nature geoscience

LETTERS

PUBLISHED ONLINE: 8 DECEMBER 2014 | DOI: 10.1038/NGEO2305

Net regional methane sink in High Arctic soils of northeast Greenland

Christian Juncher Jørgensen, Katrine Maria Lund Johansen, Andreas Westergaard-Nielsen and Bo Elberling*

Arctic tundra soils serve as potentially important but poorly understood sinks of atmospheric methane (CH_4), a powerful greenhouse gas[1–5]. Numerical simulations project a net increase in methane consumption in soils in high northern latitudes as a consequence of warming in the past few decades[3,6]. Advances have been made in quantifying hotspots of methane emissions in Arctic wetlands[7–13], but the drivers, magnitude, timing and location of methane consumption rates in High Arctic ecosystems are unclear. Here, we present measurements of rates of methane consumption in different vegetation types within the Zackenberg Valley in northeast Greenland over a full growing season. Field measurements show methane uptake in all non-water-saturated landforms studied, with seasonal averages of -8.3 ± 3.7 μmol CH_4 m^{-2} h^{-1} in dry tundra and -3.1 ± 1.6 μmol CH_4 m^{-2} h^{-1} in moist tundra. The fluxes were sensitive to temperature, with methane uptake increasing with increasing temperatures. We extrapolate our measurements and published measurements from wetlands with the help of remote-sensing land-cover classification using nine Landsat scenes. We conclude that the ice-free area of northeast Greenland acts as a net sink of atmospheric methane, and suggest that this sink will probably be enhanced under future warmer climatic conditions.

Future climate change is likely to affect the drivers for soil CH_4 oxidation in Arctic ecosystems with potential significant effects for the global consumption of atmospheric CH_4 (refs 6,14). In northeast Greenland, dry to moist tundra underlain by continuous permafrost dominates the ice-free land areas[15]. Here, the dominating soil types are typically young (<10,000 years), low in organic carbon and well aerated[16] offering favourable conditions for microbial CH_4 oxidation[1,2]. Contrasting reports from field observation studies and modelling studies have been made on the role of soil temperature and diffusive supply of CH_4 as environmental process drivers in the Arctic[1,3,6,14,17–19], and only very sporadic field measurements exist on drivers, and on the magnitude and spatiotemporal variation in CH_4 deposition fluxes of the northeast Greenland tundra and polar deserts[2,4,20]. Therefore, the extent and importance of CH_4 deposition in dry Arctic soil ecosystems for the total CH_4 exchange budget compared with CH_4-emitting Arctic wetlands is unresolved and conceptually biased towards perceiving the vast land areas of the High Arctic as being net methane emitters[12].

In this study, we combined laboratory experiments on the significance of soil temperature and CH_4 concentration on depth-specific samples with full season flux measurements of CH_4 deposition at the High Arctic tundra at Zackenberg, northeast Greenland (Supplementary Fig. 1). Experiments were performed on surface cover types representative of the well-drained parts of the northeast Greenland tundra that are barren ground and low prostrate shrub tundra heath with a dominating vegetation cover of *D. octopetala*, *C. tetragona* and *S. arctica*[15,16,21,22].

Depth- and temperature-specific potential CH_4 oxidation rates at atmospheric CH_4 levels were evaluated in a series of incubation experiments of soil samples from the active layer of the dry and moist tundra. Results from depth-specific incubation show that potential CH_4 oxidation in both dry and moist tundra profiles is overall limited to the upper 35–40 cm of the soil profiles, with maximum potential CH_4 oxidation rates in the upper 10–15 cm of the soil (Fig. 1a). The magnitudes of the CH_4 oxidation rates were negatively correlated to initial soil water content (Supplementary Fig. 2).

The temperature dependency of potential CH_4 oxidation rates at ambient CH_4 concentration was determined by thermoblock incubation of soil from the 0–10 cm depth interval of the dry tundra in approximately 0.7 °C increments across a temperature range of −4 to 18 °C at approximately 30% volumetric water/ice content (Methods). CH_4 oxidation rates at 1.8 ppm CH_4 in the top soil of the dry tundra show a temperature sensitivity coefficient (Q_{10}) of 4.2 using the Arrhenius model[18] (Fig. 1b). A first-order exponential CH_4 rate decrease of CH_4 oxidation rates in response to decreasing sub-ambient CH_4 concentrations was generally observed (Supplementary Fig. 3a) as in other studies[1,23,24], showing that depth-specific CH_4 consumption rates in tundra soils are regulated by soil temperature and CH_4 concentration in the top soil.

CH_4 fluxes from the Arctic tundra were measured in four campaigns over a full growing season (July to September 2012, $n = 280$). Measurements were made at four well-drained upland locations each representing the dominating surface cover types of the northeast Greenland tundra. All measurements were conducted using closed-static chambers connected to a mobile high-precision CH_4 analyser (DLT-100, Los Gatos Research) enabling interference-free quantification of CH_4 fluxes at sub-ambient concentration levels with very high precision and minimal ground disturbance (see Methods and Supplementary Fig. 5).

The flux measurements show consistent patterns of CH_4 uptake (negative flux) from all investigated non-saturated landforms over the entire unfrozen/growing season (Supplementary Fig. 6) with uptake rates in the range of −2 to −16 μmol CH_4 m^{-2} h^{-1} (Fig. 2a). Multiple linear regression analyses of the spatiotemporal variations in all measured CH_4 sink fluxes show that the fluxes are negatively correlated to soil moisture content and that the general magnitude of the CH_4 fluxes could be separated into two groups based on variations in the soil moisture content of the top soil, that is, dry tundra (5–25 vol% moisture) and moist tundra (25–55 vol%

Center for Permafrost (CENPERM), Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10 DK-1350 Copenhagen, Denmark. *e-mail: be@ign.ku.dk

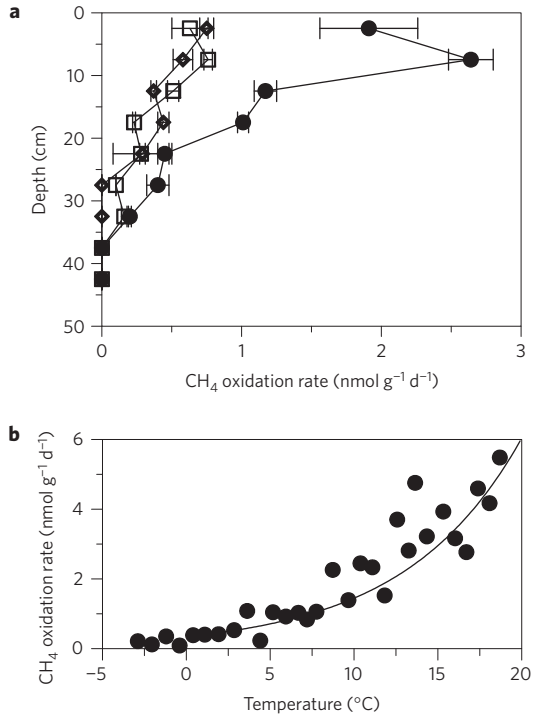

Figure 1 | Depth- and temperature-specific CH_4 oxidation rates. **a**, Depth-specific *in situ* CH_4 oxidation rates at the dry tundra plot (filled circle; $n=3$) and at the two moist tundra plots (open square/diamond; $n=3/3$); error bars show one standard deviation of the means. **b**, Temperature sensitivity plot of CH_4 oxidation rates at 1.8 ppm CH_4 concentration between −4 and +18 °C (exponential regression; $y=0.3461e^{0.143x}$; $R^2=0.86$; $p<0.05$; $Q_{10}=4.2$).

moisture; Supplementary Fig. 7). Identification of the surface and vegetation cover in the two groups reveals that the dry tundra group is occupied by plots of barren ground and *D. octopetala*, whereas the moist tundra group is dominated by *C. tetragona* and *S. arctica* in agreement with the land-cover classification study from Zackenberg[16].

CH_4 fluxes in the dry tundra group had a seasonal average flux of approximately -8.3 ± 3.7 μmol CH_4 m^{-2} h^{-1}, whereas CH_4 fluxes in the moist tundra group had a seasonal average flux of approximately -3.1 ± 1.6 μmol CH_4 m^{-2} h^{-1}. Average CH_4 fluxes in the individual measurement campaigns were between −6.9 and −8.2 μmol CH_4 m^{-2} h^{-1} in the dry tundra group and −2.0 to −3.9 μmol CH_4 m^{-2} h^{-1} in the moist tundra (Fig. 2a). No significant difference (two-sample difference of means *t*-test, $p<0.05$) in CH_4 flux magnitude was observed in the dry tundra plots with and without *D. octopetala* surface cover, or in the moist tundra *S. arctica* and *C. tetragona* plots, indicating that the plant cover itself has only an indirect or very limited effect on the rate of CH_4 deposition.

Group-specific soil moisture contents were stable with no significant difference in mean values ($p>0.05$) over the season (Fig. 2b), whereas soil temperature decreased from mid-season values of approximately 12 °C to approximately 4 °C at season end (Fig. 2c). At plot and group level, no significant correlation ($p>0.05$) was found between the seasonal variations in CH_4 flux magnitude versus soil temperature and soil moisture content.

Depth-specific potential CH_4 deposition rates were determined in the field by a manipulation experiment where chamber collars were permanently installed in the mineral soil directly below the A-horizon (approximately 10 cm depth) and at the bottom of the active layer (Methods). Observed CH_4 deposition rates in the soil below the A-horizon of the *S. arctica* moist tundra plot were 2 to 4 times lower ($p<0.05$) than the corresponding ambient control plots (Supplementary Fig. 8). A similar tendency was observed for the *C. tetragona* moist tundra with deposition values at the ambient controls similar to the *S. arctica* moist tundra plots ($p>0.05$) and approximately twice as high below the A-horizon. The largest difference between the ambient control plots and measurements below the A-horizon were observed during July and August, where the highest CH_4 deposition fluxes and highest soil temperatures were measured in the control plots (Supplementary Fig. 8).

CH_4 consumption in soil is widely assumed to be overall rate-limited by diffusion of CH_4 and O_2 to the zones of active CH_4 consumption[14,25]. Free exposure of lower parts of the soil profile to ambient atmospheric CH_4 concentration and air temperature should, by this assumption, produce CH_4 deposition fluxes of similar magnitudes as the surface fluxes. With the exception of the September 2012, *C. tetragona* moist tundra plot, observations show that deposition fluxes below the A-horizon were significantly lower ($p<0.05$) than the ambient controls. Combined with the results from the *in situ* incubation experiment (Fig. 1a), these results show that the zone of highest potential CH_4 oxidation rates and CH_4 deposition fluxes is located in close proximity to the soil–atmosphere interface. At soil depths of less than 15 cm, CH_4 and O_2 are available in near-ambient concentration in the bulk soil air (Supplementary Fig. 4) with soil temperature influencing the potential CH_4 oxidation rates, CH_4 solubility in the soil water and diffusive exchange from gas-filled soil pores across soil water films to the CH_4 oxidizing microorganisms[24].

Assuming that the CH_4 oxidation rates are not primarily diffusion-limited in these shallow Arctic soils, a stronger correlation between seasonal variations in soil temperature and net CH_4 uptake

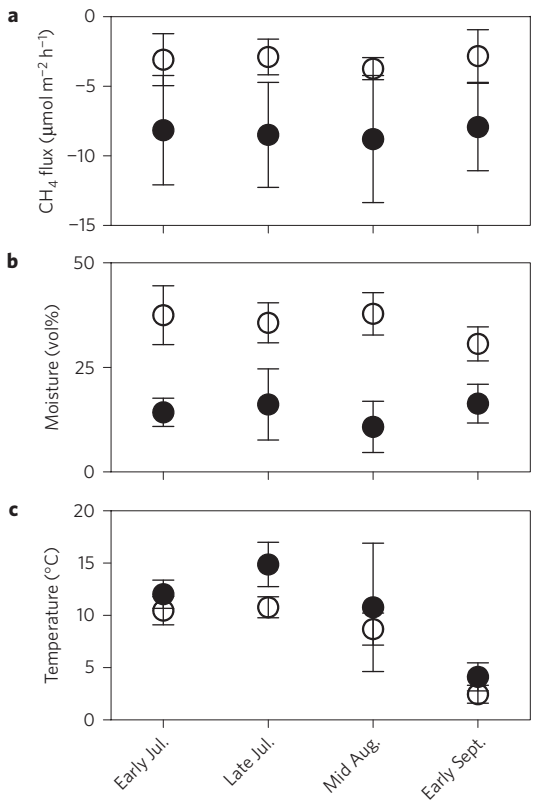

Figure 2 | Group-specific flux rates and drivers. **a**, Average CH_4 fluxes per measurement campaign (average *n* per campaign = 12). **b**, Average soil moisture content of top 5 cm (average *n* per campaign = 12). **c**, Average soil temperature at 5 cm depth (average *n* per campaign = 12). Filled circles show dry tundra; open circles show moist tundra measurements. Error bars show standard deviation.

could be expected in accordance with the Arrhenius model[18] leading to more pronounced seasonal flux dynamics and a higher climate warming response of Arctic soils compared with overall diffusion-limited soil systems[25].

A surface classification of the ice-free terrestrial areas covering the area from Zackenberg Research Station (74° 30′ N/20° 30′ W) to Station Nord (81° 36′ N/16° 40′ W) was made based on nine Landsat scenes and ground-truth data from Zackenberg[16] (see Methods; total classified area ~59.200 km^2). In the classification, the relative distribution of dry tundra (5–25 vol% moisture), moist tundra (25–55 vol% moisture) and fen areas (Fig. 3) was determined on the basis of the area coverage ratio. Areas recognized as seasonally flooded grassland were also identified in the surface classification to provide the most conservative estimate of potential CH_4-emitting land areas. Overall surface classification accuracy between 70.3% and 77.0% was achieved for the dry/moist tundra and grassland/wetland classes (Supplementary Table 3).

Results from the surface classification show that the sum of potential CH_4 source areas (positive flux) to the sum of potential CH_4 sink areas (negative flux) is of the order of 1:80 to 1:385 (Table 1), depending on whether seasonally flooded grasslands were included as net CH_4 emitters in the same order of magnitude as the Zackenberg fen areas. Annual CH_4 emissions from these fens

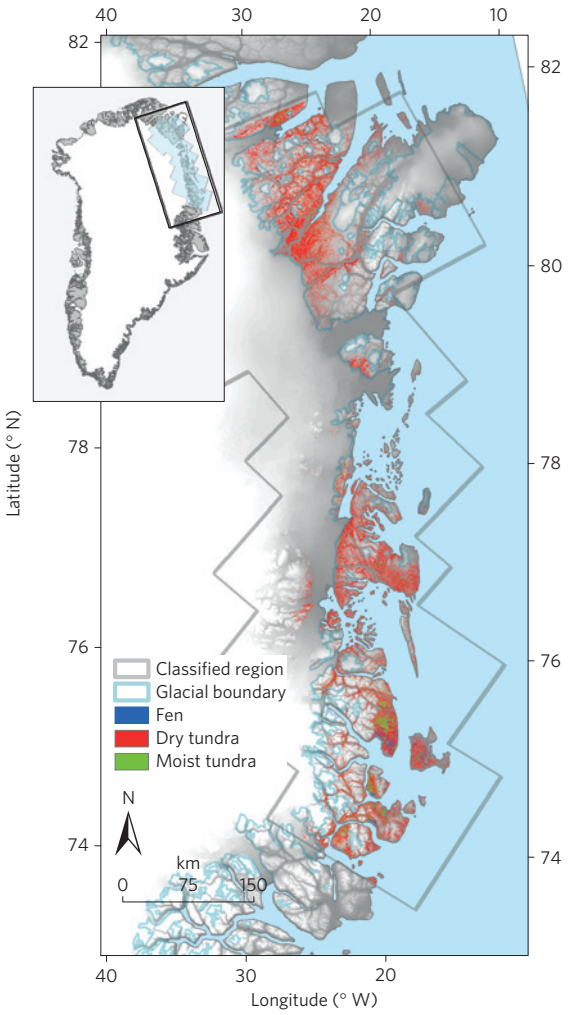

Figure 3 | Surface cover map. Generalized surface cover map of northeast Greenland from Zackenberg Research Station (74° 30′ N/20° 30′ W) to Station Nord (81° 36′ N/16° 40′ W) showing the area distribution of dry tundra, moist tundra and fen areas along with the glacial boundary and the extent of the classified region.

Table 1 | CH_4 exchange budget of northeast Greenland.

Surface classification	Area (km^2)	Seasonal CH_4 flux (g CH_4-C m^{-2})	Total CH_4 flux (tonne CH_4-C)
Dry tundra (5–25%)	9319	−0.216 ± 0.099	−2005 ± 894
Moist tundra (25–55%)	1227	−0.081 ± 0.045	−99 ± 51
Fen	27	6.2*	167
Wet grasslands	102	6.2*	632

Summary of classified surface areas for the ice-free terrestrial areas covering the area from Zackenberg Valley (74° 30′ N; 21° 00′ W) to Station Nord (81° 36′ N; 16° 40′ W) together with estimated seasonal CH_4 fluxes with an active CH_4 exchange season length of 90 days. *Average value of previously reported seasonal CH_4 emissions from Zackenberg[7,26].

are in the range of approximately 3.7–7.6 g CH_4-C m^{-2} with some inter-annual variation[7,20,26–28]. To calculate the net CH_4 exchange of northeast Greenland, an average of the reported CH_4 emissions from 2007 to 2009[7,26] of 6.2 g CH_4-C m^{-2} season is assumed to be representative of the classified fen areas and grasslands of northeast Greenland. Using this emission value together with the mean ±1s.d. deposition flux value ranges of the dry and moist tundra in the area-weighted CH_4 exchange extrapolation, it shows that northeast Greenland under the current climatic conditions is a net sink of atmospheric CH_4 with between 1.4 and 18.3 times more CH_4 consumed than emitted owing to the dominance of dry to moist tundra areas (Table 1 and Supplementary Table 1 and Figs 9 and 10).

Changes in the CH_4 oxidation capacity of the Arctic tundra might be a key process in the global CH_4 exchange budget[3,18]. To our knowledge, this paper is the first to upscale and directly link a seasonal CH_4 sink budget to the net CH_4 exchange budget of regions in the High Arctic such as northeast Greenland. Owing to the shallow and carbon-poor nature of the dry to moist tundra soils found in northeast Greenland and similar High Arctic upland ecosystems, current CH_4 deposition fluxes may be less influenced by diffusion limitation and more affected by temperature variations than soil systems where CH_4 oxidation activity may be seen deeper in the soil profile[18]. With a Q_{10} of 4.2 on CH_4 oxidation rates, the top soil of the dry High Arctic tundra has the capacity to respond effectively to elevated soil temperatures. In combination with an observed and predicted climatic shift towards warmer soil conditions in the Arctic[29,30], this could trigger increased net CH_4 depositions and a shift in the area distribution of dry and moist tundra with a subsequent positive feedback implication for the net landscape CH_4 exchange budget.

Methods

Study site. The study site for all field measurement is located in the Zackenberg heath plain lowlands (74° 30′ N/20° 30′ W) in High Arctic Greenland. The area lies inside the zone of continuous permafrost with a mean annual air temperature around −10 °C and an annual precipitation of around 150 mm. Sub-surface soil temperatures at 5 cm depth are below −18 °C for about four months per year and above 0 °C for about 120 days per year[16].

Soil sampling and incubation. Soil samples for the incubation experiments were collected in July 2012. Intact fixed volume samples were obtained from the top 10 cm of the dry tundra (*D. octopetala* and barren ground plots, $n = 5$). Depth-specific composite samples from the active layer for each 5 cm depth increment were made for each plot in five randomly chosen sample profiles. For the temperature sensitivity study, representative mass reduction and identical replicate preparation of the frozen top soil samples from the dry tundra plots were performed in a freeze laboratory (−10 °C) using a gentle crushing, homogenization and splitting procedure producing a total of 128 soil samples with approximately identical constitutions and average weights of 3.66 ± 0.52 g. Samples for the depth-specific *in situ* incubation were prepared in the soil laboratory at the Zackenberg research station on the day of soil sampling using a combination of laminar sample homogenization and cross-cutting sampling (see extended description in Supplementary Information). The temperature dependence of potential CH_4 oxidation rates in near-surface A-horizon material

(0–10 cm) from the dry tundra plots was determined by incubating 31 soil sample replicates in a stable temperature gradient using an insulated solid aluminium thermoblock of 1.85 m length. Incubation temperatures ranged from −4.3 °C to 18.7 °C in 31 increments with an average temperature difference between samples of approximately 0.75 °C. Samples for depth-specific potential CH_4 oxidation rates were incubated at the Zackenberg Research Station directly after sampling of the soil. Incubation vials were all closed with butyl rubber septa and enriched with CH_4 to a final headspace concentration of approximately 600 ppmv. The potential CH_4 oxidation rates were calculated on the basis of the decrease (exponential bivariate regression; $p < 0.05$) in CH_4 concentration over time and converted into nanomoles of CH_4 per gram of dry soil per hour. Control incubations with empty incubation tubes and an identical sampling procedure showed a constant CH_4 concentration over time (linear bivariate regression; $p > 0.05$).

Flux measurements. Fluxes of CH_4 between the soil and the atmosphere were measured in 4 measurement campaigns from June to September 2012 using transparent and opaque closed-static chambers. During measurements, the air volume in the chamber headspace was circulated in a closed loop at a flow rate of approximately 0.3 l min^{-1} to a DLT-100 Fast Methane Analyzer (Los Gatos Research). CH_4 fluxes were measured over a 10-min period with a 10-s sampling frequency (60 samples per enclosure). Air temperatures inside and outside the chambers were measured using temperature sensors mounted in the lid (107 temperature probe; Campbell Scientific). A total of 40 chamber frames were installed in the *S. arctica*, *C. tetragona*, *D. octopetala* and barren ground plots. No significant difference (two-sample difference of means *t*-test; $p > 0.05$) in CH_4 fluxes was observed with respect to usage of transparent or opaque chambers. Soil moisture and soil temperature in the upper 5 cm were measured in 4 replicates for each chamber.

Tundra classification. Surface classification of the ice-free terrestrial areas covering the area from Zackenberg Research Station (74° 30′ N/20° 30′ W) to Station Nord (81° 36′ N/16° 40′ W) was made on the basis of nine Landsat TM5 scenes publicly available at http://glovis.usgs.gov (see also Supplementary Table 2 and Figs 9 and 10). All scenes were terrain-corrected L1T products with 7 multispectral bands. The Landsat scenes were converted to top-of-atmosphere radiance (ENVI 5.0) before the classification, using the spectral radiance scaling method. Computed indices were based on top-of-atmosphere reflectance values derived as described in the Landsat Handbook, section 11.3.2 (http://landsathandbook.gsfc.nasa.gov/pdfs/Landsat7_Handbook.pdf). Ancillary data consisted of an ASTER-based 30 m digital elevation model. Ground-truth data were available from Zackenberg[16]. To distinguish between surfaces with low–medium (represented by fell field, abrasion plateaux, Dryas heath) and medium–high soil moisture contents (represented by *Salix* heath, grassland, fen and *Cassiope* heath), a classification tree was built to classify normalized difference water index composites. The classification tree was iteratively adjusted to perform optimally against the Zackenberg-land-cover classification[16], which we separated into three main classes: dry tundra with barren ground, fell and *D. octopetala*; moist tundra with *C. tetragona* and *S. arctica*; and fen and grassland. The surface classification was validated against independent ground-truth data from 2008 to 2013.

Received 12 March 2014; accepted 31 October 2014; published online 8 December 2014

References

1. Whalen, S. & Reeburgh, W. Consumption of atmospheric methane by tundra soils. *Nature* **346,** 160–162 (1990).
2. Bárcena, T. G., Finster, K. W. & Yde, J. C. Spatial patterns of soil development, methane oxidation, and methanotrophic diversity along a receding glacier forefield, Southeast Greenland. *Arct. Antarct. Alp. Res.* **43,** 178–188 (2011).
3. Curry, C. L. The consumption of atmospheric methane by soil in a simulated future climate. *Biogeosciences* **6,** 2355–2367 (2009).
4. Emmerton, C. A. *et al.* The net exchange of methane with High Arctic landscapes during the summer growing season. *Biogeosci. Discuss.* **11,** 1673–1706 (2014).
5. Flessa, H. *et al.* Landscape controls of CH_4 fluxes in a catchment of the forest tundra ecotone in Northern Siberia. *Glob. Change Biol.* **14,** 2040–2056 (2008).
6. Zhuang, Q. *et al.* Response of global soil consumption of atmospheric methane to changes in atmospheric climate and nitrogen deposition. *Glob. Biogeochem. Cycles* **27,** 650–663 (2013).
7. Mastepanov, M. *et al.* Large tundra methane burst during onset of freezing. *Nature* **456,** 628–630 (2008).
8. Ström, L., Tagesson, T., Mastepanov, M. & Christensen, T. R. Presence of *Eriophorum scheuchzeri* enhances substrate availability and methane emission in an Arctic wetland. *Soil Biol. Biochem.* **45,** 61–70 (2012).
9. Van Huissteden, J. *et al.* Methane emissions from permafrost thaw lakes limited by lake drainage. *Nature Clim. Change* **1,** 119–123 (2011).
10. Whalen, S. Biogeochemistry of methane exchange between natural wetlands and the atmosphere. *Environ. Eng. Sci.* **22,** 73–94 (2005).
11. Torn, M. S. & Chapin, F. S. Environmental and biotic controls over methane flux from Arctic tundra. *Chemosphere* **26,** 357–368 (1993).
12. O'Connor, F. M. *et al.* Possible role of wetlands, permafrost and methane hydrates in the methane cycle under future climate change: A review. *Rev. Geophys.* **48,** RG4005 (2010).
13. Olefeldt, D., Turetsky, M. R., Crill, P. M. & McGuire, A. D. Environmental and physical controls on northern terrestrial methane emissions across permafrost zones. *Glob. Change Biol.* **19,** 589–603 (2013).
14. Torn, M. & Harte, J. Methane consumption by montane soils: Implications for positive and negative feedback with climatic change. *Biogeochemistry* **32,** 53–67 (1996).
15. Walker, D. A. *et al.* The Circumpolar Arctic vegetation map. *J. Veg. Sci.* **16,** 267–282 (2005).
16. Elberling, B. *et al.* Soil and plant community-characteristics and dynamics at Zackenberg. *Adv. Ecol. Res.* **40,** 223–248 (2008).
17. King, G. & Adamsen, A. Effects of temperature on methane consumption in a forest soil and in pure cultures of the methanotroph *Methylomonas rubra*. *Appl. Environ. Microbiol.* **58,** 2758–2763 (1992).
18. King, G. Responses of atmospheric methane consumption by soils to global climate change. *Glob. Change Biol.* **3,** 351–362 (1997).
19. Spahni, R. *et al.* Constraining global methane emissions and uptake by ecosystems. *Biogeosciences* **8,** 1643–1665 (2011).
20. Christensen, T. R. *et al.* Trace gas exchange in a high-Arctic valley 1. Variations in CO_2 and CH_4 flux between tundra vegetation types. *Glob. Biogeochem. Cycles* **14,** 701–713 (2000).
21. Elberling, B., Christiansen, H. H. & Hansen, B. U. High nitrous oxide production from thawing permafrost. *Nature Geosci.* **3,** 332–335 (2010).
22. Daniëls, F. J. A. Vegetation classification in Greenland. *J. Veg. Sci.* **5,** 781–790 (1994).
23. Bender, M. & Conrad, R. Kinetics of methane oxidation in oxic soils. *Chemosphere* **26,** 687–696 (1993).
24. Koschorreck, M. & Conrad, R. Oxidation of atmospheric methane in soil: Measurements in the field, in soil cores and in soil samples. *Glob. Biogeochem. Cycles* **7,** 109–121 (1993).
25. Smith, K. A. *et al.* Oxidation of atmospheric methane in Northern European soils, comparison with other ecosystems, and uncertainties in the global terrestrial sink. *Glob. Change Biol.* **6,** 791–803 (2000).
26. Tagesson, T. *et al.* Land-atmosphere exchange of methane from soil thawing to soil freezing in a high-Arctic wet tundra ecosystem. *Glob. Change Biol.* **18,** 1928–1940 (2012).
27. Tagesson, T., Mastepanov, M. & Mölder, M. Modelling of growing season methane fluxes in a high-Arctic wet tundra ecosystem 1997–2010 using *in situ* and high-resolution satellite data. *Tellus B* **1,** 1–21 (2013).
28. Friborg, T., Christensen, T., Hansen, B. U., Nordstroem, C. & Soegaard, H. Trace gas exchange in a high-Arctic valley: 2. Landscape CH_4 fluxes measured and modeled using eddy correlation data. *Glob. Biogeochem.* **14,** 715–723 (2000).
29. Post, E. *et al.* Ecological dynamics across the Arctic associated with recent climate change. *Science* **325,** 1355–1358 (2009).
30. Kaufman, D. S. *et al.* Recent warming reverses long-term Arctic cooling. *Science* **325,** 1236–1239 (2009).

Acknowledgements

We gratefully acknowledge the financial support from the Danish National Research Foundation (CENPERM DNRF100), the European Union FP7—ENVIRONMENT project PAGE21 under contract no. GA282700, the Danish Ministry of Climate, Energy and Building and the Zackenberg Research Station. Special thanks to P. Christiansen and J. Gammeltoft for constructing the thermoblock incubator and to M. R. Cruz and M. Wahlgren for assistance in the laboratory.

Author contributions

B.E. and C.J.J. designed the study. K.M.L.J., C.J.J. and B.E. performed the field work. C.J.J. performed the laboratory experiments. A.W-N. performed the remote-sensing classification and analysis. C.J.J. and B.E. wrote the paper with contributions from all co-authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.E.

Competing financial interests

The authors declare no competing financial interests.