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Methane bubbling from northern lakes: present and future contributions to the global methane budget

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Large uncertainties in the budget of atmospheric methane (CH_4) limit the accuracy of climate change projections. Here we describe and quantify an important source of CH_4—point-source ebullition (bubbling) from northern lakes—that has not been incorporated in previous regional or global methane budgets. Employing a method recently introduced to measure ebullition more accurately by taking into account its spatial patchiness in lakes, we estimate point-source ebullition for 16 lakes in Alaska and Siberia that represent several common northern lake types: glacial, alluvial floodplain, peatland and thermokarst (thaw) lakes. Extrapolation of measured fluxes from these 16 sites to all lakes north of 45° N using circumpolar databases of lake and permafrost distributions suggests that northern lakes are a globally significant source of atmospheric CH_4, emitting approximately 24.2 ± 10.5 Tg CH_4 yr^{-1}. Thermokarst lakes have particularly high emissions because they release CH_4 produced from organic matter previously sequestered in permafrost. A carbon mass balance calculation of CH_4 release from thermokarst lakes on the Siberian yedoma ice complex suggests that these lakes alone would emit as much as approximately 49 000 Tg CH_4 if this ice complex was to thaw completely. Using a space-for-time substitution based on the current lake distributions in permafrost-dominated and permafrost-free terrains, we estimate that lake emissions would be reduced by approximately 12% in a more probable transitional permafrost scenario and by approximately 53% in a 'permafrost-free' Northern Hemisphere. Long-term decline in CH_4 ebullition from lakes due to lake area loss and permafrost thaw would occur only after the large release of CH_4 associated thermokarst lake development in the zone of continuous permafrost.

Keywords: northern lakes; methane emissions; permafrost; thermokarst; Geographical Information System; climate change

1. Introduction

Global climate change is one of the most important issues facing modern society. Global mean surface air temperatures have increased approximately 0.6°C over the past century resulting in the retreat of glaciers, thawing of permafrost and

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sea ice, increase in river discharge and alteration of terrestrial and aquatic ecosystems in ways that demand both immediate and long-term societal response (Overpeck *et al.* 1997; IPCC 2001; Peterson *et al.* 2002; Romanovsky *et al.* 2002; ACIA 2004; Hinzman *et al.* 2005; Stern Review 2006). Projections suggest even greater warming resulting from rising greenhouse gas concentrations over the twenty-first century (IPCC 2001, forthcoming).

Methane (CH_4) is the third most important greenhouse gas in the atmosphere after carbon dioxide (CO_2) and water vapour, and it is arguably the most dynamic. During the last glacial period, the concentration of atmospheric CH_4 rose and fell by 50% in association with rapid climate warming (Brook *et al.* 2000; Dallenbach *et al.* 2000). It has increased by approximately 250% since the pre-industrial era, exceeding the rate of CO_2 increase by 120% (IPCC 2001). Recent decades saw a rapid rise in atmospheric CH_4 concentration, 1% annually in the 1980s, followed by a slowing of the growth rate during the 1990s that has been attributed to a decline in fossil fuel emissions following the breakdown of the Soviet Union (Dlugokencky *et al.* 2003). Since 1999, anthropogenic emissions have increased in northern Asia, possibly reflecting acceleration of the Chinese economy (Bosquet *et al.* 2006).

Non-fossil fuel emissions associated with human activities include rice agriculture, waste treatment, animal husbandry and biomass burning. After years of study of atmospheric CH_4, natural sources were thought to have been largely identified as wetlands, oceans, termites and hydrates. However, recent work suggests that significant new sources of atmospheric CH_4 are still being identified. Keppler *et al.* (2006) proposed that methane production in terrestrial plants through an unknown mechanism can account for up to 50% of the modern methane sources. Walter *et al.* (2006) identified enhanced CH_4 emissions associated with the permafrost degradation and the arctic thermokarst (thaw)-lake expansion as a positive feedback to climate warming. It seems that the more CH_4 is studied, the more surprises we discover.

Understanding the atmospheric CH_4 budget remains limited by large uncertainties in the individual magnitudes and spatial–temporal variability of sources at both regional and global scales (Chen & Prinn 2006). Variation in hydroxyl radical photochemistry, the primary sink of atmospheric CH_4, also contributes to uncertainties in atmospheric CH_4 dynamics (Bosquet *et al.* 2006). Nonetheless, the concentration of atmospheric CH_4 is projected to increase significantly given the large pools of carbon (C) stored in permafrost that can be converted to CH_4 upon thaw, the susceptibility of CH_4 hydrates to release from the ocean floor with rising seawater temperature and the acceleration of CH_4-producing anthropogenic activities. Since regulation efforts are focused primarily on limiting CO_2 production, CH_4 may become a proportionally larger agent of climate forcing in the future. It is therefore imperative that we strive to understand sources and sinks of atmospheric CH_4 and improve constraints on their flux estimates so that we can better predict, prepare for, and perhaps even act to mitigate future changes.

The aim of this paper is to examine one particular source of atmospheric CH_4 that may be significantly larger than previously recognized: ebullition (bubbling) from northern lakes. Careful measurements of the spatial and temporal patchiness of ebullition in Siberian thermokarst lakes revealed that total emissions from lakes were five times greater than earlier estimates that did not account for the patchiness of ebullition (Zimov *et al.* 1997; Walter *et al.* 2006). Furthermore, thaw of permafrost along lake margins releases labile organic matter previously sequestered in

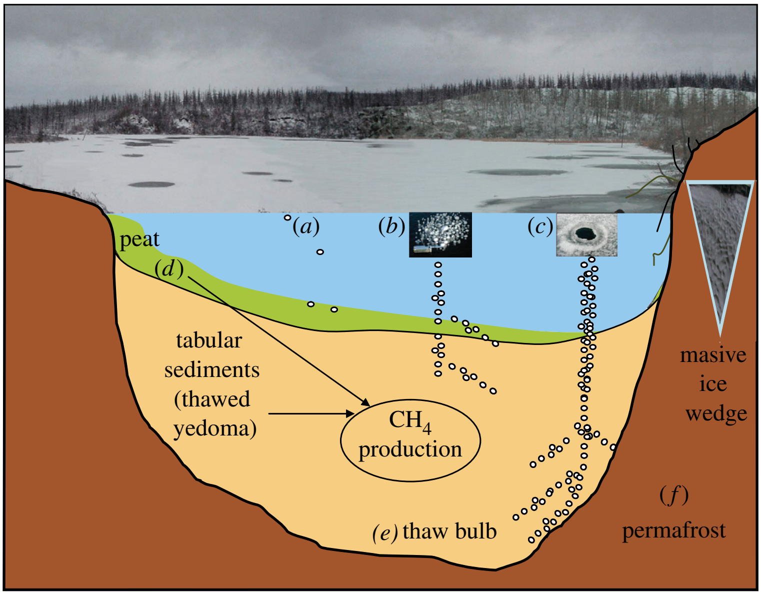

Figure 1. Cross-section of a North Siberian thermokarst lake showing dynamics of (*a*) background, (*b*) point-source and (*c*) hotspot ebullition. Background ebullition, defined as the ebullition measured by random placement of bubble traps in lakes, is typically a low-magnitude flux that covers the majority of the lake surface area. Background ebullition, characterized by lower CH_4 content and younger radiocarbon age, is often produced in surface lake sediments, typically Holocene-aged peat (*d*) from where the buoyancy of individual bubbles is sufficient to release bubbles from sediments where they are formed. In contrast, CH_4 emitted through point sources produced deeper in lake sediments is characterized by higher concentrations of CH_4 and older radiocarbon ages than background ebullition (Walter *et al.* in press *a*). Methane bubbles originating from greater depths beneath lakes flow into common bubble tubes and are emitted through single small holes at the sediment surface. Rising to the surface of the lake from these fixed points, bubbles become trapped in lake ice throughout winter, forming distinct patterns in ice depending on the magnitude of CH_4 emissions. Fixed points from which extremely high ebullition rates are sufficient to maintain open holes in lake ice throughout winter are called hotspots. Hotspots emit bubbles with a high CH_4 concentration (up to 90%) and ancient radiocarbon age (up to 43 000 years), suggesting that CH_4 is produced at great depth in the lake's thaw bulb (*e*) from an ancient organic matter source (Pleistocene-aged organics in yedoma) and discharged via a network of bubble paths that come together as a single bubble tube at the sediment surface. Stable isotope signatures suggest that lake CH_4 is of biogenic origin (Zimov *et al.* 1997; Walter *et al.* 2006). Thermokarst lakes studied occurred in the zone of continuous permafrost in the yedoma (*f*; icy, Pleistocene-aged, organic-rich permafrost) region of Siberia.

permafrost for centuries to millennia into anaerobic lake sediments, enhancing CH_4 production and ebullition emission and serving as a positive feedback to climate warming. Here we propose that consideration of point-source ebullition, a newly recognized mode of emission that dominated total lake CH_4 emissions from lakes where it was studied, will reveal that lakes are a significant source of atmospheric CH_4. Given the prominence of CH_4-producing lakes in the relatively C-rich, permafrost-dominated landscapes of the north, the fate of lakes is a critical source of uncertainty in climate change studies. In this paper, we estimate current CH_4 ebullition emissions from all northern lakes, based on measured fluxes that are extrapolated to the circumpolar zone north of 45° N. Estimates of thermokarst-lake emissions associated with degradation of a particular type of extremely ice-rich permafrost, known as the 'yedoma ice complex' (Czudek & Demek 1970; Zimov *et al.* 2006), throughout the Holocene are used as a basis for a C-mass balance calculation to project the magnitude of future CH_4 release from yedoma permafrost through lakes if permafrost continues to thaw. Finally, using a space-for-time substitution, we speculate on changes in lake emissions in two future scenarios for the north: (i) transitional permafrost (discontinuous, sporadic and isolated) disappears and lake area increases by 10% in the zone of continuous permafrost and (ii) a hypothetical permafrost-free state where surface permafrost is altogether absent.

2. The significance of methane ebullition from lakes

Much of atmospheric CH_4 originates in high northern latitudes, where its atmospheric concentration is highest (Steele *et al.* 1987; Fung *et al.* 1991). The relative contribution of various northern CH_4 sources is, however, still poorly understood (Nisbet 1989; Mikaloff Fletcher *et al.* 2004). Northern wetlands, which have been extensive through most of the Holocene (Mathews & Fung 1987; Aselmann & Crutzen 1989) were an important pre-industrial source of atmospheric CH_4 (Rasmussen & Khalil 1984; Severinghaus & Brook 1999; Smith *et al.* 2004; MacDonald *et al.* 2006). Since arctic warming is predicted to enhance wetland CH_4 emissions during the next century (IPCC 2001), improving the estimate of northern wetland contribution to atmospheric CH_4 is an important research objective (Mathews & Fung 1987; Nisbet 1989; Reeburgh *et al.* 1998; Dlugokencky *et al.* 2001; Mikaloff Fletcher *et al.* 2004).

Wetlands are not the only natural source of atmospheric CH_4 at high latitudes. Roughly 40% of the world's lakes occur north of 45° N. In some northern regions, lakes occupy as much as 22–48% of the land surface (Zimov *et al.* 1997; Hinkel *et al.* 2003; Riordan *et al.* 2006). However, despite their prominence on the landscape, lakes have been largely ignored in models that simulate the global atmospheric CH_4 budget because flux estimates based on CH_4 diffusion from lakes seemed too low to warrant inclusion in global models (Rudd & Hamilton 1978; Fallon *et al.* 1980; Whalen & Reeburgh 1990; Kling *et al.* 1992; Rudd *et al.* 1993; Bastviken *et al.* 2004). Although ebullition was also recognized as an important process, it was not well quantified due to its high temporal and spatial variability. When included in whole-lake flux estimates, ebullition was often extrapolated from short-term measurements with randomly placed bubble traps or floating chambers (Bartlett *et al.* 1988; Hamilton *et al.* 1994; Keller & Stallard 1994; Zimov 1997; Casper *et al.* 2000; Grant & Roulet 2002; Bastviken *et al.* 2004). These techniques systematically underestimate the magnitude of lake emissions because they fail to capture a particular type of ebullition, which, although spatially rare, can dominate whole-lake emissions (Walter *et al.* 2006). In Siberia, the probability of capturing point source or hotspot-bubbling points (3.7% of lake surface area) using random placement of 14 bubble traps (less than 0.03% of lake area) was only 0.001%. By walking on the surface of early winter lake ice, Walter *et al.* mapped the distribution and abundance of point sources and hotspots of ebullition, which are identified as specific classes of bubble clusters or open holes in lake ice distinct from background ebullition (figure 1). Daily measurements of ebullition associated with point sources and hotspots were conducted, so the whole-lake CH_4

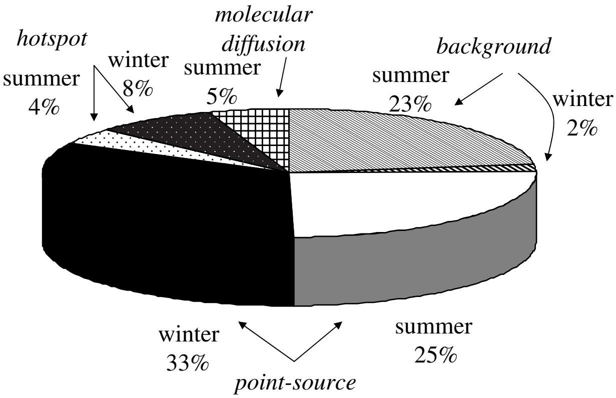

Figure 2. Pie chart depicting the relative contributions of different measured modes of CH_4 emissions from North Siberian thermokarst lakes during winter (ice-cover period, dark slices) and summer (ice-free period, light slices; after Walter *et al.* 2006). Together, point-source and hotspot ebullition dominated annual lake emissions.

emissions could be calculated based on maps of the distribution of different source types across lake surfaces. Together, point-source and hotspot ebullition accounted for 70% of total emissions from Siberian thermokarst lakes, while molecular diffusion was only 5% (figure 2). Application of this technique to glacial lakes on the north slope of Alaska's Brooks Range suggested that ebullition accounted for approximately 95% of the CH_4 flux from these lakes (Kling *et al.* 1992; Walter *et al.* submitted). Including ebullition fluxes from point sources and hotspots increased CH_4 emission estimates for lakes fivefold in Siberia (from 6.8 (Zimov *et al.* 1997) to 34 g m^{-2} yr^{-1} (Walter *et al.* 2006)) and 2.5- to 14-fold in Alaska (from 0.6 g m^{-2} yr^{-1} based on molecular diffusion (Kling *et al.* 1992) to 1.6–9.3 g CH_4 m^{-2} yr^{-1} based on point-source ebullition (Walter *et al.* submitted).

We estimated point-source ebullition sampled for 16 lakes in Alaska and Siberia (figure 3) that represent common types of pan-arctic lakes including glacial, alluvial floodplain, peatland and thermokarst lakes. Point-source ebullition occurred in all lakes sampled (except one large glacial lake in Alaska) and was greatest in thermokarst lakes, where thermokarst erosion actively deposits organic materials released from thawing permafrost. Average point-source emissions from non-thermokarst lakes were variable (17.9 ± 12.1 g CH_4 m^{-2} yr^{-1}) and did not differ by lake type. Areas of thermokarst lakes influenced by thermokarst erosion, on the other hand, had 7.5-fold higher average CH_4 point-source emissions (135 ± 51.8 g CH_4 m^{-2} yr^{-1}; SAS ANOVA. $F=17.98_{3,12}$, $p<0.0001$).

3. Estimating CH_4 ebullition from all northern lakes

The current spatial distribution of lakes and wetlands in the Northern Hemisphere is influenced by numerous factors including climate (precipitation minus evapotranspiration, P−E), geomorphology, substrate permeability, glacial history, the presence or absence of permafrost and permafrost properties (Wetzel 2001; Yoshikawa & Hinzman 2003; Klein *et al.* 2005; Smith *et al.* in press). By combining global databases on the location of large lakes (sized 0.1–50 km^2;

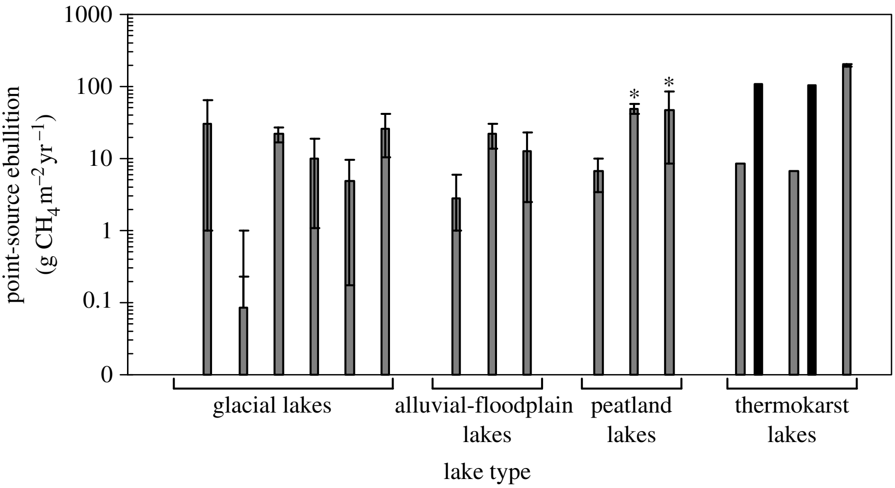

Figure 3. Point-source ebullition measured from 16 lakes in Alaska and Siberia representing several common northern lake types: glacial, alluvial-floodplain, peatland and thermokarst lakes. Error bars represent standard deviation of ebullition based on 2–3 transects of point-source surveys per lake. Data sources were previously described by Walter *et al.* (2006) and Walter *et al.* (submitted), except data for two peatland lakes, noted by asterisks, in Alaska which are presented here for the first time.

Lehner & Doll 2004), topography, permafrost (Brown *et al.* 1997, 2001), peatlands (MacDonald *et al.* 2006) and extent of Last Glacial Maximum glaciation (Ray & Adams 2001), Smith *et al.* (in press) identified glaciation history and the presence of permafrost to be the greatest first-order controls on the current distribution of lakes in the Northern Hemisphere (north of 45° N). Lake densities and lake area fractions were 300–350% greater in glaciated versus non-glaciated terrain, and approximately 100–170% greater in permafrost influenced versus permafrost-free terrain. Geomorphological processes associated with glaciation promote lake formation by reducing topographic relief, carving depressions in bedrock and depositing dead ice that forms kettle lakes upon thaw. The Canadian Shield is particularly rich in lakes formed following deglaciation (figure 4). Excluding Greenland, nearly two-thirds (27.3×10^6 km^2) of the total land area (approx. 41.3×10^6 km^2) was classified as lowlands or previously ice covered and 95% of northern lakes occur in these lowland and postglacial terrains. Of those lakes, 75% occur in permafrost. Permafrost promotes lakes by reducing infiltration of surface water into the subsurface and through its role in thermokarst-lake cycles (Carson & Hussey 1962; Sellmann *et al.* 1975; Jorgenson & Osterkamp 2005). Organic-rich soils, such as peat and gytija, and lacustrine or glacio-marine clays with low hydraulic conductivities can also promote lakes in peatland areas by reducing infiltration. Climate ($P-E$), a critical factor that influences lake area and distributions on shorter time-scales (Klein *et al.* 2005; Riordan *et al.* 2006), was not evaluated by Smith *et al.*

The amount of CH_4 emitted from northern lakes annually is unknown. The few studies that have actually measured CH_4 emissions (Rudd & Hamilton 1978; Whalen & Reeburgh 1990; Naiman *et al.* 1991; Kling *et al.* 1992; Rudd *et al.* 1993; Hamilton *et al.* 1994; Nakayama *et al.* 1994; Roulet *et al.* 1994, 1997; Zimov 1997; Bastviken *et al.* 2004) probably missed the large flux associated with

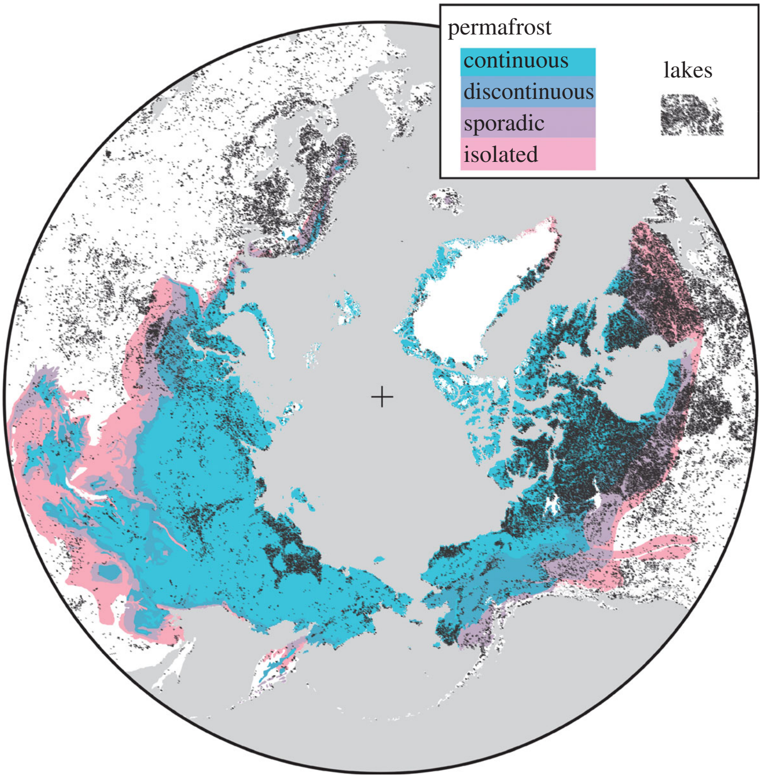

Figure 4. Pan-arctic distribution of lakes using GLWD data northward of 45° N overlaying permafrost zones (continuous, discontinuous, sporadic and isolated) depicted by colour. Lakes are particularly abundant in North Siberia and on the Canadian Shield.

point-source bubbling. To determine whether or not such emissions are of sufficient magnitude to be included as important sources in the global atmospheric CH_4 budget, we applied the average CH_4 point-source emission measured across the non-thermokarst lake types (17.9 ± 12.1 g CH_4 m^{-2} yr^{-1}) to the area of lakes north of 45° N (table 1) except in thermokarst lakes of the Russian zone of continuous permafrost, where we applied CH_4 emission estimates from detailed field-based measurements of Siberian thermokarst lakes (34.5 ± 9.5 g CH_4 m^{-2} yr^{-1}; Walter *et al.* 2006). We calculated the area of Russian thermokarst lakes based on Geographical Information System (GIS) analyses showing that 65.5% of lakes north of the Arctic Circle occur in Russia (Holmes & Lammers 2006) and estimate (Mostakhov 1973) that 90% of Russian lakes in the permafrost zone are thermokarst lakes. We excluded all large lakes (more than 50 km^2) from our estimate owing to the possibility of low rates of point-source ebullition (table 2). Altogether, we estimate point-source ebullition from northern lakes to be approximately 24.2 ± 10.5 Tg CH_4 yr^{-1} (table 1). In contrast, the diffusive flux is 1.1 ± 0.2 Tg CH_4 yr^{-1} assuming a constant flux for all lake area (1.0 ± 0.2 g CH_4 m^{-2} d^{-1}), which is the average diffusive flux measured for glacial lakes on the north slope of Alaska's Brooks Range (Kling *et al.* 1992) and for Siberian thermokarst lakes (Walter *et al.* 2006), assuming 120 days of open water annually (Walter *et al.* 2006).

Table 1. Estimating CH_4 emissions from northern lakes based on GIS calculations of lake area in permafrost-dominated and permafrost-free regions for the (*a*) present day and for future scenarios where (*b*) transitional permafrost disappears (scenario 1) and where (*c*) surface permafrost disappears altogether (scenario 2).

current permafrost-land classification	GLWD lake area[a] (km^2)	corrected lake area (10^3 km^2)	lake ebullition (Tg CH_4 yr^{-1})	diffusion (Tg CH_4 yr^{-1})
(*a*) present day Northern Hemisphere				
continuous	213 300	427	11.8±2.1	0.43±0.09
discontinuous	61 000	122	2.2±1.5	0.12±0.02
sporadic	67 400	135	2.4±1.6	0.13±0.03
isolated	54 500	109	2.0±1.3	0.11±0.02
all permafrost	396 200	792	18.4±6.5	0.79±0.15
all non-permafrost	164 000	328	5.9±4.0	0.33±0.07
total land	560 200	1120	24.2±10.5	1.12±0.22
percent loss	—	—	—	—
(*b*) future scenario 1 (transitional)				
continuous	234 400	469	13.0±5.0	0.47±0.09
discontinuous	23 500	47	0.8±0.6	0.05±0.01
sporadic	25 100	50	0.9±0.6	0.05±0.01
isolated	23 000	46	0.8±0.6	0.05±0.01
all permafrost	306 000	612	15.5±6.7	0.61±0.12
all non-permafrost	164 000	328	5.9±4.0	0.33±0.07
total land	470 000	940	21.4±10.7	0.94±0.19
percent loss	—	16%	12%	16%
(*c*) future scenario 2 (permafrost-free)				
continuous	80 500	161	2.9±1.9	0.16±0.03
discontinuous	23 500	47	0.8±0.6	0.05±0.01
sporadic	25 100	50	0.9±0.6	0.05±0.01
isolated	22 300	46	0.8±0.6	0.05±0.01
all permafrost	152 100	304	5.4±3.7	0.30±0.06
all non-permafrost	164 000	328	5.9±4.0	0.33±0.07
total land	316 100	632	11.3±7.7	0.63±0.13
percent loss	—	44%	53%	44%

[a] Area of lakes according to GIS analysis of Smith *et al.* (in press) using the finest resolution of the Global Lake and Wetlands Database (GLWD, Level 2, a global archive of lakes with surface area between 0.1 and 50 km^2; Lehner & Doll 2004). We applied a 50% correction factor because although the GLWD is the best pan-arctic coverage that we know of, it significantly underestimates lake numbers and area (Frey & Smith 2007). Comparison with finer resolution ASTER data revealed that approximately 50% of the lakes in the Kolyma study region of Walter *et al.* in North Siberia, including many small lakes, were also not captured by the GLWD (figure 5). Similarly, Grosse *et al.* (2005) studied lake distribution on the Bykovsky Peninsula in North Siberia and found that the majority of lakes were smaller than 0.1 km^2, the smallest lake size in the GLWD, and many of the lakes were thermokarst lakes. This is a conservative correction factor for CH_4 emissions because small lakes, with lower area: perimeter ratios, are expected to have higher CH_4 emissions on an aerial basis compared with large lakes because they have more influence of shoreline processes such as thermokarst erosion and macrophyte production, processes that enhance CH_4 production and emission.

Our estimates of the ebullition flux from northern lakes are conservative for several reasons. (i) Although thermokarst lakes are common in the discontinuous permafrost zone of Russia as well as in North America and Europe, their areal

Table 2. Estimating CH_4 emissions from northern lakes and global lakes in the context of the global atmospheric CH_4 budget.

region	lake size	no. lakes GLWD	lake area[a] GLWD (km^2)	corrected lake area (10^3 km^2)	lake ebullition (Tg CH_4 yr^{-1})	percent of global CH_4 emissions[b]
Northern Hemisphere lakes	small (0.1 to 50 km^2)	78 900	533 205	1066	24.2 ± 10.5	up to 6%
	large ($>$50 km^2)	21 310	61 025	122	—	
global lakes	small (0.1 to 50 km^2)	243 068	743 028	1486	31.7 ± 15.6	up to 8%
	large ($>$50 km^2)	3067	1 684 639	3369	—	

[a] Small lake area of GLWD was doubled in calculation of CH_4 emission based on our observations that this course-resolution database underestimates lake area by approximately 50%, excluding many smaller lakes. Our estimate of lake CH_4 ebullition excludes emissions from large lakes (more than 50 km^2) owing to the possibility that large, deep lakes may not exhibit significant CH_4 bubbling. No point-source ebullition sampling was conducted in large lakes. Bubbling has been observed to occur in shallow parts of other lakes more often than the deep centres of lakes (Walter *et al.* 2006). Furthermore, at water depths greater than 100 m, which is admittedly rare for lakes, bubbles dissolve before they reach the lake surface (Guinasso & Schink 1973), and in oxygenated water columns much of dissolved CH_4 is oxidized to CO_2 (Happell *et al.* 1994). [b] Based on global emission estimate 600 Tg CH_4 yr^{-1} (IPCC 2001).

extent is unknown; therefore, we assigned the lower, non-thermokarst lake CH_4-emission value to all lakes in these regions in our calculations. (ii) Preliminary measurements in several boreal thermokarst ponds in Alaska suggest that fluxes from thermokarst lakes and ponds could be higher than we assume in our calculations. For example, the point-source ebullition from a boreal thermokarst pond in Alaska was 5.6-fold higher (195 ± 8 g CH_4 m^{-2} yr^{-1}) than the thermokarst-lake emission value used in our calculation (34.5 ± 9.5 g CH_4 m^{-2} yr^{-1}; Walter *et al.* submitted). (iii) The fine-scale lake database from which we estimated lake area, which is the best available (Lehner & Doll 2004), excludes lakes smaller than 0.1 km^2 and therefore significantly underestimates thermokarst-lake numbers and area (Frey & Smith 2007; our observation figure 5). These small lakes are particularly important contributors to CH_4 ebullition because they are the most numerous lakes in North Siberia (Grosse *et al.* 2005). In addition, small lakes have the largest fluxes per unit area because their low area: perimeter ratio causes lake-margin carbon inputs (thermokarst erosion and aquatic plant production) to be relatively more influential. (iv) On several occasions, we observed pulses of CH_4 release that were large enough to lift thick carpets of lake-bottom peat to the surface for several days (observed twice) or to produce violent eruptions of CH_4 along lake margins lasting seconds to tens of seconds (Walter *et al.* 2006). These large CH_4 release events occurred too infrequently to measure. All these sources of uncertainty suggest that there is still much to learn about CH_4 emission from northern lakes and that future research is likely to increase the magnitude of our current estimate of CH_4 flux. Improved information on different lake types and sizes could be particularly important. Synthetic Aperture Radar (SAR), which provides a remote-sensing signal of CH_4 bubbles in lake ice, may provide a new tool for upscaling field measurements of CH_4 ebullition to the pan-arctic scale (Walter *et al.* in press *b*).

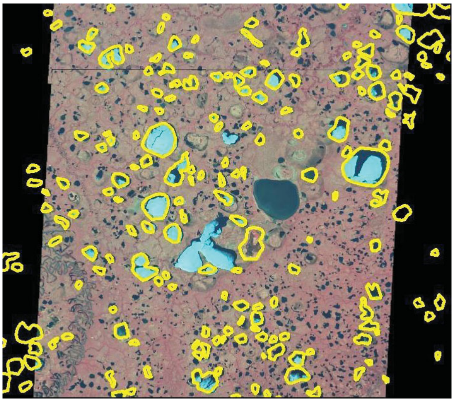

Figure 5. Quantifying lake area at the pan-arctic scale using the Global Lakes and Wetlands Database (Lehner & Doll 2004) with applied correction factor from ASTER data analysis. Though it is the best pan-arctic GIS lake coverage we know of, the Global Lake and Wetlands Database (bright lake perimeters) significantly underestimated lake area for the Kolyma region of northeastern Siberia. Comparison with finer resolution ASTER data revealed that many small lakes were not captured by the GLWD.

Ebullition also occurs in low-latitude lakes, reservoirs, rivers and wetlands, particularly where there are large organic matter inputs to sediments (Rudd *et al.* 1993; Keller & Stallard 1994; Casper *et al.* 2000; St Louis *et al.* 2000). Ebullition rates could be higher in low-latitude lakes than in the Arctic because higher sediment temperatures should speed methanogenesis (Valentine *et al.* 1994; Galy-Lacaux *et al.* 1999; St Louis *et al.* 2000) and make CH_4 less soluble (Yamamoto *et al.* 1976; Fearnside 2004), forming bubbles more readily in sediments. Nonetheless, if we apply the conservative non-thermokarst lake point-source ebullition rate to low-latitude lakes, where point-source ebullition has not been specifically quantified ($1.5\times10^6\ \mathrm{km}^2$), then ebullition emissions of small lakes (0.1–$50\ \mathrm{km}^2$) globally would be approximately 31.7 ± 15.6 Tg CH_4 yr^{-1} or up to 8% of global emissions (table 2).

4. Siberian thermokarst: a time bomb for future CH_4 emissions?

Northern lakes are not only important sources of atmospheric CH_4 today, but their importance will increase as climate change proceeds. Northern Hemisphere permafrost contains approximately 950 Gt of C (Zimov *et al.* 2006), an amount that would more than double the current atmospheric CO_2 concentration if oxidized upon thaw under aerobic conditions. Roughly half of this C is contained in the yedoma ice complex of North Siberia, whose extent is $10^6\ \mathrm{km}^2$ (Zimov *et al.* 2006), only 7.6% of permafrost area and 3.7% of the land surface area north of 45° N. The yedoma ice complex formed in the Late Pleistocene primarily on the extensive unglaciated lowlands of Siberia is unique among permafrost substrates given its high ice-wedge content (50% by volume) and large pool of labile organic matter (Zimov *et al.* 2006; figure 1*f*). Laboratory incubations and field studies revealed that the C in yedoma is extremely labile, and if thawed under aerobic conditions it is nearly 100% mineralized within a century (Dutta *et al.* 2006;

Zimov *et al.* 2006). Analyses of permafrost degradation in this ice complex revealed that since the Last Glacial Maximum roughly half of yedoma has thawed, mostly under inundated, anaerobic conditions either by coastal erosion associated with sea-level rise (Romanovskii *et al.* 2000) or by inland thermokarst-lake formation and expansion (Czudek & Demek 1970). Under anaerobic conditions, CH_4, whose relative greenhouse effect is 23 times greater than that of CO_2, is produced in equal proportion to CO_2 (Conrad *et al.* 2002). Since the mean annual temperature of lake water exceeds that of surrounding permafrost, thermal erosion of permafrost occurs along lake margins and at the edges of thaw bulbs beneath lakes. Given the high ice content of yedoma, melting ice causes the ground surface to collapse, releasing previously frozen organic C stored in yedoma to microbial decomposition in the lake bottoms. This process, called 'thermokarst', continuously exposes new frozen surfaces to thermal erosion, particularly during periods of high summer insolation or years of high precipitation (Bosikov 1991). In large lakes, wave-driven erosion enhances thermokarst along lake margins and, together with thermal erosion (Carson & Hussey 1962; Czudek & Demek 1970), constitutes the mechanism by which thermokarst lakes migrate and degrade ice-rich permafrost.

Using patterns of thermokarst-lake development throughout the Holocene and a C-mass balance calculation based on the amount of C decomposed in yedoma beneath lakes, we predict here the magnitude of CH_4 that may escape from lakes to the atmosphere in the future if yedoma thaws completely. Today yedoma contains approximately 450 Gt of C (Zimov *et al.* 2006), of which approximately 269 Gt C are contained in yedoma that has remained frozen since the Pleistocene. We assume that 50% of the 269 Gt of C will be exposed to anaerobic decomposition conditions beneath lakes in the future as permafrost thaws, consistent with the pattern of lake development throughout the Holocene evidenced by lake scars that cover 50% of the yedoma region (Czudek & Demek 1970; Walter *et al.* 2006; Zimov *et al.* 2006). Measurements of the C content of samples collected from exposures of yedoma frozen since the Pleistocene and from cross-sections of the refrozen thaw bulbs of former lakes exposed along the cut banks of Siberian rivers revealed that 33% of the C stored in yedoma is decomposed beneath lakes under anaerobic conditions (Kholodov *et al.* 2003; Walter *et al.* 2006; Zimov *et al.* 2006). Applying a 16.5% conversion factor of yedoma C to CH_4 in accordance with the stoichiometry of methanogenesis whereby CO_2 and CH_4 are produced in equal proportions (Conrad *et al.* 2002), 135 Gt of C from yedoma that has remained frozen since the Pleistocene would be converted to CH_4 as yedoma warms and thaws in the future. This is equivalent to approximately 30 000 Tg of CH_4. This estimate does not include CH_4 that would also be produced from thermokarst lakes that form in the basins of relict drained lakes, a source which has not yet been quantified, but which we expect would further increase regional lake emissions. We can, however, estimate additional CH_4 emissions associated with CH_4 that would be produced from allochthonous and autochthonous organic matter sources other than yedoma permafrost. Radiocarbon analysis of CH_4 emitted from modern thermokarst lakes in the yedoma region of Siberia revealed that approximately 60% of CH_4 emitted from lakes today is fuelled by Pleistocene-aged organic C, while decomposition of contemporary organic detritus contributes to the remaining lake-CH_4 emissions (Walter *et al.* 2006). If this pattern holds in the future, then we could expect a total of approximately 49 000 Tg of CH_4 to be emitted from lakes fuelled by both permafrost and contemporary C sources if yedoma warms and thaws as predicted (ACIA 2004; Sazonova *et al.* 2004).

Variability in global climate models gives rise to uncertainties in predicting rates of yedoma degradation and thermokarst lake expansion; however, the mean annual temperature of Siberian permafrost increased up to 3°C during recent decades (Romanovsky *et al.* 2001; Sazonova *et al.* 2004) and is predicted to continue warming and thawing during this century (Romanovsky *et al.* 2001; ACIA 2004; Sazonova *et al.* 2004; Lawrence & Slater 2005). In the discontinuous permafrost zone in Alaska, permafrost temperatures are within 1°C of thawing (Osterkamp & Romanovsky 1999). Thus, the large pool of still-frozen Pleistocene-age C in Siberia can be considered a potential CH_4 time bomb, with sufficient C stores that thermokarst lake development would release approximately 10 times the current atmospheric CH_4 burden (4850 Tg CH_4, IPCC) by bubbling at some (as yet unknown) rate as the zero degree temperature threshold of yedoma is crossed. If this CH_4 were to be released during the next 500–1000 years, then average CH_4 emissions rates from lakes would be approximately 50–100 Tg $CH_4\,yr^{-1}$, rates that are approximately 8–50% of those predicted for global anthropogenic CH_4 emissions under different scenarios of global warming by 2100 (236–597 Tg $CH_4\,yr^{-1}$, IPCC SRES Emissions Scenarios 2000; mean, 184 Tg $CH_4\,yr^{-1}$, de la Chesnaye & Weyant 2006). Our estimates of CH_4 emission from future yedoma thermokarst lakes also do not include degradation of permafrost in the remainder of the Northern Hemisphere. Another approximately 450 Gt of C is thought to reside in surface permafrost of other northern terrestrial soils (ACIA 2004; Smith *et al.* 2004), and thermokarst lakes in these regions will also be important sources of CH_4 to the atmosphere.

5. Future of northern lake emissions in a permafrost-free Arctic

Widespread permafrost warming and degradation are projected to intensify during the twenty-first century (ACIA 2004). Permafrost in the interior of Alaska has already warmed by 1.5°C since the 1980s (Osterkamp & Romanovsky 1999; Osterkamp 2003), and temperatures in boreholes on the north slope of Alaska rose by 2–4°C during the past 50–100 years (Lachenbruch & Marshall 1986). Warm temperatures from 1989 to 1998 led to the thaw of massive ice wedges that had been stable for thousands of years in northern Alaska (Jorgenson *et al.* 2006). The occurrence of thermokarst ponds and depressions has long been observed in association with permafrost degradation in Alaska and Canada (Sellmann *et al.* 1975; Burn & Smith 1990; Jorgenson *et al.* 2001) as well as in Mongolia (Sharkuu 1998), China (Ding 1998) and Russia (Czudek & Demek 1970; Bosikov 1991; Pavlov 1994). More recently, studies have documented changes in lake area occurring during the past half century associated with permafrost degradation (Yoshikawa & Hinzman 2003; Smith *et al.* 2005; Riordan *et al.* 2006; Walter *et al.* 2006). Other factors suggested to influence lake area dynamics in association with permafrost thaw are climatic changes ($P-E$, Riordan *et al.* 2006); wildfires, which lower albedo and increase soil thermal conductivity and ground heat flux (Chambers & Chapin 2002; Yoshikawa *et al.*

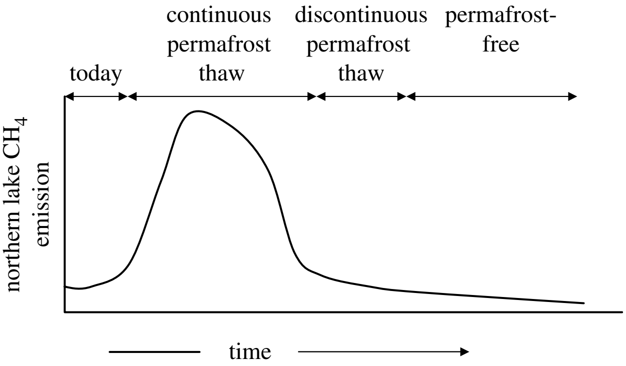

Figure 6. Schematic depicting future of CH_4 emissions from northern lakes as the north changes from a permafrost-rich landscape to a landscape free of surface permafrost. A large release of CH_4 is anticipated in association with thermokarst lake degradation of permafrost in the zone of continuous permafrost, particularly in the region of Siberian yedoma permafrost. As permafrost degradation proceeds, eventually there will be a loss of lake area and thermokarst lakes. In the long-term permafrost-free north, a net loss in lake area is estimated to result in a decrease in northern lake CH_4 emissions.

2003); and the interaction between surface and groundwater, particularly when permafrost degradation leads to open thaw bulbs beneath lakes (Kane & Slaughter 1973; Yoshikawa & Hinzman 2003). In areas of discontinuous permafrost, remote-sensing studies revealed a decrease in lake area (Yoshikawa & Hinzman 2003; Riordan 2006), while areas in continuous permafrost have seen a net increase in lakes (Smith *et al.* 2005; Walter *et al.* 2006) and water-filled pits (Jorgenson *et al.* 2006) or no change in lake area (Riordan *et al.* 2006). Despite the observed changes in particular regions of Siberia and Alaska, Smith *et al.* (in press) found surprisingly little difference in the abundance of lakes at the pan-arctic scale between the different zones of continuous, discontinuous, sporadic and isolated permafrost. It was the lack of permafrost altogether that had the greatest effect (decrease) on lake abundance, even in the previously glaciated regions where, over large spatial scales, the prevalence of lakes decreases by approximately a factor of two in the absence of permafrost (Smith *et al.* in press).

Given that lakes are net emitters of CH_4, the fate of lakes in the north is an important question to be reconciled in models of climate change. In the short term, permafrost degradation through thermokarst-lake formation and expansion, particularly in the zone of continuous permafrost, is expected to release a large amount of CH_4 as explained above. However, widespread loss of lakes over the long term as surface permafrost disappears (Smith *et al.* in press) should cause a corresponding reduction in Northern Hemisphere CH_4 emissions (figure 6), particularly if lakes are replaced by aerobic, non-wetland ecosystems. If permafrost degradation and lake area loss cause wetland area to increase, changes in regional CH_4 emissions may be offset by emissions from wetlands (Vourlitis & Oechel 1997; Friborg *et al.* 2003; Christensen *et al.* 2004).

To what extent might lakes disappear and what will be the effect on atmospheric CH_4? To address this question, we used the ‘space-for-time’ substitution of lake area and lake area fraction (L_f) for two future scenarios of permafrost degradation after Smith *et al.* (in press; table 1), applying the 50%

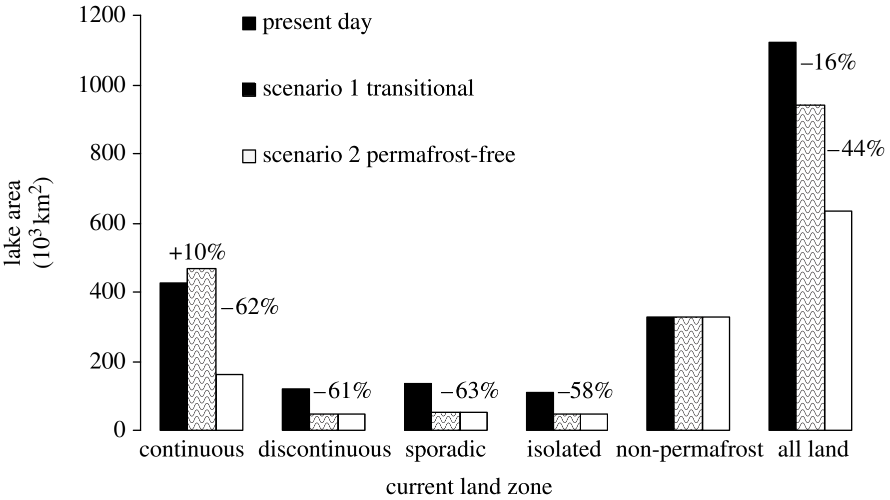

Figure 7. Changes in northern lake area predicted for future scenarios in which transitional permafrost disappears (scenario 1) and surface permafrost altogether disappears (scenario 2) based on a space-for-time substitution of lake area fractions from current permafrost-free land surfaces to current permafrost-dominated land areas. Corrected lake area values (*y*-axis) were calculated from the GIS estimates of GLWD lakes by Smith *et al.* (in press).

correction factor for small lakes missed in the GLWD (figure 5). In a more probable transitional scenario (scenario 1), areas that are today transitional permafrost (discontinuous, sporadic and isolated) become permafrost free, while the prevalence of lakes increases by 10% in the area that is currently continuous permafrost, roughly doubling the lake area increase observed in the region of continuous permafrost in Siberia since 1973 (Smith *et al.* 2005, in press). To estimate changes in lake area in scenario 1, we replaced the lake area fraction (L_f=total lake area/total land area×100) attributed to transitional zones of permafrost (discontinuous $L_\mathrm{f}=6.02$; sporadic $L_\mathrm{f}=6.24$, and isolated $L_\mathrm{f}=5.50$) with the area of lakes characteristic of modern permafrost-free landscapes ($L_\mathrm{f}=2.32$). The result was a 58–63% loss in lake area depending on the permafrost zone (figure 7). The lake area fraction in the zone of current continuous permafrost ($L_\mathrm{f}=6.14$) was increased by 10% to $L_\mathrm{f}=6.75$. In the more extreme scenario (permafrost-free, scenario 2), replacing the area of lakes attributed to each of the currently permafrost-dominated regions with the area of lakes characteristic of permafrost-free landscapes, we found a 58–63% loss in lake area in the various permafrost zones (figure 7). The area of lakes in the current permafrost-free zone remains the same in both future scenarios. As a result, if permafrost thaws according to scenarios 1 and 2 then the land north of 45° N would experience a net lake area loss of 16% (scenario 1) and eventually 44% (scenario 2) compared with today (figure 7). Applying CH_4 ebullition rates associated with non-thermokarst lakes to all lakes in the transitional and permafrost-free scenarios, except Russian thermokarst lakes in the continuous permafrost zone in scenario 1, resulted in a net 12 and 53% decline in CH_4 ebullition emissions from northern lakes, respectively (21.4 ± 10.7 Tg CH_4 yr^{-1} transitional scenario; 11.3 ± 7.7 Tg CH_4 yr^{-1} permafrost-free scenario), compared with the estimate of modern emissions (24.2±10.6 Tg CH_4 yr^{-1}; table 1). Predicted changes in diffusive emission estimates are also shown in table 1, but are significantly lower than the dominant mode of ebullition emission. This approach provides a rough estimate of changes in lake area and CH_4 emissions associated with potential future disappearance of surface permafrost.

6. Conclusion

In northern high latitudes, where the concentration of atmospheric CH_4 is highest and where much of atmospheric CH_4 originates (Steele *et al.* 1987; Fung *et al.* 1991), lakes are a dominant landscape feature occupying as much as 48% of the land surface in some regions (Riordan *et al.* 2006). Lakes are important emitters of CH_4, particularly when attention is paid to ebullition (Hamilton *et al.* 1994; Keller & Stallard 1994; Zimov *et al.* 1997; Walter *et al.* 2006). However, the role of lakes in the atmospheric CH_4 budget had not previously been assessed. The abundance of lakes in the north appears to be governed in part by the presence or absence of permafrost (Yoshikawa & Hinzman 2003; Smith *et al.* 2005, in press). Landscape processes such as permafrost degradation and thermokarst erosion are known to enhance CH_4 production and emissions from expanding thermokarst lakes in permafrost regions (Zimov *et al.* 1997; Walter *et al.* 2006). In this study, we extrapolated measurements of point-source ebullition from 16 lakes representing common northern lake types to the extent of current lake distributions in regions with and without permafrost to estimate total northern lake CH_4 emissions (approx. 24.2±10.5 Tg CH_4 yr^{-1}).

Rather than attempting to provide a precise estimate of lake CH_4 emissions, we sought to demonstrate that ebullition from lakes may be a much larger and globally significant source of atmospheric CH_4 than that previously thought because (i) point-source ebullition is a dominant (and previously unrecognized) source of CH_4 emissions from lakes, and (ii) lakes are a prominent landscape feature in the north that convert organic C sequestered for hundreds to thousands of years in permafrost into the radiatively important CH_4 in the atmosphere. Our calculations suggest that tens of thousands of teragrams of CH_4 will be released from thermokarst lakes as permafrost warms and thaws in the future, but that, eventually, disappearance of permafrost altogether will result in a net, approximately 50%, loss of lake area and associated CH_4 emissions from lakes. These estimates can be refined by research that accounts for variability in CH_4 emissions from different types of northern lakes and lake regions. The estimates presented here are conservative in that they do not account for the many high-emission thermokarst lakes in North America, Europe and the discontinuous permafrost zone of Russia. The magnitude of both current and future emission estimates from northern lakes is large and should be accounted for in models of atmospheric CH_4 dynamics and ecosystem feedbacks to climate change.

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References

ACIA 2004 *Impacts of a warming climate—arctic climate impact assessment*, p. 140. Cambridge, UK: Cambridge University Press.

Aselmann, I. & Crutzen, P. J. 1989 Global distribution of natural freshwater wetlands, rice paddies, their net primary productivity, seasonality, and possible methane emissions. *J. Atmos. Chem.* **8**, 307–358. (doi:10.1007/BF00052709)

Bartlett, K. B., Crill, P. M., Sebacher, D. I., Harriss, R. C., Wilson, J. O. & Melack, J. M. 1988 Methane flux from the Central Amazonian Floodplain. *J. Geophys. Res.* **93**, 1571–1582.

Bastviken, D., Cole, J., Pace, M. & Tranvik, L. 2004 Methane emissions from lakes: dependence of lake characteristics, two regional assessments, and a global estimate. *Global Biogeochem. Cycles* **18**, GB4009. (doi:10.1029/2004GB002238)

Bosikov, N. P. 1991 *Evolutsia alasov tsentralnoi Jaukutii*, p. 128. Yakutsk, USSR: IMZ CO AN USSR.

Bosquet, P. *et al.* 2006 Contribution of anthropogenic and natural sources to atmospheric methane variability. *Nature* **443**, 439–443. (doi:10.1038/nature05132)

Brook, E. J., Harder, S., Severinghaus, J., Steig, E. J. & Sucher, C. M. 2000 On the origin and timing of rapid changes in atmospheric methane during the last glacial period. *Global Biogeochem. Cycles* **14**, 559–572. (doi:10.1029/1999GB001182)

Brown, J., Ferrians, O. J., Heginbottom, J. A. & Melnikov, E. S. 1997 (revised 2001) *Circum-arctic map of permafrost and ground ice conditions.* Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. Digital Media.

Burn, C. R. & Smith, M. W. 1990 Development of thermokarst lakes during the Holocene at sites near Mayo, Yukon Territories. *Permafrost Periglac. Process* **1**, 161–175. (doi:10.1002/ppp.3430010207)

Carson, C. E. & Hussey, K. M. 1962 The oriented lakes of Arctic Alaska. *J. Geol.* **70**, 417–439.

Casper, P., Maberly, S. C., Hall, G. H. & Finlay, B. J. 2000 Fluxes of methane and carbon dioxide from a small productive lake to the atmosphere. *Biogeochemistry* **49**, 1–19. (doi:10.1023/A:1006269900174)

Chambers, S. & Chapin III, F. S. 2002 Fire effects on surface atmosphere energy exchange in Alaskan black spruce ecosystems: implications for feedbacks to regional climate. *J. Geophys. Res.* **107**, 8145. (doi:10.1029/2001JD000530)

Chen, Y.-H. & Prinn, R. G. 2006 Estimation of atmospheric methane emission between 1996 and 2001 using a three-dimensional global chemical transport model. *J. Geophys. Res.* **111**, D10307. (doi:10.1029/2005JD006058)

Christensen, T. R., Johansson, T., Akerman, H. J., Mastepanov, M., Malmer, N., Friborg, T., Crill, P. & Svensson, B. H. 2004 Thawing sub-arctic permafrost: effects on vegetation and methane emissions. *Geophys. Res. Lett.* **31**, L04501. (doi:10.1029/2003GL018680)

Conrad, R., Klose, M. & Clause, P. 2002 Pathway of CH_4 formation in anoxic rice field soil and rice roots determined by 13C-stable isotope fractionation. *Chemosphere* **47**, 797–806. (doi:10.1016/S0045-6535(02)00120-0)

Czudek, T. & Demek, J. 1970 Thermokarst in Siberia and its influence on the development of lowland relief. *Q. Res.* **1**, 103–120. (doi:10.1016/0033-5894(70)90013-X)

Dallenbach, A., Blunier, T., Fluckiger, J. & Stauffer, B. 2000 Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the Last Glacial and the transition to the Holocene. *Geophys. Res. Lett.* **27**, 1005–1008. (doi:10.1029/1999GL010873)

de la Chesnaye, F. C. & Weyant J. P. (eds) 2006 Multigas mitigation and climate policy. The energy Journal Special Issue. See http://www.iaee.org/en/publications/journal.aspx. Energy Modeling Forum, Working Group 21 (EMF-21) on Multigas Mitigation and Climate Policy.

Ding, Y. 1998 Recent degradation of permafrost in China and response to climatic warming. In *Proc. Int. Conf. on Permafrost, 2–5 August 1998, Yellowknife, Canada, Universte Laval, Quebec, Collection Nordiana*, vol. 57 (eds A. G. Lewkowicz & M. Allard), pp. 225–231.

Dlugokencky, E. J., Walter, B. P., Masarie, K. A., Lang, P. M. & Kasischke, E. S. 2001 Measurements of an anomalous global methane increase during 1998. *Geophys. Res. Lett.* **28**, 499–502. (doi:10.1029/2000GL012119)

Dlugokencky, E. J., Houweling, S., Bruhwiler, L., Masarie, K. A., Lang, P. M., Miller, J. B. & Tans, P. P. 2003 Atmospheric methane levels off: temporary pause or a new steady-state? *Geophys. Res. Lett.* **30**. (1992 doi:1029/2003GL018126).

Dutta, K., Schuur, E. A. S., Neff, J. C. & Zimov, S. A. 2006 Potential carbon release from permafrost soils of Northeastern Siberia. *Global Change Biol.* **12**, 2336–2351. (doi:10.1111/j.1365-2486.2006.01259.x)

Fallon, R. D., Harris, S., Hanson, R. S. & Brock, T. D. 1980 The role of methane in internal carbon cycling in Lake Mendota during summer stratification. *Limnol. Oceanogr.* **25**, 357–360.

Fearnside, P. M. 2004 Greenhouse gas emissions from hydroelectric dams: controversies provide a springboard for rethinking a supposedly 'clean' energy source. *Clim. Change* **66**, 1–8. (doi:10.1023/B:CLIM.0000043174.02841.23)

Frey, E. F. & Smith, L. C. 2007 How well do we know northern land cover? Comparison of four global vegetation and land cover products with new ground-truth database for West Siberia. *Global Biogeochem. Cycles* **21**, GB1016. (doi:10.1029/2006GB002706)

Friborg, T., Soegaard, H., Christensen, T. R., Lloyd, C. R. & Panikov, N. S. 2003 Siberian wetlands: where a sink is a source. *Geophys. Res. Lett.* **30**, 2129. (doi:10.1029/2003GL017797)

Fung, I., John, J., Lerner, J., Mathews, E., Prather, M., Steele, L. P. & Fraser, P. J. 1991 Three-dimensional model synthesis of the global methane cycle. *J. Geophys. Res.* **96**, 13 033–13 065.

Galy-Lacaux, C., Delmas, R., Kouadio, G., Richard, S. & Gosse, P. 1999 Long-term greenhouse gas emission from hydroelectric reservoirs in tropical forest regions. *Global Biogeochem. Cycles* **13**, 503–517. (doi:10.1029/1998GB900015)

Grant, R. F. & Roulet, N. T. 2002 Methane efflux from boreal wetlands: theory and testing of the ecosystem model ecosys with chamber and tower flux measurements. *Global Biogeochem. Cycles* **16**, 1054. (doi:10.1029/2001GB001702)

Grosse, G., Shirrmeister, L., Kunitsky, V. V. & Hubberten, H.-W. 2005 The use of CORONA images in remote sensing of periglacial geomorphology: an illustration from the NE Siberian Coast. *Permafrost Periglac. Process* **16**, 163–172. (doi:10.1002/ppp.509)

Guinasso, N. L. & Schink D. R. 1973 A simple physicochemical acoustic model of methane bubbles rising in the sea. Report reference 73-15-T. College of Geosciences, Texas A & M University.

Hamilton, D. J., Kelly, C. A., Rudd, J. W. M., Hesslein, R. H. & Roulet, N. T. 1994 Flux to the atmosphere of CH_4 and CO_2 from wetland ponds on the Hudson Bay Lowlands (HBLs). *J. Geophys. Res.* **99**, 1495–1510. (doi:10.1029/93JD03020)

Happell, J., Chanton, J. P. & Showers, W. 1994 The influence of methane oxidation on the stable isotope composition of methane emitted from Florida Swamp forests. *Geochemica et Cosmochimica Acta* **58**, 4377–4388. (doi:10.1016/0016-7037(94)90341-7)

Hinkel, K. M., Eisner, W. R., Bockheim, J. G., Nelson, F. E., Peterson, K. M. & Dai, X. 2003 Spatial extent, age, and carbon stocks in drained Thaw Lake Basins on the Barrow Peninsula, Alaska. *Arctic Antarct. Alpine Res.* **35**, 291–300. (doi:10.1657/1523-0430(2003)035[0291:SEAACS]2.0.CO;2)

Hinzman, L. D. *et al.* 2005 Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Clim. Change* **72**, 251–298. (doi:10.1007/s10584-005-5352-2)

Holmes, R. M. & Lammers, R. 2006 The arctic system and global change: why bother with Russia. In *Proc. Workshop on Facilitating U.S.–Russian Environmental Change Research in the Russian Arctic, St. Thomas, U.S. Virgin Islands, June 11–16 2005*. See http://arctic.bio.utk.edu/RAISE/index.html.

Intergovernmental Panel on Climate Change (IPCC) 2001 *The scientific basis*. New York. NY: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC) Forthcoming. Fourth Assessment Report.

IPCC SRES Emissions Scenarios 2000 *Special report of the Intergovernmental Panel on Climate Change*. IPCC SRES Emissions Scenarios—Version 1.1 (eds N. Nakicenovic & R. Swart). Cambridge, UK: Cambridge University Press.

Jorgenson, M. T. & Osterkamp, T. E. 2005 Response of boreal ecosystems to varying modes of permafrost degradation. *Can. J. Forest Res.* **35**, 2100–2111. (doi:10.1139/x05-153)

Jorgenson, M. T., Racine, C. H., Walters, J. C. & Osterkamp, T. E. 2001 Permafrost degradation and ecological changes associated with a warming climate in central Alaska. *Clim. change* **48**, 551–579.

Jorgenson, M. T., Shur, Y. L. & Pullman, E. R. 2006 Abrupt increase in permafrost degradation in Arctic Alaska. *Geophys. Res. Lett.* **33**, L02503. (doi:10.1029/2005GL024960)

Kane, D. L. & Slaughter, C. W. 1973 Recharge of a central Alaska lake by subpermafrost groundwater. In: *Permafrost: Proceedings of the 2nd International Conference*, Yakutsk, North American Contribution (eds T. L. Pewe & J. R. MacKay), pp. 458–462. Washington, DC: National Academy of Sciences.

Keller, M. & Stallard, R. F. 1994 Methane emission by bubbling from Gatun Lake, Panama. *J. Geophys. Res.* **99**, 8307–8319. (doi:10.1029/92JD02170)

Keppler, F., Hamilton, J. T. G., Braß, M. & Rockmann, T. 2006 Methane emissions from terrestrial plants under aerobic conditions. *Nature* **439**, 187–191. (doi:10.1038/nature04420)

Kholodov, A. L., Rivkina, E. M., Gilichinsky, D. A., Fyodorov-Davydov, D. G., Gubin, S. V., Sorokovikov, V. A., Ostroumov, V. E. & Maksimovich, S. V. 2003 Estimation of the organic carbon input into Arctic ocean due to erosion of the East-Siberian seashore. *Kriosphera Zemli* **VII**, 3–12. [In Russian]

Klein, E., Berg, E. E. & Dial, R. 2005 Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska. *Can. J. For. Res.* **35**, 1931–1941. (doi:10.1139/x05-129)

Kling, G., Kipphut, G. W. & Miller, M. C. 1992 The flux of CO_2 and CH_4 from lakes and rivers in arctic Alaska. *Hydrobiologia* **240**, 23–36.

Lachenbruch, A. H. & Marshall, B. V. 1986 Changing climate: geothermal evidence from permafrost in the Alaskan Arctic. *Science* **234**, 689–696. (doi:10.1126/science.234.4777.689)

Lawrence, D. M. & Slater, A. G. 2005 A projection of severe near-surface permafrost degradation during the 21st century. *Geophys. Res. Lett.* **32**, L24401. (doi:10.1029/2005GL025080)

Lehner, B. & Doll, P. 2004 Development and validation of a global database of lakes, reservoirs and wetlands. *J. Hydrol.* **296**, 1–22. (doi:10.1016/j.jhydrol.2004.03.028)

MacDonald, G. M., Bielman, D. W., Kremenetski, K. V., Sheng, Y., Smith, L. C. & Velichko, A. A. 2006 Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. *Science* **314**, 285–288. (doi:10.1126/science.1131722)

Mathews, E. & Fung, I. 1987 Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources. *Global Biogeochem. Cycles* **1**, 61–86.

Mikaloff Fletcher, S. E., Tans, P. P., Bruhwiler, L. M., Miller, J. B. & Heimann, M. 2004 CH_4 source estimated from atmospheric observations of CH_4 and its $^{13}C/^{12}C$ isotopic ratios: 1. Inverse modelling of source processes. *Global Biogeochem. Cycles* **18**, GB4004. (doi:10.1029/2004GB002223)

Mostakhov, S. E. 1973 Ozernost' crioolitozony SSSR. In *Mezhdunarodnaia conferentsiia po merzlotovedeniiu, Podzemnye vody kriolitosfery* (ed. N. I. Tolstikhin), pp. 118–120. Iakutsk, Russia: Iakustkoe Knizhnoe Izdeatel'stvo.

Naiman, R. J., Manning, T. & Johnston, C. A. 1991 Beaver population fluctuations and tropospheric methane emissions in boreal wetlands. *Biogeochemistry* **12**, 1–15. (doi:10.1007/BF00002623)

Nakayama, T., Nojiri, Y. & Zeng, Y. 1994 Measurement of methane flux from alasses around Yakutsk, eastern Siberia in 1993. In *Proc. Second Symp. the Joint Siberian Permafrost Studies Between Russia and Japan in 1993* (ed. G. Inoue), pp. 40–44. Tsukuba, Japan: National Institute of Environmental Studies.

Nisbet, E. G. 1989 Some northern sources of atmospheric methane: production, history, and future implications. *Can. J. Earth Sci.* **26**, 1603–1611.

Osterkamp, T. E. 2003 A thermal history of permafrost in Alaska. In *Proc. Eight Int. Conf. on Permafrost, 21–25 July 2003*, pp. 863–868. Zurich, Switzerland: Balkema Publishers.

Osterkamp, T. E. & Romanovsky, V. E. 1999 Evidence for warming and thawing of discontinuous permafrost in Alaska. *Permafrost Periglac.* **10**, 17–37. (doi:10.1002/(SICI)1099-1530(199901/03)10:1<17::AID-PPP303>3.0.CO;2-4)

Overpeck, J. T. *et al.* 1997 Arctic and environmental change of the last four centuries. *Science* **278**, 1251–1256. (doi:10.1126/science.278.5341.1251)

Pavlov, A. V. 1994 Current changes of climate and permafrost in the Arctic and sub-Arctic of Russia. *Permafrost Periglac.* **5**, 101–110. (doi:10.1002/ppp.3430050204)

Peterson, B. J., Holmes, R. M., McClelland, J. W., Vorosmarty, C. J., Lammers, R. B., Shiklomanov, A. I. & Rahmstorf, S. 2002 Increasing river discharge to the Arctic Ocean. *Science* **298**, 2171–2173. (doi:10.1126/science.1077445)

Rasmussen, R. A. & Khalil, M. A. K. 1984 Atmospheric methane in the recent and ancient atmospheres: concentrations, trends and interhemispheric gradient. *J. Geophys. Res.* **89**, 11 599–11 605.

Ray, N. & Adams, J. M. 2001 A GIS-based vegetation map of the world at the last glacial maximum (25 000–15 000 BP). *Internet Archaeol.* 11.

Reeburgh, W. S., King, J. Y., Regli, S. K., Kling, G. W., Auerbach, N. A. & Walker, D. A. 1998 A CH_4 emission estimate for the Kuparuk River basin, Alaska. *J. Geophys. Res.* **103**, 29 005–29 013. (doi:10.1029/98JD00993)

Riordan, B., Verbyla, D. & McGuire, A. D. 2006 Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *J. Geophys. Res.* **11**, G04002. (doi:10.1029/2005JG000150)

Romanovskii, N. N., Hubbertten, H.-W., Gavrilov, A. V., Tumskoy, V. E., Tipenko, G. S., Grigoriev, M. N. & Siergert, C. 2000 Thermokarst and land–ocean interactions, Laptev Sea Region, Russia. *Permafrost Periglac.* **11**, 137–152. (doi:10.1002/1099-1530(200004/06)11:2<137::AID-PPP345>3.0.CO;2-L)

Romanovsky, V. E., Osterkamp, T. E., Sazonova, T. S., Shender, N. I. & Balobaev, V. T. 2001 Permafrost temperature dynamics along the East Siberian transect and Alaskan transect (extended abstract). *Tohoku Geophys. J. (Sci. Rep. Tohoku Univ. Ser. 5)* **36**, 224–229.

Romanovsky, V. E., Burgess, M., Smith, S., Yoshikawa, K. & Brown, J. 2002 Permafrost temperature records: indicators of climate change. *EOS* **83**, 593–594. 589

Roulet, N. T., Jano, A., Kelly, C. A., Klinger, L. F., Moore, T., Protz, R., Ritter, J. A. & Rouse, W. R. 1994 Role of Hudson Bay lowland as a source of atmospheric methane. *J. Geophys. Res.* **99**, 1439–1454. (doi:10.1029/93JD00261)

Rudd, J. W. M. & Hamilton, R. D. 1978 Methane cycling in a eutrophic shield lake and its effects on whole lake metabolism. *Limnol. Oceanogr.* **23**, 337–348.

Rudd, J. W. M., Harris, R., Kelly, C. A. & Hecky, R. E. 1993 Are hydroelectric reservoirs significant sources of greenhouse gases? *Ambio* **22**, 246–248.

Roulet, N. T., Crill, P. M., Comer, N. T., Dove, A. & Boubonniere, R. A. 1997 CO_2 and CH_4 flux between a boreal beaver pond and the atmosphere. *J. Geophys. Res.* **102**, 29 313–29 319. (doi:10.1029/97JD01237)

Sazonova, T. S., Romanovsky, V. E., Walsh, J. E. & Sergueev, D. O. 2004 Permafrost dynamics in the 20th and 21st centuries along the East Siberian transect. *J. Geophys. Res.* **109**, D01108. (doi:10.1029/2003JD003680)

Sellmann, P. V., Brown, J., Lewellen, R. I., McKim, H. & Merry, C. 1975 The classification and geomorphic implication of thaw lakes on the Arctic Coastal Plain, Alaska. US Army CRELL, Research Report 334.

Severinghaus, J. P. & Brook, E. J. 1999 Abrupt climate change at the end of the Last Glacial Period inferred from trapped air in polar ice. *Science* **286**, 930–934. (doi:10.1126/science.286.5441.930)

Sharkuu, N. 1998 Trends of permafrost development in the Selenge River Basin, Mongolia. In *Proc. Int. Conf. on Permafrost, Yellowknife, Canada, 2–5 August 1998* (eds A. G. Lewkowicz & M. Allard), pp. 979–985. Universte Laval, Quebec, Collection Nordiana 57.

Smith, L. C., MacDonald, G. M., Velichko, A. A., Beilman, D. W., Borisova, O. K., Frey, K. E., Kremenetski, K. V. & Sheng, Y. 2004 Siberian peatlands a net carbon sink and global methane source since the early Holocene. *Science* **303**, 353–356. (doi:10.1126/science.1090553)

Smith, L. C., Sheng, Y., MacDonald, G. M. & Hinzman, L. D. 2005 Disappearing Arctic lakes. *Science* **308**, 1429. (doi:10.1126/science.1108142)

Smith, L. C., Sheng, Y. & MacDonald, G. M. In press. A first pan-Arctic assessment of the influence of glaciation, permafrost, topography and peatlands on northern lake distribution. *Permafrost Periglac. Process.* **18**.

St Louis, V. L., Kelly, C. A., Duchemin, E., Rudd, J. W. M. & Rosenberg, D. M. 2000 Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. *BioScience* **50**, 766–775. (doi:10.1641/0006-3568(2000)050[0766:RSASOG]2.0.CO;2)

Steele, L. P., Conway, T. J., Fraser, P. J., Rasmussen, R. A. & Khalil, M. A. K. 1987 The global distribution of methane in the troposphere. *J. Atmos. Chem.* **5**, 125–171. (doi:10.1007/BF00048857)

Stern, N. 2006 *The economics of climate change: the Stern review*. Cambridge, UK: Cambridge University Press.

Valentine, D. W., Holland, E. A. & Schimel, D. S. 1994 Ecoystem and physiological controls over methane production in northern wetlands. *J. Geophys. Res.* **99**, 1563–1571. (doi:10.1029/93JD00391)

Vourlitis, G. L. & Oechel, W. C. 1997 The role of northern ecosystems in the global methane budget. In *Global change and Arctic terrestrial ecosystems, ecological studies*, vol. 124 (eds W. C. Oechel, T. Callaghan, T. Gilmanov, J. I. Holten, B. Maxwell, U. Molau & B. Sveinbjornsson), pp. 266–289. New York, NY: Springer.

Walter, K. M., Zimov, S. A., Chanton, J. P., Verbyla, D. & Chapin III, F. S. 2006 Methane bubbling from Siberian Thaw Lakes as a positive feedback to climate warming. *Nature* **443**, 71–75. (doi:10.1038/nature05040)

Walter, K. M., Zimov, S. A., Chapin III, F. S. & Zhuang, Q. Submitted. Bioscience, methane bubbles in lake ice: a new method to evaluate emissions from Arctic and sub-Arctic lakes.

Walter, K. M., Chanton, J., Schuur, T., Zimov, S. A. & Chapin III, F. S. In press *a*. Methane production and bubble emissions from Arctic Lakes: implications from ^{14}C and stable isotope compositions. *J. Geophys. Res. Biogeosci.*

Walter, K. M., Duguay, C., Jeffries, M., Engram, M. & Chapin III, F. S. In press *b*. Estimating methane ebullition from arctic lakes using synthetic aperture radar (SAR). *J. Am. Water Res. Assoc.*

Wetzel, R. G. 2001 *Limnology: lake and river ecosystems*. San Diego, CA: Academic Press.

Whalen, S. C. & Reeburgh, W. S. 1990 A methane flux transect along the trans-Alaska Pipeline Haul road. *Tellus B* **22**, 237–249. (doi:10.1034/j.1600-0889.1990.t01-2-00002.x)

Yamamoto, S., Alcauskas, J. & Crozier, T. 1976 Solubility of methane in distilled water and seawater. *J. Chem. Eng. Data* **21**, 78–80. (doi:10.1021/je60068a029)

Yoshikawa, K. & Hinzman, L. D. 2003 Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. *Permafrost Periglac.* **14**, 151–160. (doi:10.1002/ppp.451)

Yoshikawa, K., Bolton, W. R., Romanovsky, V. E., Fukuda, M. & Hinzman, L. D. 2003 Impacts of wildfire on the permafrost in the boreal forests of interior Alaska. *J. Geophys. Res.* **108**, 8148. (doi:10.1029/2001JD000438)

Zimov, S. A., Voropaev, Y. V., Semiletov, I. P., Davidov, S. P., Prosiannikov, S. F., Chapin III, F. S., Chapin, M. C., Trumbore, S. & Tyler, S. 1997 North Siberian Lakes: a methane source-fueled by pleistocene carbon. *Science* **277**, 800–802. (doi:10.1126/science.277.5327.800)

Zimov, S. A., Schuur, E. A. G. & Chapin III, F. S. 2006 Permafrost global carbon budget. *Science* **312**, 1612–1613. (doi:10.1126/science.1128908)