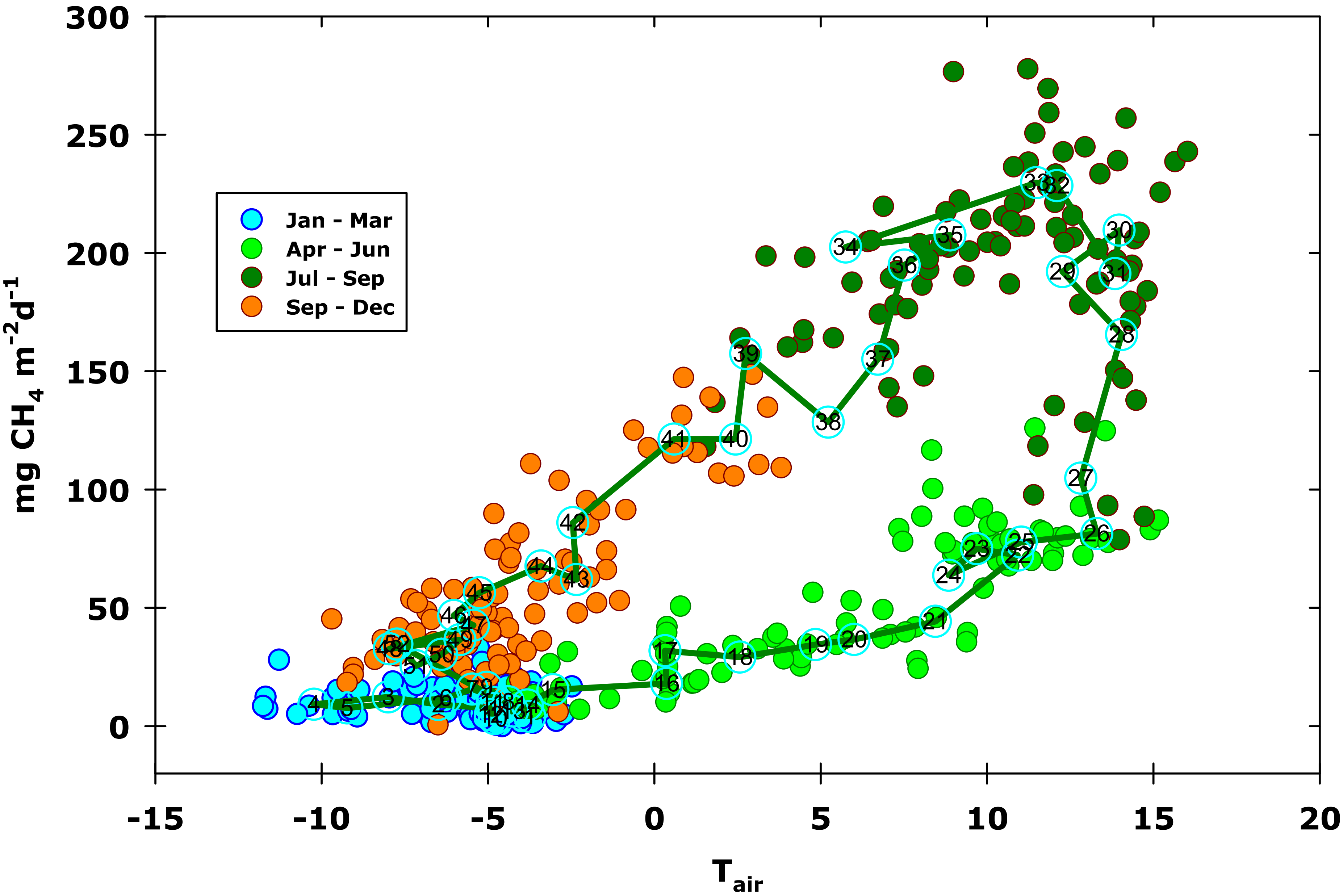


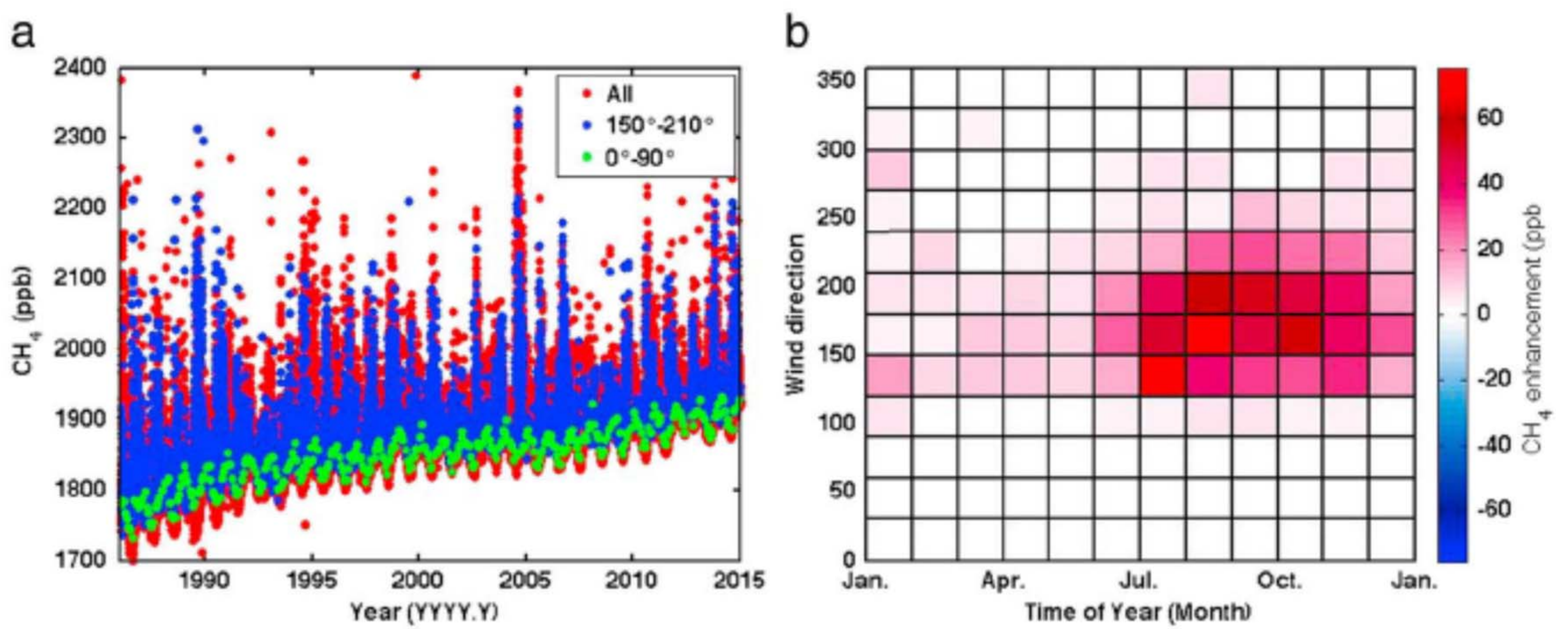
Temperature affects CH_4 flux from Northern Wetlands

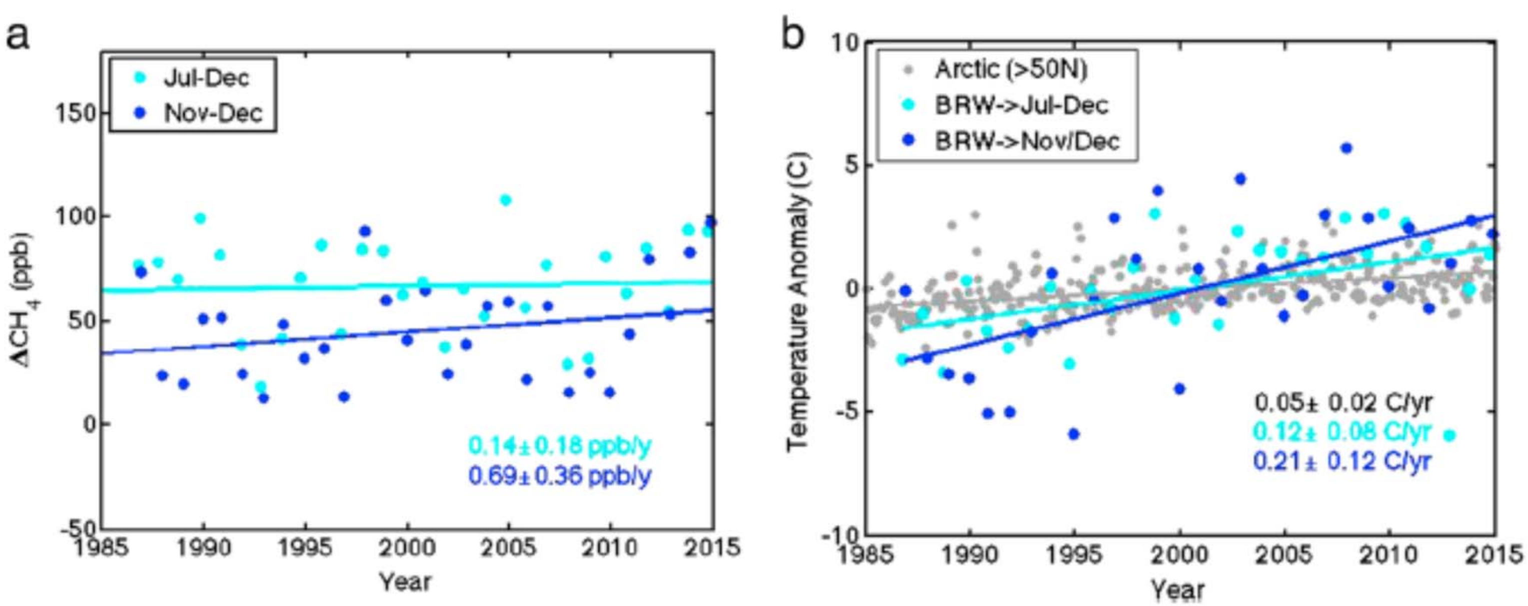


Bartlett and Harriss 1993

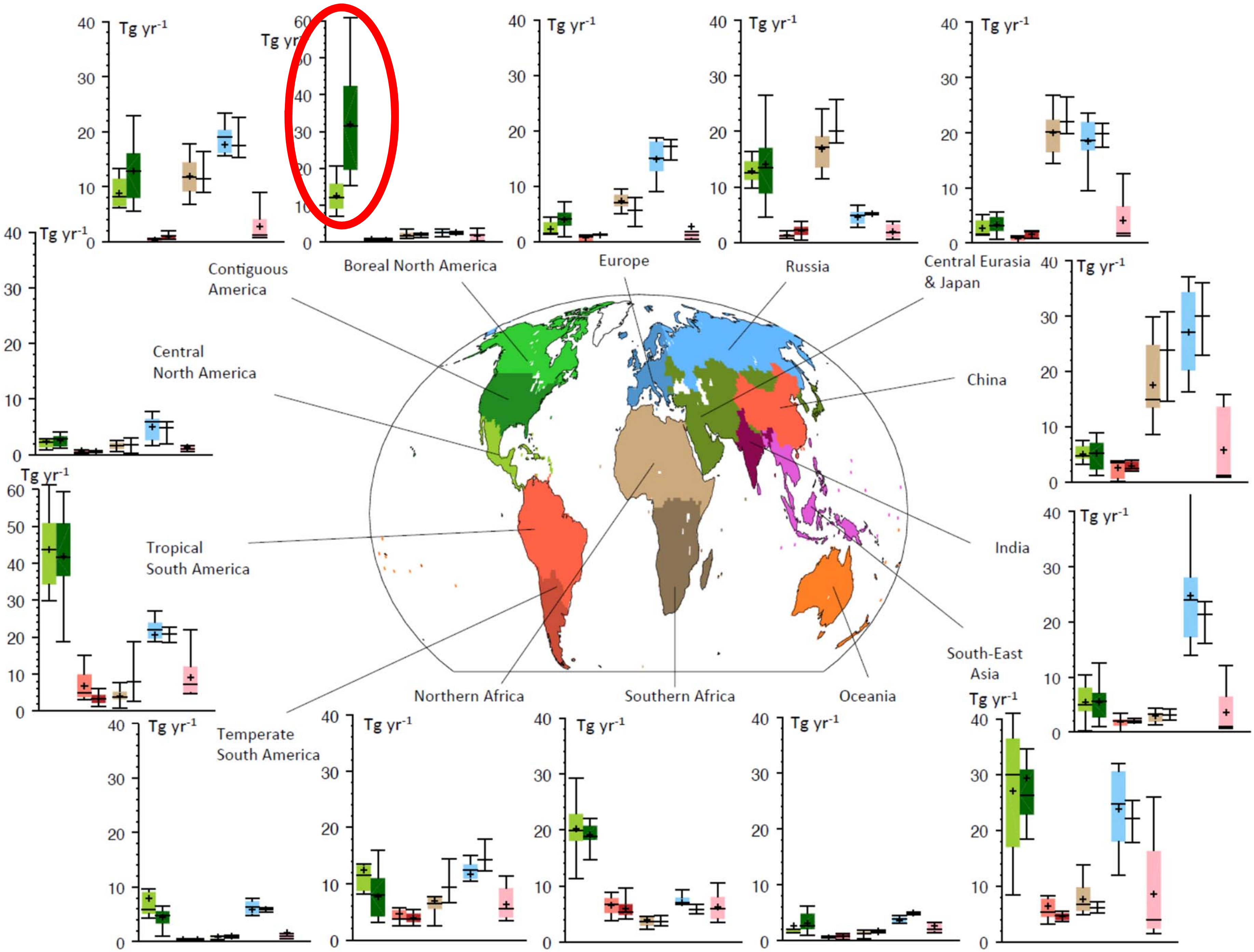
Though not always in the way you expect







Sweeney et al. GRL 2016



Saunois et al. ESSD 2016

Table 1. Arctic CH_4 Budget; Bottom-Up Versus Top-Down[a]

	$Tg\,y^{-1}$	Study
	Bottom-Up Estimates	
Lakes and ponds > 50°N	16.5 ± 9.2	*Wik et al.* [2016b]
Lakes and ponds > 60°N (bLake4Me model)	11.9	*Tan and Zhuang* [2015]
Rivers and streams > 54°N	0.3	*Bastviken et al.* [2011]
Rivers and streams > 54°N	7.5	*Stanley et al.* [2016]
Reservoirs > 54°N	1.2	*Bastviken et al.* [2011]
Arctic Ocean + Beaufort and Chukchi Seas (<82°N)	2	*Kort et al.* [2012]
ESAS	2.9	*Thornton et al.* [2016]
ESAS	17	*Shakhova et al.* [2014]
Wetlands > 60°N	23.2	*Zhang et al.* [2004]
Wetlands > 53.1°N (CarbonTracker prior model, based on *Bergamaschi et al.* [2005])	31	*Bruhwiler et al.* [2014]
Wetlands > 50°N (ORCHIDEE model)	31 ± 5	*Bousquet et al.* [2011]
Sources sum (minimum–maximum)	59.7 (36.9–89.4)	
	Top-Down Inverse Model Estimates	
>60°N, all natural sources	23 ± 5	*Bruhwiler et al.* [2014] *Saunois et al.* [2016]
ESAS	0–4.5	*Berchet et al.* [2016]

[a]Recent bottom-up estimates for various Arctic CH_4 source flux strengths are sorted into categories of lakes and ponds, rivers and streams, reservoirs, Arctic Ocean, ESAS, and wetlands. Estimates are based on extrapolations of measurements, except for the three process models noted. Note that the latitude bands differ, which partly account for the ultimate bottom-up uncertainty seen here. Arctic Ocean flux is from the reported $2\,mg\,m^{-2}\,d^{-1}$ extrapolated over $10 \times 10^6\,km^2$ of seasonally ice-free Arctic Ocean regions for 100 ice-free days [*Kort et al.*, 2012]. Rivers and streams high estimate is based on the *Stanley et al.* [2016] global fluvial flux database distributed into fluvial surface areas reported by *Bastviken et al.* [2011]. Sum uses averages of the all estimates per category. Minimum uses category low values and lower bound of the *Wik et al.* [2016b] lake estimates; maximum uses category high values and upper bounds of ORCHIDEE wetland model and the *Wik et al.* [2016b] lake estimates. Including subarctic and boreal wetlands from 45°N to 60°N would add $34\,Tg\,yr^{-1}$ to the *Zhang et al.* [2004] wetland estimate.

Thornton *et al*. GRL, 2016

High Latitude CH_4 Emissions

inverse models (top-down):

23 Tg yr-1

measurement-based (bottom-up):

59.7 Tg yr-1

Are some sources double-counted in bottom-up accounting,

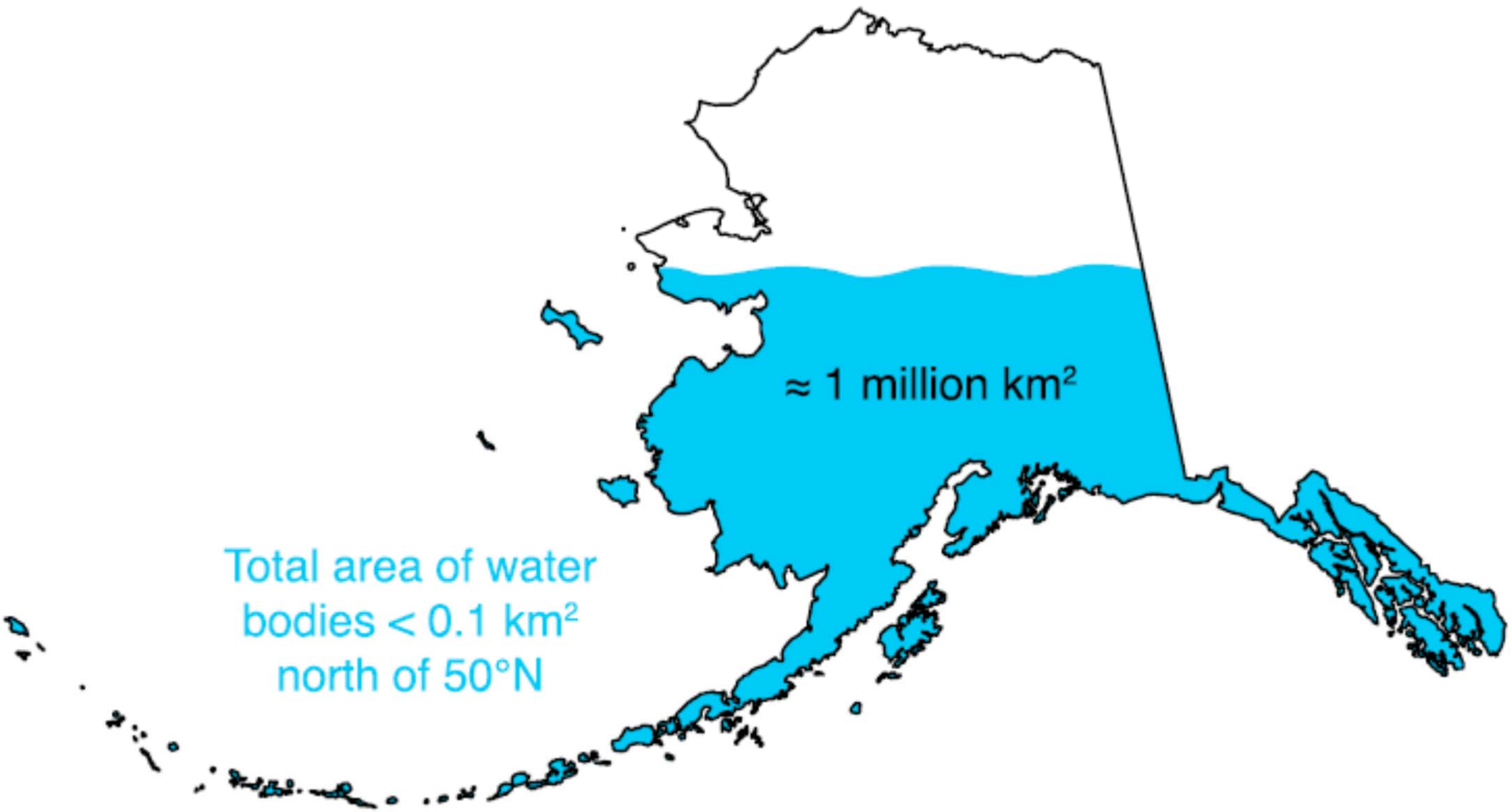
or are top-down inverse models wrong, or we don’t understand the sinks??

1. shallow lakes look like wetlands

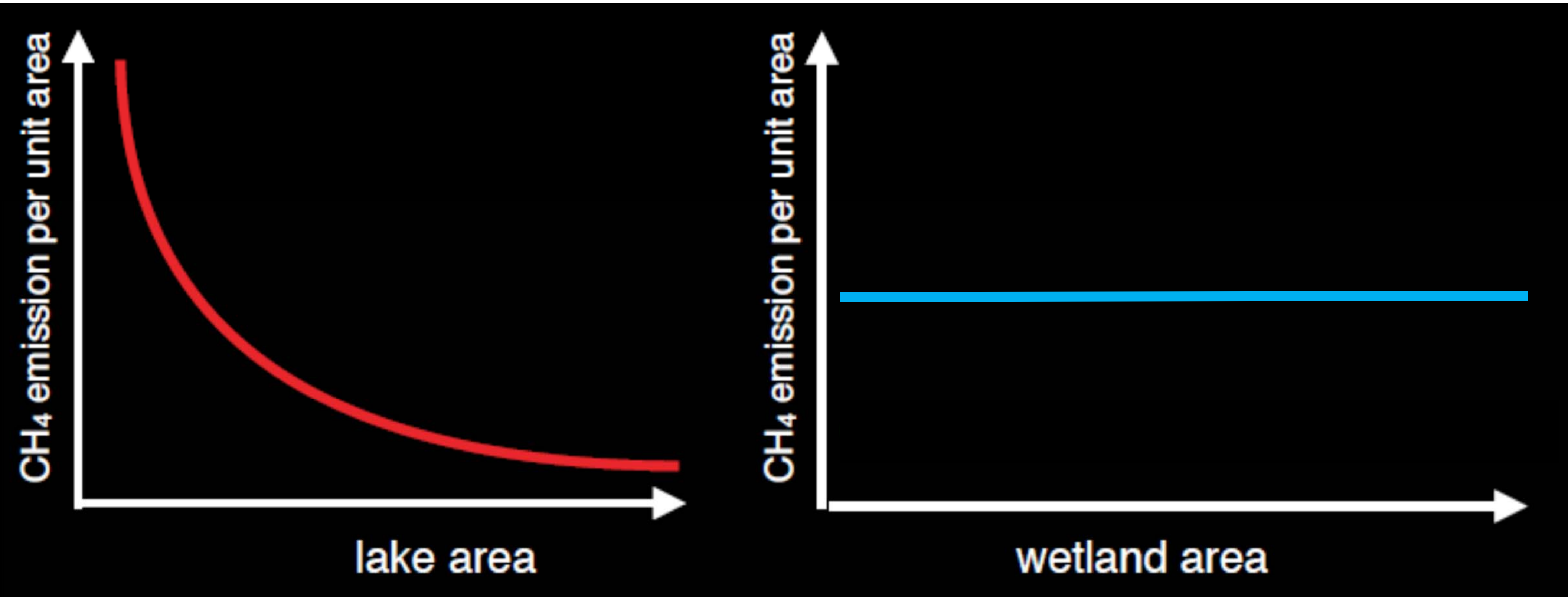
wetlands definitions generally include most shallow Arctic lakes:

< 2 m depth, < 0.1 km^2 = wetland

2. higher resolution surveys now resolve small lakes/ponds

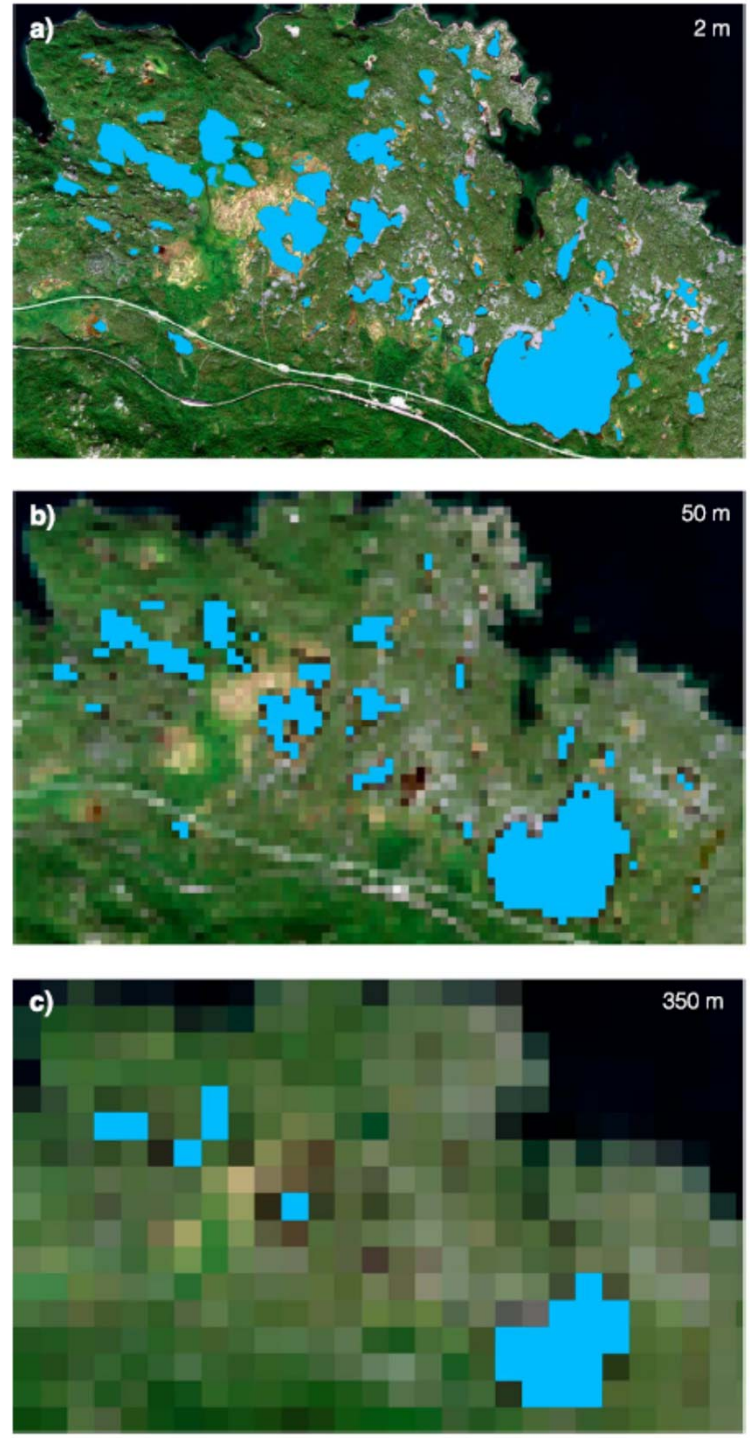


3. small lakes don't emit CH_4 like wetlands



small lakes and ponds emit more CH_4 per unit area

4. Pixilation loses area of open water

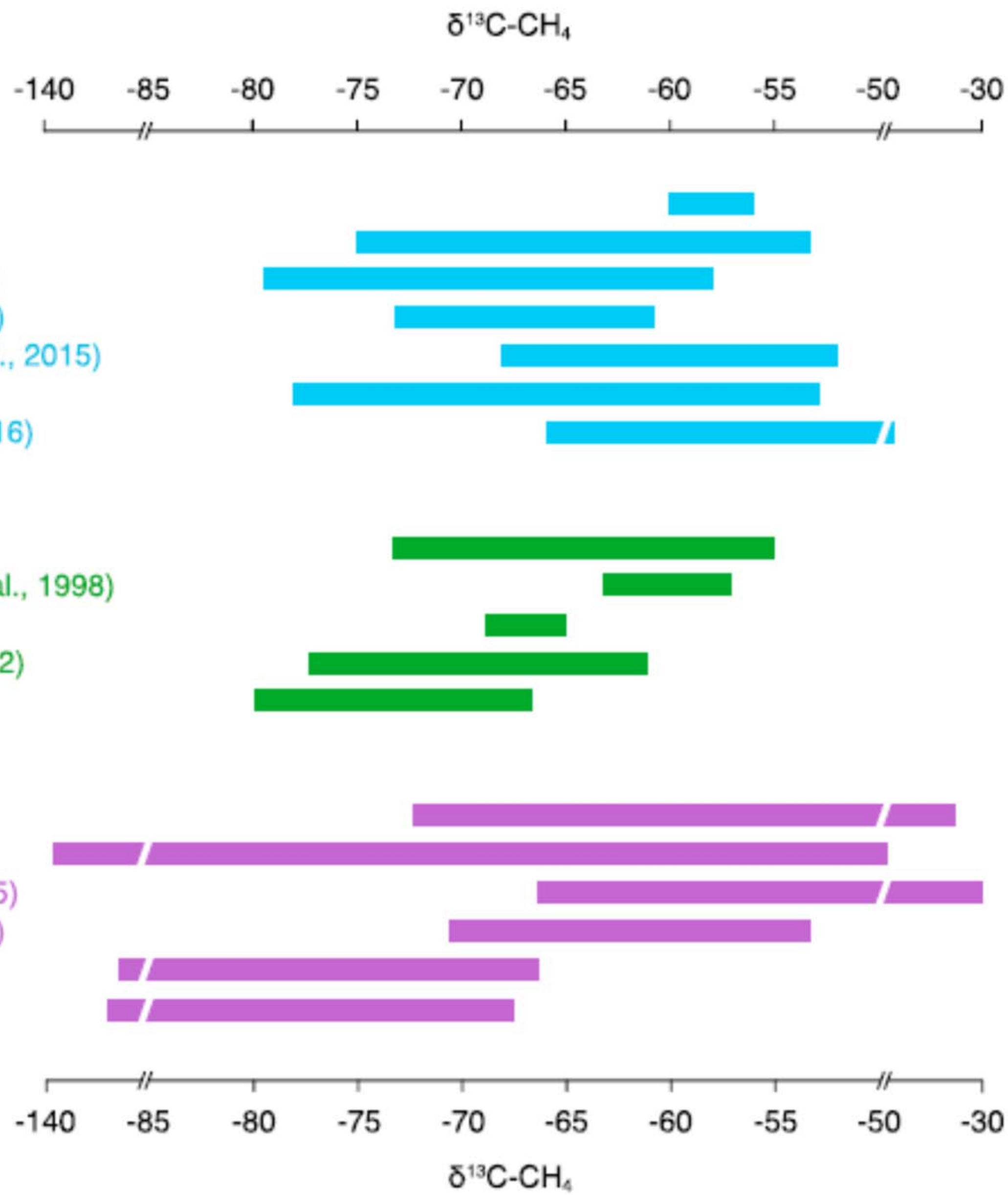


Stordalen Mire, Sweden

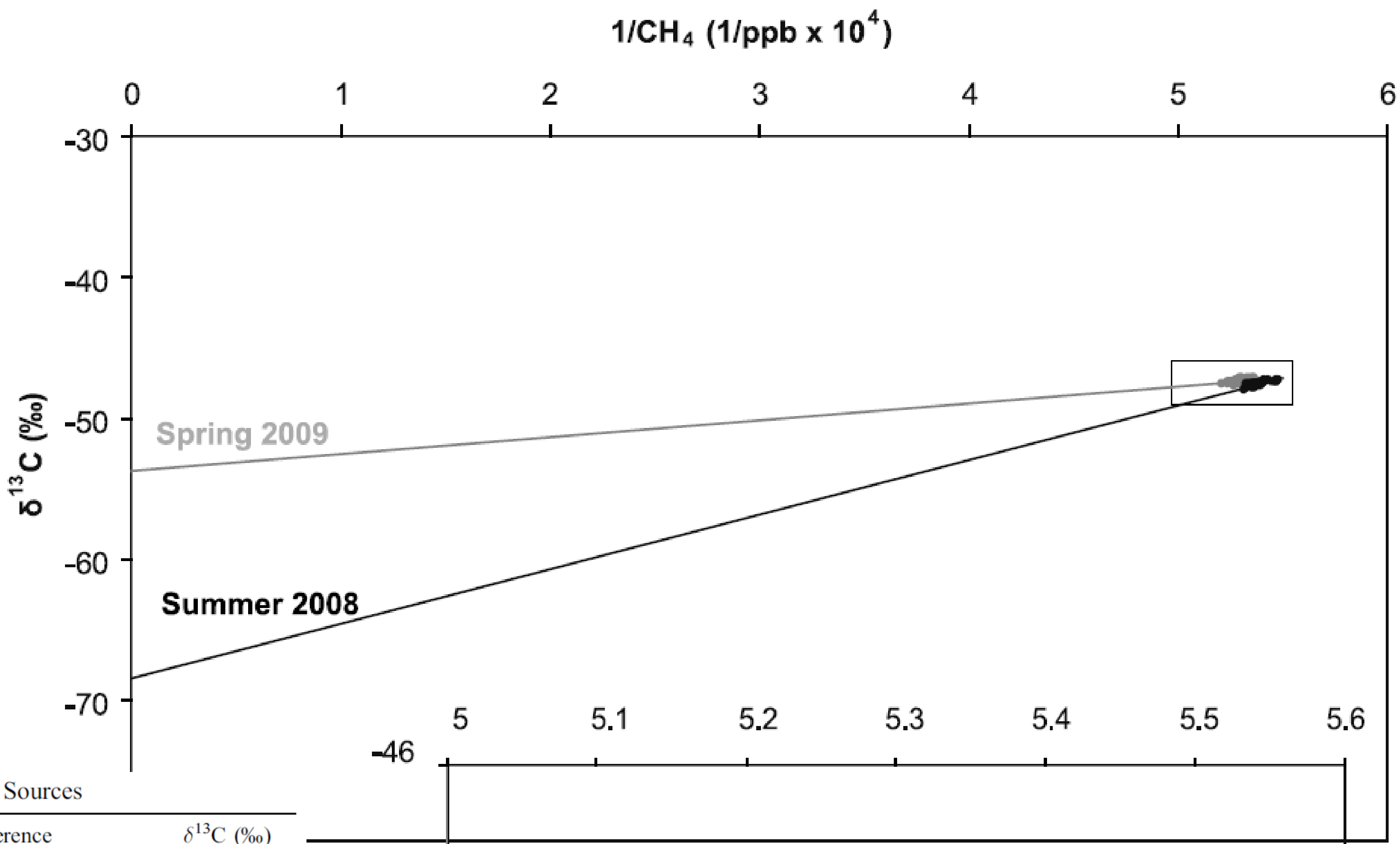
49% loss of estimated open water area when decreasing from 2 m to 350 m pixel resolution

Thornton *et al*. GRL, 2016

Can δ^{13}C-CH_4 help us?



Thornton *et al*. GRL, 2016



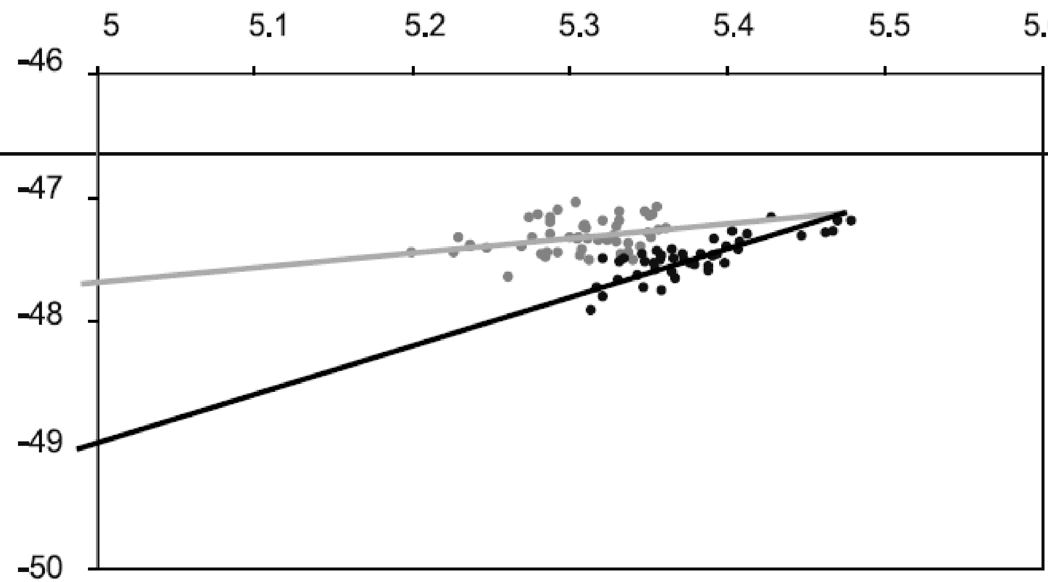
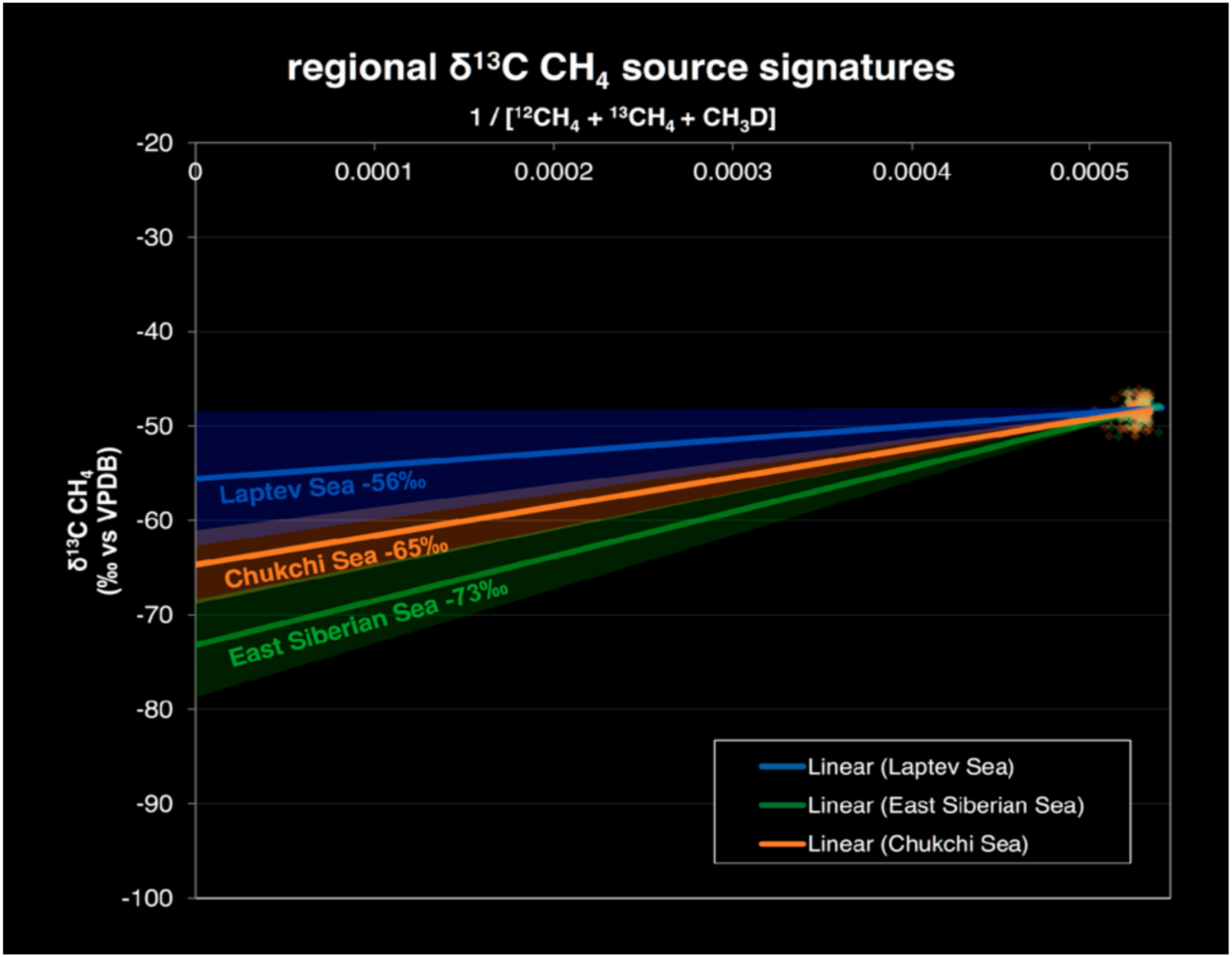


Table 1. $\delta^{13}C$ in Northern Methane Sources

Source	Reference	$\delta^{13}C$ (‰)
Wetland, N. Finland: summer spring thaw autumn freeze-up	S. Sriskantharajah (unpublished data)	−68.5 ± 0.7 −66.3 ± 0.6 −64.9 ± 4.0
Wetland, Hudson Bay Lowlands, Canada	*Kuhlmann et al.* [1998]	−60 ± 3
Tundra, Alaska	*Quay et al.* [1988]	−73 to −55
Wetland, Siberia	*Nisbet* [2005]	−67 ± 2
Ebullition from thermokarst lakes, N. Siberia	*Walter et al.* [2006]	−83 to −58
W Siberian natural gas	*Cramer et al.* [1999]	−51 ± 3
Marine clathrate, W. Spitsbergen	This work	−50 ± 5
Onshore hydrate, Mackenzie delta, Canada	*Lorenson et al.* [1999]	−48.7 to −39.6
Pine forest fires, Canada	This work	−28 ± 1

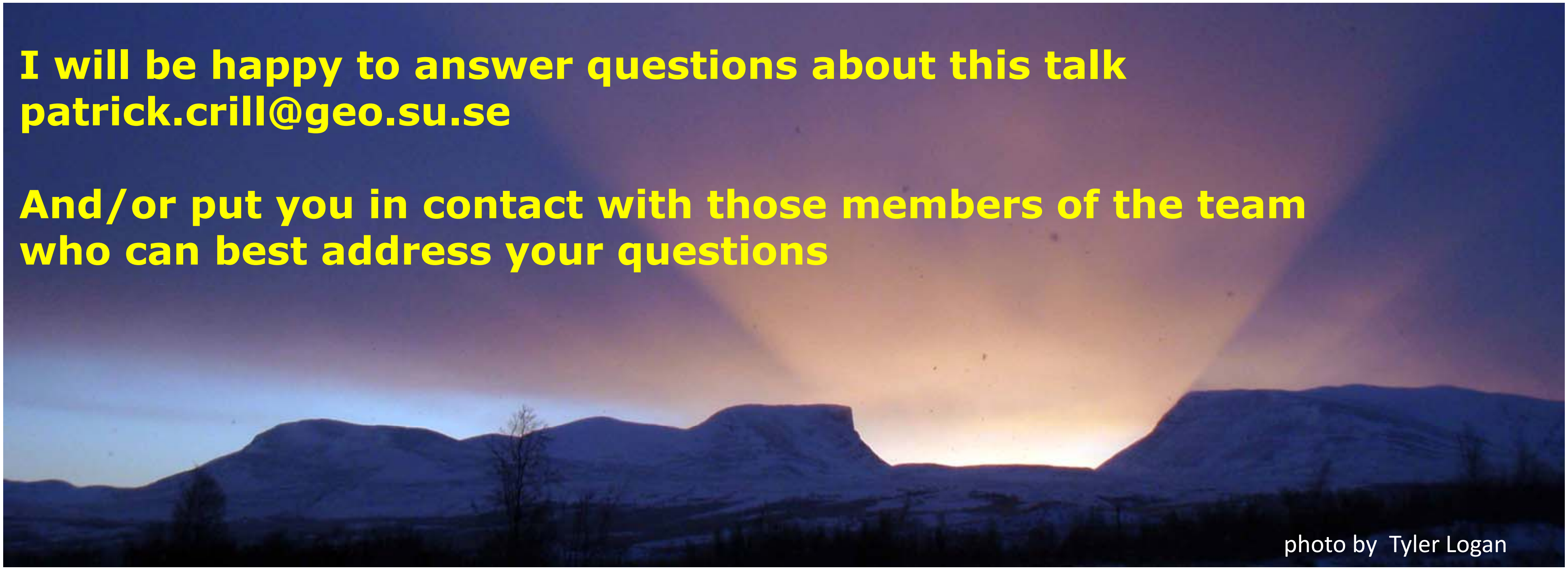
Fisher et al. Arctic Methane Sources. GRL, 2012

Atmospheric $\delta^{13}C$-CH_4 above Laptev, East Siberian, Chukchi Seas (2014)



Some Challenges

- Driving Data Sets are Poor in High Latitude Regions
- Need more data for isotopologues for source apportionment in mixing models δD-CH_4
- Representation of Hydrology/Methane Dynamics
- Effects of Permafrost Dynamics on Hydrology
- Representation of Lakes/Ponds, Disturbance and Biological Community Change
- Report model output in consistent latitude ranges: >50°N, >60°N, above Arctic Circle



Thanks to the Stockholm University
Trace Gas Biogeochemistry Lab:
Brett Thorton
Martin Wik
Joachim Jansen
Kristian Andersson

Abisko Scientific Research Station
Abisko summer field crews
I/B Oden crew
The IsoGenie Team

Vetenskapsrådet
Knut and Alice Wallenberg Foundation
POLARFORSKNINGS SEKRETARIATET
SWEDISH POLAR RESEARCH SECRETARIAT