Chapter 5
Methane and Biogenic Volatile Organic Compound Emissions in Eastern Siberia

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5.1 Introduction

Several landmark publications on CH_4 originate from data collected in Eastern Siberia (Walter et al. 2006, 2007a, b; Shakhova and Semiletov 2007; Rivkina et al. 2007; Zimov et al. 2006). These have put the spotlight on CH_4 emissions from thawing permafrost as a feedback that accelerates global warming (Schuur et al. 2008). Most of Eastern Siberia has not been glaciated during the Late Pleistocene (e.g. Zimov et al. 2006 and references therein), which allowed the accumulation of successions of ice-rich sediment under cold glacial conditions, known as 'Yedoma' (Schirrmeister et al. 2008, 2013). These deposits are highly vulnerable to thawing of permafrost, causing subsidence and ponding of water followed by increased CH_4 formation (Walter et al. 2006).

A recent review publication (Schuur et al. 2015) concluded that greenhouse gas (GHG) emissions from permafrost soils are unlikely to provoke abrupt climate change. They assume that release is gradual over decades and centuries, rather than showing large and rapid pulse emissions, and estimate these emissions are 13–17% of global fossil fuel emissions. Furthermore, it is uncertain how these greenhouse gas emissions are partitioned between CO_2 and CH_4. Incubation experiments suggest a more important role for CO_2 than for CH_4 because of the much more rapid aerobic decomposition versus anaerobic decomposition, although the ultimate effect depends on landscape changes (Schädel et al. 2016).

However, this does not dismiss the importance of CH_4. First, its radiative contribution to climate change has been upgraded. The 100 year global warming potential of CH_4 was revised upwards from 23 (Houghton et al. 2001) to 34 (Stocker et al. 2013) in the IPCC reports. Second, a renewed rise of atmospheric CH_4 concentration has started in 2007. The factors that contributed to this renewed rise

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remain unclear (Kirschke et al. 2013; Bergamaschi et al. 2013; Houweling et al. 2014). Worden et al. (2017) infer a net emission increase for both fossil fuel (±50–75% of total increase) and biogenic sources (including wetlands and agriculture) to reconcile isotope and atmospheric chemistry data with strength of sources. Model inversion by Bruhwiler et al. (2014) did not find an increase in CH_4 emission in the Arctic, but report large year-to-year variability. Third, there is high uncertainty in the emissions, and surprises cannot be ruled out (Schuur et al. 2015; Schädel et al. 2016).

Various CH_4 sources can be distinguished using isotopic signatures of the sources and atmospheric modelling (e.g. Worden et al. 2017; Thonat et al. 2017). Based on atmospheric modelling of CH_4 data collected at stations in Siberia and other Arctic sites, Thonat et al. (2017) conclude that CH_4 emissions from Eastern Siberia originate largely from terrestrial wetlands and freshwater sources in summer, while winter sources are dominated by marine, geologic, and anthropogenic (largely fossil fuel industry) emissions. At the East Siberian stations Tiksi and Cherskii, wetlands and freshwater sources dominate contributions to the concentration of CH_4 with resp. 68% and 82% from May to November; in winter these fall to 8% and 11%. The oceanic emissions from the East Siberian Arctic shelf at these stations are relatively high compared to other Arctic stations, with 17% and 11% in summer and 44% and 41% in winter. Anthropogenic emissions are modest and contribute resp. 25% and 23% in winter and 6% and 3% in summer, due to relatively minor East Siberian fossil fuel activities compared to West Siberia. Emissions from biomass burning are small, 1–2% in summer and 3–6% in winter. Geologic sources consisting of gas seepage at both sites contribute 24% in winter and 3–7% in summer (Thonat et al. 2017).

This chapter reviews these terrestrial sources and processes of CH_4 emission, with emphasis on research in Eastern Siberia (Yakutia and eastern provinces of Russia), but where necessary, reference to research in other parts of Siberia or other cold-climate areas will be made. The review will be process- and data-oriented and will focus on the CH_4 emissions from terrestrial environment in relation to the total greenhouse gas (GHG) budget of ecosystems; marine sources of CH_4 are not included; also CH_4 emission from wildfires or fossil fuel extraction is excluded. Three types of terrestrial biosphere CH_4 sources can be distinguished and will guide the discussion in this article (Fig. 5.1).

The ecosystem CH_4 source consists of wetlands, ponds, and lakes which are sources of CH_4, where the CH_4 carbon is largely derived from recent photosynthesis products of the ecosystem, although older soil carbon may be included. It is the balance of CO_2 uptake by vegetation and emission of CH_4 that matters whether ecosystems are net sources or sinks of greenhouse gases (Van der Molen et al. 2007; Walther-Anthony et al. 2014). Neither can ecosystem CH_4 be isolated from the nutrient cycle as discussed below.

The old-carbon CH_4 source in soil and sedimentary deposits may become available for methanogenesis by thaw of permafrost (e.g. Walter et al. 2006). Liberation of old carbon (fossil C of Holocene and Pleistocene age) contributes the strength of the permafrost carbon feedback, although part of its reworking may be the result of normal ecosystem processes.

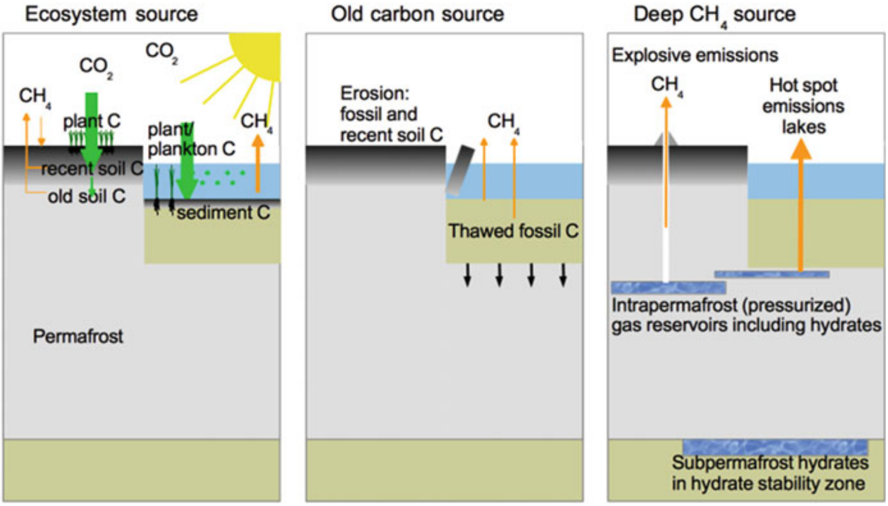

Fig. 5.1 Methane sources from permafrost: ecosystem source, old (fossil, Pleistocene) carbon source, and deep CH_4 sources from intra- and sub-permafrost gas and hydrate reservoirs

The deep CH_4 *source* is CH_4 stored in the deeper subsoil as gas hydrates or pressurized gas at tens to hundreds of metres depth is a third potential source (Rivkina et al. 2007; Kraev et al. 2012; Archer 2007). On the land surface, this may be liberated on deeper thaw of permafrost beneath lakes (e.g. Walter et al. 2007a, b) or, as recently observed in West Siberia, by eruptive emission (Leibman et al. 2016). These geological emissions may be triggered by climate change. Also in Eastern Siberia, this potential source is present (Rivkina et al. 2007; Kraev et al. 2012).

Besides CH_4, other volatile organic compounds originate from East Siberian ecosystems. Both forests and tundras are an important source of biogenic volatile organic compounds (BVOCs), emitted by plants during growth. BVOCs interact with CH_4: they compete with CH_4 for oxidation by the OH radical and therefore influence the lifetime of CH_4 (O'Connor et al. 2010, Thonat et al. 2017). Although the interactions of BVOC with CO_2, CH_4, and aerosols are complex (Arneth et al. 2016), emission of BVOCs may increase with climate warming (e.g. Kramshøj et al. 2016) and need to be considered in the interaction of ecosystems with climate.

5.2 The Ecosystem CH_4 Source

5.2.1 Data Uncertainty

Because of the challenging field research conditions, the spatial density of observations on terrestrial CH_4 fluxes is low in Eastern Siberia. Full winter season data – crucial for a full understanding of the CH_4 budget of permafrost ecosystems (e.g. Mastepanov et al. 2008; Zona et al. 2016) – have been published only very recently for Eastern Siberia (Kittler et al. 2017). Sources of data uncertainty arise from differences of spatial scale of measurement methods (e.g. eddy covariance vs. chamber flux measurements), data gaps, and data processing. Eddy covariance data processing and gap filling for CH_4 is still a developing field (Wille et al. 2008; Parmentier et al. 2011b).

For assessing the spatial variability of fluxes from eddy covariance with a footprint typically in the order of tens to hundreds of metres across, a statistical footprint model is necessary to relate CH_4 sources to spatial variability of wetlands (Parmentier et al. 2011b; Budishchev et al. 2014). Chamber flux measurements can exactly pinpoint small-scale spatial variability but need many replicates for reliable flux estimation and are vulnerable to disturbance of the measurements (Sachs et al. 2008a, b; Kutzbach et al. 2004, 2007).

Data cited (e.g. in Table 5.1) are the data as presented by respective authors. Because data are reported in a wide range of units (fluxes in moles, units of mass, carbon mass flux, and with varying time scales), all fluxes have been converted to mg CH_4 m^{-2} h^{-1} for comparison purposes.

5.2.2 Processes

Water table and temperature, controlling the presence of anaerobic environments and reaction rate, are the most important drivers for CH_4 emission from wetlands (Turetsky et al. 2014). Permafrost impedes subsurface drainage by the presence of impervious frozen subsoils, while microrelief may impede surface runoff (Kutzbach et al. 2004). However, soil biogeochemistry and transport mechanisms of CH_4 from soil or water to atmosphere contribute to high spatial variability.

The ecosystem CH_4 source is CH_4 mostly driven by recently photosynthesized, labile organic material, released from the plant root system (Ström et al. 2003). Photosynthesis products can be transferred into CH_4 in a matter of hours as shown by ^{14}C-labelling experiments (King et al. 2002; Ström et al. 2003), and as a result a small percentage (2–3%) of the primary production of wetland ecosystems is returned to the atmosphere as CH_4 (King et al. 2002; Christensen et al. 2003; Wagner and Liebner 2009). The environment needs not be strictly anaerobic as shown by recent research; methanogens in anaerobic microsites in otherwise oxygenated soil may contribute to CH_4 production (Angle et al. 2017).

Methanogens prefer small and simple molecules which are usually end products of the metabolism of other microbes, e.g. iron reducers. The mineralization of organic matter under anaerobic conditions is performed by a chain of specialized microorganisms, with as intermediate products hydrogen, carbon dioxide, and acetate (Metje and Frenzel 2007; Wagner and Liebner 2009; Fig. 5.2). The two most well-known processes of bacterial methanogenesis are the acetoclastic pathway, using methyl groups of acetate and similar compounds, and CO_2 reduction (hydrogenotrophy), producing equal amounts of CO_2 and CH_4 (e.g. Sugimoto and

Table 5.1 Representative CH_4 emission and uptake in various terrestrial wetland environments in Siberia

References	Vegetation/microrelief	CH_4 flux mg m^{-2} h^{-1}
1	Dry floodplain levee, *Salix* brush	−0.04 ±0.04
1	Dry floodplain, grasses	1.3 ±1.8
1	Floodplain wetland, *Arctophila fulva* grass and mosses	37.0 ±5.3
1	Floodplain wetland, *Carex*, *Eriophorum*, grasses	12.6 ±10.1
1	Dry tundra, *Betula nana*, mosses, lichens	−0.22 ±0.34
1	Dry tundra, *Eriophorum* tussocks	−0.09 ±0.05
1	Dry tundra, grasses	0.71 ± 1.1
1	Tundra wetland, usually inundated, *Carex*, *Eriophorum*	8.0 ±3.0
1	Tundra wetland, *Sphagnum* hummocks	2.0 ±1.7
1	Tundra wetland, inundated polygon pond with *Sphagnum* or mosses	4.0 ±1.9
1	Ice wedge thaw pond	4.4 ±2.8
2	Polygon centres with mosses (*Scorpidium*, *Drepanocladus*, *Carex*)	±4.2*
2	Polygon rim	<0.42*
3	Polygon centre, mosses, *Carex aquatilis*, and other vascular plants	1.2 ±2*
3	Polygon rim, species-rich	0.18 ±0.03*
4	Floodplain with *Carex appendiculata* tussocks	8.2 ±3.4*
5	Floodplain with *Carex appendiculata* tussocks	13.8±7.0*
6	Mesotrophic fen in Larch forest, *Molinea* tussocks	1.3 ± 1.7
6	Eutrophic lake bank, grasses	11.9 ±15.5
6	Moist forest floor, water table 10–27 cm below surface, *Betula*	−0.26±0.45
6	Dry forest floor, *Larix* and *Pinus* with shrub and lichen understory	−0.37 ±0.47
7	Mineral forest soil, no permafrost, *Betula/Picea/Larix*, shrub understory	−0.06–0*
7	Mineral forest soil with permafrost	−0.04–0*
7	Peat plateau, permafrost, *Betula nana*, *Ledum palustre*, *Sphagnum*, mosses	−0.025–0*
7	Permafrost thaw pond	12 and larger

References: 1. Van Huissteden et al. (2009), 2. Sachs et al. (2008a, b), 3. Kutzbach et al. (2004), 4. Corradi et al. (2005), 5. Kwon et al. (2017), 6. Van Huissteden et al. (2008), Corradi et al. (2005) and 7. Flessa et al. (2008). Stars (*) mark values that have been recalculated to mg m^{-2} h^{-1}; negative values represent uptake from the atmosphere into the soils

Wada 1993; Corbett et al. 2015). Additionally, there is evidence that various other methylated substrates are being used for methanogenesis in wetland soils (Zalman et al. 2018). It has been assumed that CO_2 reduction is the main process in high-latitude wetlands (Hines et al. 2001) since acetate accumulates over the season in these soils. However, Ström et al. (2003, 2015) and Metje and Frenzel (2007) have

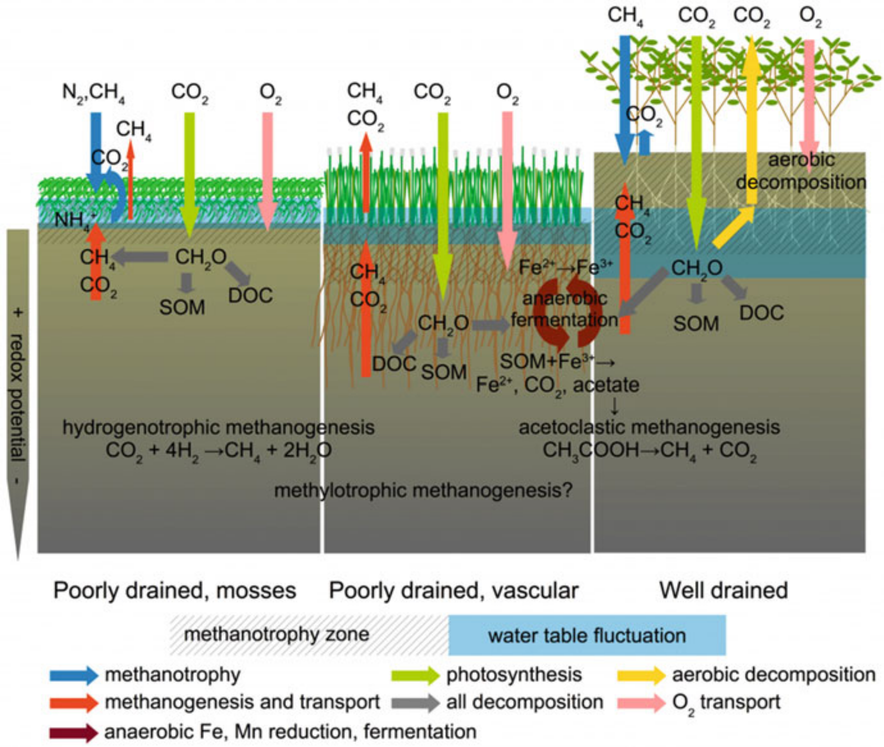

Fig. 5.2 Biochemical processes involved in CH_4 formation and oxidation in soil environments with varying water table and vegetation (non-vascular mosses without root system vs. vascular plants). Indicated processes are photosynthesis and transfer of organic compounds (CH_2O) to the soil, methanogenesis pathways, CH_4 oxidation by methanotrophy including N fixation (methanotrophy in mosses), transfer of O_2 to the soil, and anaerobic fermentation by Fe reduction producing substrate for methanogens, including recycling of Fe^{2+} to Fe^{3+} by oxidation (similar anaerobic reduction involves Mn, not shown here). *SOM* soil organic matter, *DOC* dissolved organic carbon

shown that acetate is a major substrate in high-latitude wetland soils, although CO_2 reduction remains locally important (Vaughn et al. 2016).

Despite the extreme climatic conditions in East Siberian permafrost soils, the abundance and composition of the methanogenic bacterial population is similar to that of temperate wetland soils (Wagner and Liebner 2009), although a distinct vertical zonation is found in permafrost, with more psychrophilic archaea at depth in the soil, close to the permafrost table. Activity of psychrophilic methanogenic archaea has been recorded at subzero temperatures (Rivkina et al. 2000).

The surface CH_4 flux from wetland soils is determined by the balance between CH_4 production by methanogens and its consumption by oxidation and bacterial methanotrophy (Wagner and Liebner 2009). In high Arctic areas with drier soils, the soil CH_4 sink dominates (Jørgenson et al. 2014). Also taiga forest soils in Siberia,

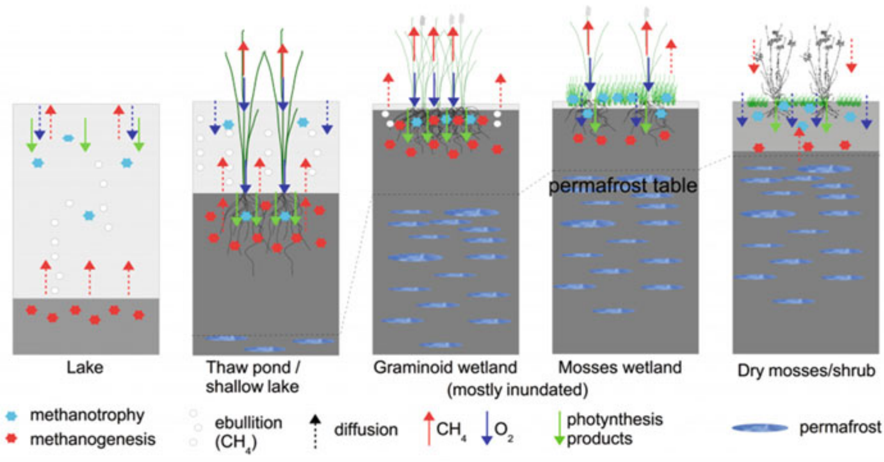

Fig. 5.3 Conceptual diagram of interactions between plants, substrate supply for methanogenesis, methanotrophy, and methane transport pathways in various lake and wetland environments in permafrost areas, from lake to dry soil. The main locations of methane formation and methanotrophy are indicated with stars

dry tundra soils and dry peat soils on peat plateaus are a significant sink of CH_4 (Morishita et al. 2003; Van Huissteden et al. 2005, 2008, 2009; Flessa et al. 2008).

In soils, several groups of prokaryotes oxidize CH_4 for carbon assimilation (e.g. Frenzel and Karofeld 2000; Wagner and Liebner 2009). Methanotrophic bacteria have a loose symbiosis with *Sphagnum* species (Raghoebarsing et al. 2006; Kip et al. 2010) and submerged brown mosses (Liebner et al. 2011). CO_2 from methanotrophy may account for up to 30% of carbon uptake of mosses (Larmola et al. 2010). Rates of this soil and moss-related methanotrophy have shown to be very high in East Siberian tundra environments (Knoblauch et al. 2008; Kip et al. 2010). Methanotrophy in brown mosses decreases the CH_4 emission from polygon ponds by at least 5% (Liebner et al. 2011); Knoblauch et al. (2015) found that 61–99% of produced CH_4 was consumed in submerged *Scorpidium scorpioides* moss. Symbiotic methanotrophs in *Sphagnum* contribute strongly to N_2 fixation in ombrotrophic peat bogs and are therefore related to the N cycle of peatlands (Vile et al. 2014; Larmola et al. 2014).

CH_4 is transported from soil and water bottom to the atmosphere by bubbles (ebullition), diffusion, and transport through plants (Fig. 5.3). The physical transport mechanisms of ebullition and diffusion depend on weather conditions. Ebullition fluxes can be triggered by air pressure variation (Sachs et al. 2008a, b; Kwon et al. 2017) and near-surface turbulence and atmospheric stability (Wille et al. 2008 and Parmentier et al. 2011b); higher turbulence and unstable conditions result in higher fluxes.

Vegetation has a strong and complicated effect on ecosystem CH_4 fluxes (Figs. 5.2 and 5.3). Aerenchyma in wetland plants transport CH_4 to the atmosphere;

the plant-mediated transport lies between 30% and 100% of the CH_4 flux and is species-dependent: graminoids transport more methane (±80%) than forbs (±60%) (Bhullar et al. 2013). In ponds in Northern Siberia, plant-mediated transport of CH_4 by emergent vegetation amounted between 70% and 90% of the total CH_4 flux (Kutzbach et al. 2004). However, the main function of aerenchyma is the transport of oxygen to the anoxic root zone. A part of this oxygen contributes to oxidation of CH_4 in the rhizosphere. On the other hand, this oxygen also regenerates alternative electron acceptors, such as Fe oxides, contributing to the anaerobic organic matter decomposition that produces the substrates for methanogens. The complex interplay between exudation of methanogenic substrate by roots, oxidation of CH_4 in the rhizosphere and transport of CH_4 is species-specific: *Carex rostrata* had higher CH_4 emissions due to lower CH_4 oxidation than *Eriophorum vaginatum* and *Juncus effusus* (Ström et al. 2005).

In lakes, a similar balance between CH_4 production and oxidation is found. In deeper lakes, bottom waters may be anoxic due to thermal stratification, which impedes the exchange of gases other than by slow diffusion. These deeper, anoxic bottom layers of the lakes (the hypolimnion) are the main CH_4 production zone. However, shallower, epilimnetic zones may emit more to the atmosphere. In these shallower zones, turbulence enhances CH_4 transport to the atmosphere, bypassing oxidation. In the littoral zone with emergent plants, plant transport in emergent water plants also contributes (Bastviken et al. 2008). The proportion of produced CH_4 that is oxidized in sediments and water column may amount 30–99% and includes anaerobic CH_4 oxidation (e.g. Deutzmann et al. 2014). The oxidation of CH_4 contributes carbon to the food web in lakes, influencing its carbon isotopic signature (Bastviken et al. 2003).

In deeper lakes CH_4 is stored in anoxic bottom water, which is released when the stratification is overturned seasonally. Turbulence also enhances the exchange of CH_4 from the bottom sediment to the water column (Bastviken et al. 2008). In many lakes the main transport pathway of CH_4 to the surface is ebullition (Bastviken et al. 2008). This is facilitated by energy input into the lake, as relations have been found with ice-free period, incoming shortwave radiation and water/sediment temperature (Wik et al. 2014).

5.2.3 Terrestrial Ecosystems: Spatial and Seasonal Variation

Table 5.1 shows studies of CH_4 fluxes in Eastern Siberia (Christensen et al. 1995; Nakano et al. 2000; Wagner et al. 2003; Kutzbach et al. 2004; Corradi et al. 2005; Van der Molen et al. 2007; Van Huissteden et al. 2005, 2008, 2009; Flessa et al. 2008; Sachs et al. 2008a, b; Takakai et al. 2008; Parmentier et al. 2011b; Budishchev et al. 2014). All these papers show significant variation of fluxes between vegetation types, including vegetation with similar water table (e.g. Van Huissteden et al. 2009). Large differences are shown between graminoid and moss-dominated vegetations, where methanotrophy in mosses may play a role (e.g. Parmentier et al. 2011a).

Van Huissteden et al. (2005, 2008, 2009) found higher emissions in eutrophic environments compared to mesotrophic and oligotrophic environments: differences between a mesotrophic flooded fen and a nearby eutrophic lake and between mesotrophic sedge vegetations and sedge vegetations on a nutrient-rich river floodplain. Similar high fluxes on a floodplain were observed by Corradi et al. (2005). Floodplains, with a supply of additional nutrients by spring snowmelt flooding, are an overlooked strong source of ecosystem CH_4 (Table 5.1).

Microrelief (ice wedge polygons) created by the presence of permafrost also results in spatial variation of CH_4 fluxes (Fig. 5.4). This microrelief effect has been the subject of several studies in Eastern Siberia (Wagner et al. 2003; Kutzbach et al. 2004; Knoblauch et al. 2015). Ponded water is often present in the poorly drained centres of polygons (low-centred polygons) or troughs above (thawing) ice wedges. Other forms of microrelief have been described by Van Huissteden et al. (2005) and Berritella et al. (2017): a pattern of flat elongated ridges dominated by dwarf birch

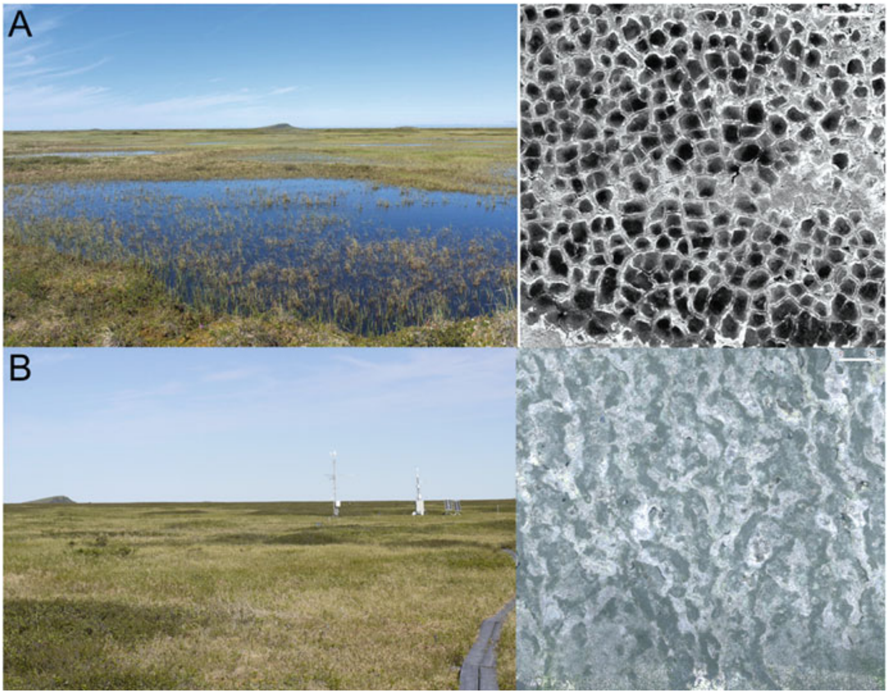

Fig. 5.4 Two types of microrelief that influence wetland characteristics in the Siberian north. A: polygonal ice wedge network, with low-centred polygons with central ponds. Left: view from the surface. Right: view from above at the same location (GeoEye panchromatic satellite image). B: peat mound – sedge meadow relief with *Betula nana*-covered peat mounds (dark patches.) Below right: view from above, air-photo, same location. The sedge meadows serve partly as drainage channels. Kytalyk tundra research station, near Chokurdagh, Indigirka lowlands, Northeast Siberia

(*Betula nana*) separated by shallow, densely vegetated (*Carex* and *Eriophorum* spp.) drainage channels. The ridges – resembling palsas – are a sink of CH_4.

At least three variables determine the spatial variability of CH_4 fluxes in East Siberian ecosystems: water table/microrelief, vegetation characteristics, and eutrophic-ombrotrophic gradients. Comparing summer fluxes in various ecosystem settings (Table 5.1), the following pattern with respect to vegetation emerges. Graminoid wetland vegetations with high water table, usually dominated by *Carex* and *Eriophorum* spp. and grasses like *Arctophila fulva*, show the highest fluxes. Eutrophic wetlands in floodplains and agriculturally used meadows are the strongest emitters of CH_4. Meso- and oligotrophic sites show lower fluxes with otherwise similar water table conditions. Thaw ponds formed by ground ice thaw show similar fluxes as the eutrophic graminoid vegetations. Stable ice wedge polygon centre ponds generally show lower fluxes than fresh thaw ponds. *Sphagnum*-rich and other mosses-rich ecosystems show the lowest fluxes. Dry environments, in particular on peat plateaus, palsas, and polygon rims, are a sink of CH_4. Also forests are sinks of CH_4, even when the water table is relatively high. However, forested wetlands are poorly represented in the data, and CH_4 fluxes through tree trunks (Gauci et al. 2010) never have been measured in Siberia.

Seasonal variation of emissions largely follows the growing season (Wille et al. 2008; Sachs et al. 2008b; Kwon et al. 2017). Also daily flux variation driven by soil temperature has been observed (Nakano et al. 2000). In permafrost environments high CH_4 emissions may occur in autumn and winter (Mastepanov et al. 2008, 2013) that even may surpass that of the growing season (Zona et al. 2016). Most of these emissions occur during soil freezing, when the soil remains for a long period at the freezing point (‘zero curtain’) due to the effect of latent heat of soil water. These fluxes are attributed to physical expulsion of stored soil CH_4 by freezing (Mastepanov et al. 2008, 2013) and ongoing bacterial activity at subzero temperatures (Zona et al. 2016).

The high autumn CH_4 fluxes are also observed in Eastern Siberia. Eddy covariance data by Wille et al. (2008) in the Lena Delta extending into October show erratic higher fluxes comparable to the highest summer emissions. Kwon et al. (2017) and Kittler et al. (2017) observed high fluxes in October–November in the Kolyma floodplain. These fluxes contribute 23% to the total annual flux and correlated with drops in air pressure. This is confirmed by the model inversions of Thonat et al. (2017). The high winter emissions show the urgency of all-season CH_4 flux observations in permafrost environments (Kittler et al. 2017).

Van der Molen et al. (2007) concluded that the tundra in the Indigirka lowlands is a net sink of greenhouse gases in summer. However, lack of autumn and winter data hampers construction of a year-round GHG budget including CH_4 at several sites. Wille et al. (2008) concluded that the tundra in the Lena Delta is a small source of greenhouse gases, because radiative forcing from CH_4 emission exceeds the effect of ecosystem CO_2 uptake over the year. A river floodplain near Cherskii was in summer a net source of greenhouse gases (CO_2 + CH_4) of 475±253 g C-CO_2-equivalent m^{-2} because of the high CH_4 flux (Merbold et al. 2009); also the more recent data from this site indicate a small net source (Kwon et al. 2017; Kittler et al. 2017).

5.2.4 The Ecosystem CH_4 Source in Ponds and Lakes

Alas lakes (thaw or thermokarst lakes) and ponds produced by thawing of ice-rich permafrost are of widespread occurrence in Siberia (Brouchkov et al. 2004; Grosse et al. 2013) and have attracted attention as CH_4 sources (Nakagawa et al. 2002; Walter et al. 2006, 2007a, b). The global northern latitude lake area is at least twice higher in permafrost regions than in non-permafrost regions (Grosse et al. 2013).

The lake sediment temperature beneath the maximum ice thickness remains above zero, permitting continuous methanogenesis. In high northern latitudes, lake ice thickness may reach over 2 m (Duguay et al. 2003). With ongoing ebullition of CH_4 from the sediment in winter, the lake ice becomes a large store of CH_4 frozen in bubbles in the ice (Zimov et al. 1997; Walter et al. 2006; Wik et al. 2011). Walter et al. (2006) make a distinction between low rate background ebullition, point sources, and hotspots with larger bubble plumes. Winter ebullition has been estimated by counting and sampling various type of bubble clusters (Walter et al. 2006), resulting in a 10–63% higher estimate of northern wetland CH_4 emission. However, quantification of ebullition emissions using bubble counting on ice has large uncertainties (Wik et al. 2011), and the CH_4 trapped in lake ice may be subject to microbial oxidation (Walter et al. 2008). Based on extrapolation from East Siberian and Alaskan lakes, Walter et al. (2007a, b) estimate the CH_4 emission of lakes in permafrost areas (total area 396.200 km^2) at 19.2±6.7 Tg CH_4 year^{-1}.

The background ebullition shows an isotopic signature (δ^{13}C, δD, ^{14}C age of CH_4) that indicates approximately equal contributions from acetate and CO_2 reduction and a young age, representing decomposition of young organic material in surface sediments (Walter et al. 2008). CH_4 from point sources was much older than CH_4 derived from background ebullition, and the isotope fraction of C and H stable isotopes indicated CH_4 generated by the CO_2 reduction pathway (Walter et al. 2007a). The apparent ages of hotspot CH_4 in Siberian lakes ranged between 35.3 and 42.9 kyr BP, suggesting sources deep in the thawed Pleistocene deposits below the lakes. Point source CH_4 was younger but still ranging between 5.6 and 22.1 kyr BP, while surface sediment and background ebullition CH_4 had ages of Holocene to recent age.

Nakagawa et al. (2002) studied alases (thaw lake and wetland complexes) near Yakutsk. ^{14}C data of CH_4 from smaller alases indicated a modern origin, while that of larger alases was older, indicating a larger proportion of fresh organic matter supplied from the banks in smaller alases. The hotspot CH_4 of Walter et al. (2007a, b) is considerably older than the CH_4 from more southerly alases described by Nakagawa et al. (2002). Alas lakes in Central Yakutia behave differently compared to their northern counterparts. Water table and lake size vary stronger, shrinking during summer. Alases have a grass cover at low water table, often used as meadow or hay pasture. Morishita et al. (2003) and Takakai et al. (2008) report high CH_4 emissions from an alas pond and the frequently flooded grasslands surrounding the pond. Takakai et al. (2008) report fluxes from 5.7 to 54.6 mg m^{-2} h^{-1} from flooded grasslands, which considerably decreased after the sites dried out. In the pond the fluxes varied strongly with water temperature, ranging from 1.3 to 146.7 mg m^{-2} h^{-1}.

Thawing of lake ice in spring releases the stored CH_4 from the ice; however, data have not been published for Eastern Siberia. In a lake in Northern Sweden, 53% of the annual emission of CH_4 was released in spring (Jammet et al. 2015).

Small lakes and ponds dominate the lowlands of Siberia rather than large lakes (Grosse et al. 2008). Although small lakes and ponds may freeze to the bottom, the thermal effect of the presence of a water body results in prolonged above-zero temperatures. Langer et al. (2015) quantified CH_4 stored in pond ice in the Lena Delta. Winter emissions ranged between 0.01 and 5.8 mg m^{-2} day^{-1}. Sachs et al. (2010) measured summer fluxes in polygon ponds ranging on average between 78 and 100 mg m^{-2} day^{-1}.

Although thaw lakes are sources of CH_4, the net long-term effect may be still be a greenhouse gas sink due to carbon accumulation. Walter Anthony et al. (2014) assessed the carbon accumulation in 49 Holocene lake infill successions (including East Siberian lakes) in thaw lakes dating from the Last Glacial Termination and Early Holocene. The thaw lakes switched from a net radiative source from CH_4 emission to a sink by greenhouse gas uptake about 5000 years ago.

5.3 Old Soil Carbon as a Source of CH_4

Old soil carbon may become an increasing source of carbon for the ecosystem respiration upon warming of the permafrost in Eastern Siberia. Estimates of the soil carbon stocks in the Arctic are improving (Tarnocai et al. 2009; Strauss et al. 2013; Hugelius et al. 2014). Older, frozen soil carbon becomes available for decomposition by gradual increase of active layer thickness (ALT) or by rapid geomorphological processes such as erosion and pond formation (Van Huissteden and Dolman 2012).

To be available for methanogenesis, older soil carbon should contain labile organic compounds or needs to be converted into labile compounds. Zimov et al. (1997, 2006) were the first to draw attention to the labile nature of carbon in Pleistocene Yedoma (Ice Complex) deposits in Eastern Siberia. A survey of the carbon content of quaternary deposits in Northeast Siberia by Schirrmeister et al. (2011) shows that the superficial Pleistocene Yedoma deposits date mostly from the Last Glacial and consist of cold-climate fluvial and loessic sediments with large, syngenetic ice wedges. The ice content varies between 22 and 59 weight % (or roughly 50–80 volume %), and average total organic carbon (TOC) content varies between 1% and 5%. Holocene deposits (thaw lake infills and fluvial deposits) are equally ice-rich but have a somewhat higher TOC, ranging between 5% and 11% on average. Cold climatic conditions during deposition are assumed to have contributed to the preservation of labile compounds. C/N ratios (ranging between 0.03 and 38.4) and $\delta^{13}C$ values (−31.0–23.4‰) confirm the poorly decomposed and labile nature of the organic matter in the Yedoma deposits. It contains hardly *Sphagnum* peat and consists mostly of graminoid plant material which is more labile

(Schirrmeister et al. 2008, 2011). Recent incubation data of permafrost carbon from Yedoma deposits further confirms the very high lability of this organic matter store (Vonk et al. 2013).

However, Ganzert et al. (2007) and Hershey et al. (2013) showed that CH_4 production in sediment in East Siberian soils and in a small lake are substrate-limited. This suggests that despite the high lability of Arctic soil carbon, further biochemical transformations of the organic matter are needed and still limit methanogenesis (Metje and Frenzel 2007). Incubation experiments along a gradient of progressive thaw of permafrost in Swedish and Canadian bogs have shown that as thaw progresses, the lability of the thawed-out peat increases over the years, resulting in a larger CH_4 production and a shift from hydrogenotrophic to acetoclastic methanogenesis (Corbett et al. 2015; Hodgkins et al. 2014).

5.4 Deep Permafrost CH_4 Sources

Permafrost thaw may activate geologic seeps of CH_4 from ^{14}C-depleted deeper geologic reservoirs (Walter Anthony et al. 2012). Occurrences of deep gas seeps in Eastern Siberia are unknown, but there is abundant evidence for intra-permafrost gas, mainly of biogenic origin, that may be emitted to the atmosphere.

Brouchkov and Fukuda (2002) found values as high as 6000 ppmv CH_4 in frozen soil and ice wedges and low rate CH_4 production in deeper soil material at subzero temperatures. Thawing of permafrost may release this CH_4 if it does not pass through an aerobic soil zone where it is oxidized. Rivkina et al. (2001) measured CH_4 concentrations in drill cores up to 50 m depth in the East Siberian coastal plain west of the Kolyma River. These cores penetrated Holocene thaw lake and alluvial sediments, the Yedoma, and Plio-Pleistocene marine and terrestrial sands and silts. The CH_4 concentrations were highest in the Holocene (up to 20 ml/kg) and the Middle Pleistocene-Pliocene deposits (up to 50 ml/kg), but very low in the Yedoma. The dry, steppic environment under which the Ice Complex accumulated was assumed to be unfavourable for CH_4 accumulation. The CH_4 concentration did not show systematic trends with depth that would suggest seepage from a deep subsurface source.

Also evidence for the presence of CH_4 hydrates at shallow depths is found by Rivkina et al. (2001), well above the normal hydrate stability zone based on sediment column pressure and temperature (O'Connor et al. 2010). Rivkina et al. (2001) assume that within the pore spaces of the permafrost, high pressures may be created during freezing, allowing hydrate formation. $\delta^{13}C$ data of CH_4 from these cores demonstrate a biogenic origin of the CH_4, not thermogenic CH_4 from deeper gas sources. Active methanogenic cultures of both acetoclastic and hydrogenotrophic Archaea from Holocene and Pliocene samples were obtained (Rivkina et al. 2007). In West Siberia, hydrates and pressurized biogenic gas at shallow depths result in blowout risks for oil and gas drilling (Yakushev and Chuvilin 2000).

Gas seeps also have been observed in the Yana-Indigirka and Kolyma lowlands. Kraev et al. (2012) report a reservoir in coarse-grained fluvial deposits at 23 m depth in the Kolyma lowlands, which contained CH_4 with a considerable younger age (± 12 000 year) than the deposits in which it was found (±31 000 kyr). This gas should have been migrated into the reservoir from other (unfrozen) deposits. The proposed migration mechanism is expulsion of CH_4 by freezing of an unfrozen body of sediment. Epigenetic refreezing of taliks underneath former thaw lakes is common in the Northeast Siberian lowlands, as shown by the many closed system pingos which result from expulsion of pressurized water.

It is unlikely that deep gas hydrates in the gas hydrate stability zone are a source of CH_4 from permafrost in the near future (O'Connor et al. 2010), but shallower biogenic gas reservoirs may become a source upon warming of the permafrost. Part of the emission hotspots in thaw lakes could originate from this type of reservoir (Walter et al. 2008). The recent discovery of gas outburst craters in Yamal also originates from sources at depths of tens of metres. The first were discovered in 2014 and were up to then completely unknown to the permafrost research community (Leibman et al. 2014). The diameters of these craters are in the order of a few tens of metres; depths may be more than 50 m. Ejecta attest of a violent explosion. Inside the first crater, very high concentrations of CH_4 and H_2S were measured. Leibman et al. (2014) hypothesize that the crater may have originated from dissociation of a shallow hydrate reservoir following warming of the permafrost, which proceeds at a high pace in Yamal. It is expected that within a few years, it will look like a normal tundra lake (Babkina et al. 2017). On further climatic warming, it cannot be excluded that similar outbursts of CH_4 also appear in East Siberian Arctic lowlands.

5.5 Effects of Environmental Change

5.5.1 Climate Change

Warming in Eastern Siberia is strongest in winter (AMAP 2017). Decrease of sea ice cover is associated with higher temperatures over the nearby land areas, in particular in spring and late summer/autumn, and possibly also with precipitation increase (Bintanja and Selten 2014). Higher winter precipitation results in a thicker snow cover, warming the soil (Iijima et al. 2010; Johansson et al. 2013). Climate change also includes changes in the water balance (precipitation vs. evapotranspiration) of ecosystems. Model projections predict an increase in snow water equivalent of 15–30% over the Siberian sector. Snow cover duration decreases throughout the Arctic, but the least (10%) over Siberia (Callaghan et al. 2012).

From basic principles, higher soil and water temperatures should increase CH_4 emission, since the temperature sensitivity (Q10) of methanogenesis is higher than that of methanotrophy (Segers 1998). However, also wetter soil conditions will increase CH_4 emission. It is decisive to what extent climate change results in changes in temperature, water table, and other soil environmental conditions that enhance methanogenic activity and exposure of additional SOM to methanogenesis. For the effects of climate change on permafrost, Grosse et al. (2011) make distinction between slow but gradual and widespread press disturbances, and rapid, generally local, and destructive pulse disturbances. To quantify the net effects of pulse disturbances, also ecosystem recovery needs to be taken into account (Van Huissteden and Dolman 2012).

5.5.2 *Direct Climate Warming Effects*

As yet, press disturbances for the CH_4 cycle in Eastern Siberia are difficult to distinguish from interannual variability because of the short and sparse observation time series (Parmentier et al. 2013). Evidence results from the analysis of the effects of short-term variability, space-for-time substitutions, and field and model experiments.

Land surface bottom-up models include soil and lake CH_4 emission models (e.g. McGuire et al. 2012). However, because of differences in model structure (Mi et al. 2014; Chadburn et al. 2017) and uncertainty in wetland and lake distribution (Petrescu et al. 2010), model results may deviate strongly from each other (Melton et al. 2013) and need model tuning on data (Petrescu et al. 2007; Budishchev et al. 2014).

Melton et al. (2013) evaluated the performance of ten CH_4 emission models with various resolution and model structure. Simulated wetland areas and CH_4 emissions over large subarctic wetland complexes (West Siberia, Hudson Bay lowlands) showed very large differences among models and deviations from data. The wetlands in the Yana-Indigirka-Kolyma lowlands were even missed by some of the models.

Parmentier et al. (2015) assessed the effect of decreasing sea ice cover on wetland CH_4 emission along the Circum-Arctic coast with three soil CH_4 models (LPJ-GUESS, TEM6, and PEATLAND-VU), driven by ERA-interim reanalysis data from 1981 to 2010 and a prescribed wetland distribution. Sea-ice cover area correlated negatively with nearby land surface temperatures, but no significant trend of precipitation was found. A clear negative correlation between modelled May–October CH_4 fluxes and sea ice extent was found for most of the Arctic including Northeast Siberia, with higher temperature-driven CH_4 emissions in years of lower sea ice extent. Compared to a baseline period of 1981–1990, the CH_4 emission between 2005 and 2010 increased on average by 1.7 (+0.4–4.1) Tg CH_4 $year^{-1}$. For Northeast Siberia, correlations of CH_4 emission with sea ice decline are strongest in June and September (Fig. 5.5).

Other evidence comes from the effects of short-term variability (yearly variations and shorter) of temperatures on CH_4 fluxes. Wille et al. (2008), Sachs et al. (2010), and Parmentier et al. (2011a, b) found a significant effect of soil surface temperature in chamber and eddy covariance CH_4 flux data. Radiocarbon datings on molecular soil organic markers (*n*-alkanes) exported by Siberian rivers (Ob, Yenisey, Lena,

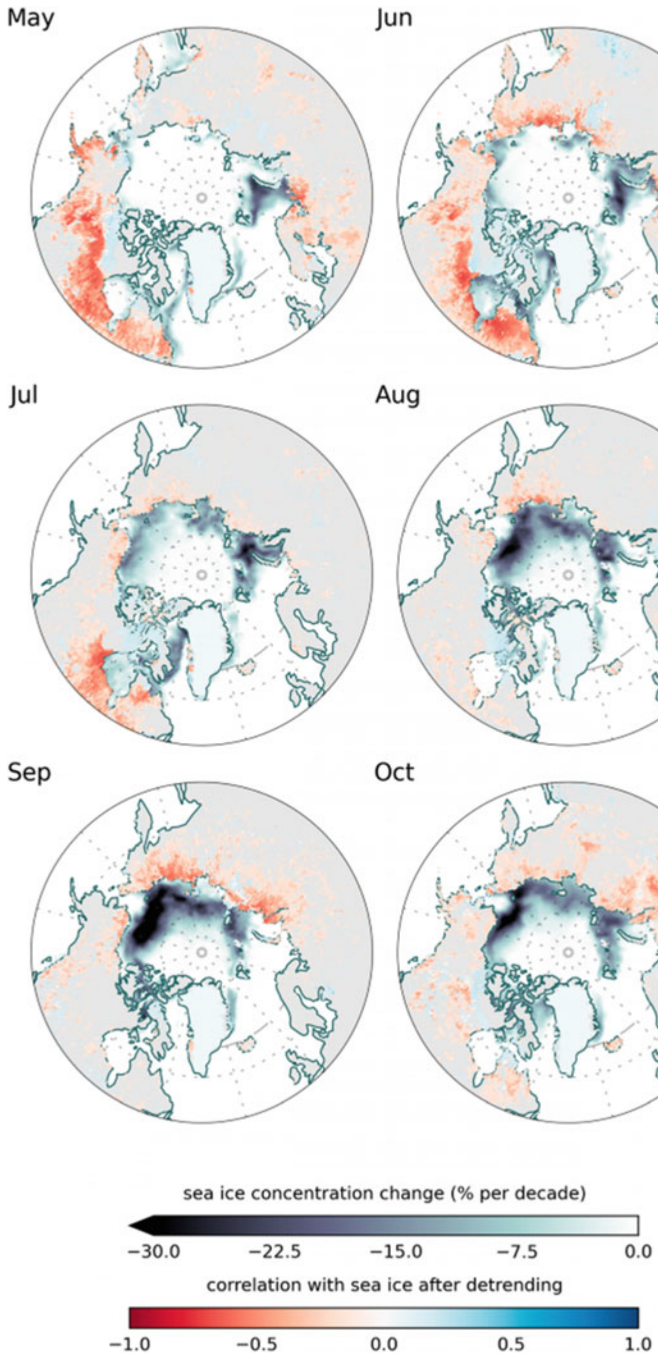

Fig. 5.5 Per month correlations between model-simulated 1981–2010 terrestrial methane emissions and sea ice concentration in a model study by Parmentier et al. (2015). Red to blue colours

Indigirka, and Kolyma) show an increasing age from east to west, which is also the gradient of increasing climate warming (Gustafsson et al. 2011). It is therefore likely that older soil carbon is contributing to CH_4 emitted from soils on a large scale.

Given the important role of vegetation in CH_4 emission, vegetation change is also a form of press disturbance on CH_4 emission. Extension of the growing season and higher growing season temperatures could enhance primary production, but since many ecosystems in Siberia are nutrient-limited (e.g. Beermann et al. 2015), the liberation of nutrients from thawing SOM may be a more important factor. Model simulations using a tundra vegetation model (Van der Kolk et al. 2016) suggest that warming favours shrub dominance, while graminoids (including wetland graminoids) profit from increased precipitation. Graminoids have better access to nutrients liberated in deeper soil layers compared to shrubs.

Warming soils may also result in bacterial community changes. Wagner and Liebner (2009) note a lack of experimental research on this subject. In a high Arctic peat from Spitsbergen, CH_4 production rates, the abundance of methanogenic archaea and their community structure changed with increasing temperature (Høj et al. 2008). On the other hand, little change was seen in the methanogenic archaea population in East Siberian peat soils (Metje and Frenzel 2007). Bacterial isolates from Siberian tundra soils still have their optimum in the temperature range between 25 and 35 °C. The bacterial diversity and quantity of active cells in a polygonal tundra soil in Northeast Siberia were found to be strongly related to the content of organic matter (Kobabe et al. 2004; Wagner and Liebner; 2009). Therefore, changes in the organic matter quality and quantity are likely to have a more important effect on bacterial communities than soil temperature itself.

The effect of warming on lake emissions has not been studied in Eastern Siberia. Data from the extreme warm summer of 2012 in West Siberia show an up to five times higher lake water CH_4 concentration compared to the previous summers (Pokrovsky et al. 2013). Hardenbroek et al. (2012) applied a paleoecological approach for lakes in the Indigirka lowlands, making use of the carbon isotopic effect of CH_4 on the lake food web (Bastviken et al. 2003). Low plankton $\delta^{13}C$ provides a proxy on the recycling of CH_4-derived carbon into a lake's food web. $\delta^{13}C$ in lake zooplankton was lowest in sediments deposited from ca AD 1250 to ca AD 1500 and after AD 1970. This coincided with warmer climate as indicated by tree rings (Sidorova et al. 2008).

Model-predicted summer precipitation trends for the end of the century indicate an increase of precipitation over Siberia by up to 10 mm per month (Overland et al. 2011), which could result in higher soil water tables in the summer, thicker active

Fig. 5.5 (continued) depict the correlation coefficient value of the correlation between modelled methane emissions and sea ice concentration within 2000 km distance, averaged for three ecosystem CH_4 emission models. The linear trend in sea ice concentration is shown to indicate areas of high sea ice retreat. Note that high correlations do not necessarily equal high emissions. (From Parmentier et al. 2015) layer, and more widespread anaerobic soil conditions. Ohta et al. (2008) showed an increase of soil moisture and ALT between 1998 and 2006 in East Siberian larch (*Larix cajanderii*) forest, which could potentially increase CH_4 emission. Higher winter precipitation also produces higher and more prolonged flooding the next spring. Regional climate model simulations coupled to a hydrological model predict that flooded area increases by 2–5%; the highest increase is predicted in Northern Siberia (Shkolnik et al. 2017). Prolonged and more widespread flooding may result in higher CH_4 emissions from highly reactive floodplains (Van Huissteden et al. 2005, 2013).

5.5.3 Geomorphological Change

Pulse disturbances are largely the effect of geomorphological processes induced by thawing of ice-rich permafrost (Walvoord and Kurylyk 2016). The volume loss of Ice Complex deposits with volumetric ice content up to 90% (Schirrmeister et al. 2013) or of palsas and peat mounds in peatlands results in subsidence and formation of ponds (e.g. Kirpotin et al. 2011; Glagolev et al. 2011). Ponds may also form from coalescing low-centred polygon ponds as a result of general subsidence due to permafrost thaw or change of the water balance (Lara et al. 2015; Van Huissteden in prep). Pond formation alters the heat balance of the surface (Boike et al. 2015). In particular thawing ice wedges results in the formation of deeper ponds (Jorgenson et al. 2006; Liljedahl et al. 2016). If subsidence results in ponds that are deeper than the winter ice thickness, a perennial thaw bulb below the pond results. However, even shallow ponds prolong the period of time in which soil material is thawed (Langer et al. 2015).

The transition of ponds to larger thaw lakes is poorly documented. Fedorov and Konstaninov (2009) and Fedorov et al. (2014) describe the growth of an alas lake near Yakutsk, monitored since 1992. The average rate of subsidence of individual thaw depressions was 5–10 cm $year^{-1}$. Individual ice wedge thaw ponds coalesced into larger lakes and ponds. The lake expanded from an estimated volume of 195 m^2 in 1993 to 3135 m^2 in 2008. About one third of the water volume was derived from ground ice. When the lake expands, surface currents in summer cause erosion of banks, redistributing sediment and exposing more permafrost ice to the impact of solar radiation. Erosion rates are largest in deep and large lakes (Jorgenson and Shur 2007; Fig. 5.6). The thaw bulb below a lake can reach depths of tens of metres (Grosse et al. 2013).

Langer et al. (2015) quantified winter emissions in ponds based on CH_4 stored in ice. Stable ponds in stable polygonal tundra had emissions below 0.0058 mg m^{-2} h^{-1}, while ponds that showed clear signs of erosional expansion had emissions of two orders of magnitude higher. Goovaerts (2016) measured in the Indigirka lowlands an average CH_4 flux of 9.4 mg m^{-2} h^{-1} in shallow, active thaw ponds in summer. These ponds were also a large source of CO_2: 482.5 mg m^{-2} h^{-1}. Flessa

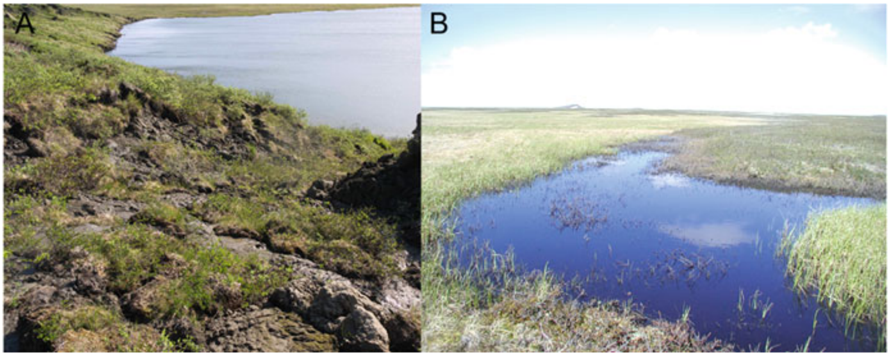

Fig. 5.6 Left: erosion of thaw lake bank in ice-rich Yedoma deposits, showing high transport of recent vegetation and topsoil along a thaw slump into the lake. Kytalyk tundra research station near Chokurdagh, Indigirka lowlands. Right: thaw pond at the transition of a sedge meadow to a *Betula nana*-covered peat mound (Fig. 5.2), with dead *Betula* branches protruding above the water

et al. (2008) report larger fluxes from thaw ponds in west Siberian mires, in the order of 5–12 mg m^{-} h^{-1} and higher.

Ponds develop easily in superficial ice bodies (Jorgenson et al. 2006; Nauta et al. 2014; Van Huissteden in prep). Given their high number, high rate of development, high CH_4 emission, and development in environments that were mostly CH_4 sinks, small thaw ponds are an important source of CH_4 emission resulting from permafrost thaw. Expansion of thaw ponds also results in drowning and erosion of vegetation at the edges of ponds (Fig. 5.6). This fresh organic matter contributes to high CH_4 production. The chain of bacterial organic matter decomposition that contributes to the substrate for methanogens should also be very active in these ponds, because much of the material is contributed from the biologically active topsoil. Therefore, in the early stages of permafrost collapse, CH_4 emission is very active, but not necessarily fed by old soil carbon. Since the CH_4 transport pathway to the atmosphere is short, the CH_4 production at the bottom of these ponds enters the atmosphere without much oxidation (Langer et al. 2015).

However, there are limits to pond expansion and associated CH_4 emission. Shallow ponds are in a few years colonized by wetland vegetation restoring at least the CO_2 sink (Li et al. 2017; Van der Kolk et al. 2016). Liljedahl et al. (2016) show that pond development on ice wedges can result in better drainage through ice wedge troughs. However, the net effect of drainage on GHG emissions is uncertain. The artificial drainage experiment by Kittler et al. (2017) shows a decrease of CH_4 emission, but the increase of aerobic CO_2 respiration and decline of CO_2 uptake resulted in a total net increase of the GHG source.

Compared to ponds, emissions from lakes are lower (Langer et al. 2015). In thaw lakes, ebullition is strongest in the nearshore zones where the contribution of soil carbon eroded from the banks is highest. Whole-year lake emissions in the Kolyma lowlands amounted to 24.9±2.3 g m^{-2} $year^{-1}$ (2.8 mg m^{-2} day^{-1}), but fluxes from the 15-m-wide band adjacent to actively eroded banks are considerably higher, 128±24 g m^{-2} $year^{-1}$(14 mg m^{-2} day^{-1}), representing 79% of the total lake flux (Walter et al. 2006). Isotopic analysis and radiocarbon dating of the emitted CH_4 from thaw lakes in Siberia and Alaska has shown that the CH_4 carbon is derived from old Pleistocene soil carbon and that methanogenesis shifts from the acetoclastic pathway towards CO_2 reduction if more old carbon is involved (Nakagawa et al. 2002; Walter et al. 2007).

Do thaw lakes and ponds expand in area, replacing terrestrial sink areas with large CH_4 sources, and can this be attributed to climate change? The areal changes of lakes and ponds are difficult to estimate; the area of ponds and lakes is influenced on year-to-year variability of the water balance (e.g. Plug et al. 2008; Fedorov et al. 2014). Smith et al. (2005) report an overall decrease of lake area by ±6% but in continuous permafrost an area increase of 12% with a 45% increase in the number of lakes, while in discontinuous permafrost areas, the lake area decreased. Kirpotin et al. (2009) observe a similar pattern in western Siberian peatlands. However, Karlsson et al. (2014) did not find a consistent trend in lake area in West Siberia based on a remote sensing study. Fedorov et al. (2014) report large expansion of a thaw lake from 195 m^2 in 1993 to 3135 m^2 in Central Yakutia.

Thawing permafrost can result in both decrease of lake area (if lakes drain through talik development or erosion of drainage thresholds) or increase (if lake recharge increases through thicker active layer and supra-permafrost taliks). Permafrost lake hydrology often lacks data on groundwater flow (Fedorov et al. 2014; Walvoord and Kurylyk 2016). Lakes and ponds disappear in various ways, in which catastrophic drainage by erosion is a frequent process (Kirpotin et al. 2008; Jones et al. 2011; Grosse et al. 2013). Other processes may be infilling by sedimentation, including peat formation (Walter Anthony et al. 2014). After drainage or infilling with sediments, ice-rich permafrost can be established again over time (Grosse et al. 2013). These lake basins may become carbon and greenhouse gas sinks by uptake of CO_2 in peat and vegetation (Walter Anthony et al. 2014; Van der Molen et al. 2007).

Large areas of Northern Siberia are covered with overlapping drained thaw lake basins, dating from the Last Glacial Termination to recent (Walter et al. 2007b). Assuming accelerated reworking of Yedoma deposits with labile carbon by thaw lake growth, Walter et al. (2007a) estimate that 50–100 Tg CH_4 year$-^1$) could be produced with future climate warming. However, many present lakes are secondary lakes, developing in older thaw lake basin sediments with less ice volume than Yedoma and probably less labile carbon because carbon in these sediments has undergone already a decomposition cycle from previous lake growth (Morgenstern et al. 2011, 2013). Also, present lakes expand in areas that already contain CH_4-emitting wetlands, of which the emission has to be taken into account. Future estimates of CH_4 emission from lake growth will strongly depend on rates of geomorphological processes of lake growth and drainage, lake hydrology, and carbon transformation. An approximation of landscape-scale lake development with a probabilistic cellular automata model of thaw lake expansion and erosional drainage shows that lake expansion has limits (Van Huissteden et al. 2011). For all future climate scenarios, the model shows a gradual expansion of lake area at first, followed by a decrease of lake area due to drainage. To reliably estimate future CH_4

emission from expanding thaw lakes, long-term geomorphological process and hydrological studies are necessary.

The net effect on carbon release from permafrost of push disturbances such as pond and lake development should include the life cycle and recovery rate of these features (Van Huissteden and Dolman 2012). Ponds revegetate over time, in the order of several years to decades, and may become sinks of CO_2 again; this CO_2 sink may even be stimulated by nutrient release from thawing SOM (Li et al. 2017). If recovery effects are not considered, an overestimate of the total emission results (Van Huissteden and Dolman 2012).

5.5.4 Other Anthropogenic Disturbances

Human activities increase in vulnerable permafrost ecosystems as a result of economic development. Permafrost ecosystems are fragile, and soils and vegetation are easily disturbed by frequent walking or motorized traffic. The vegetation shields permafrost soils from incoming solar radiation and high air temperatures. Blok et al. (2010, 2011) and Nauta et al. (2014) have demonstrated that the removal of a shrub cover on dry, ice-rich permafrost leads to an increased ALT and the development of thaw ponds, turning the shrub removal areas from a sink of CH_4 into a source in 5 years.

A drainage experiment on the Kolyma River floodplain near Cherskii started in 2004, resulting in an average water table drop of 20 cm (Merbold et al. 2009; Kwon et al. 2016, 2017). The main vegetation in the area consists of *Carex appendiculata* tussocks and *Eriophorum angustifolium* cotton grass. Drainage lowered the growing season of CH_4 flux by a factor of 20 as measured in 2013. The soil temperature profile changed as a result of changed thermal properties (dry organic soil has lower thermal conductivity). The deeper subsoil in the drained areas was colder, resulting in a decrease of thaw depth, while in the top layer temperature fluctuated more strongly. This water table and temperature profile change drives the differences in CH_4 flux, reducing methanogenesis at depth and promoting methanotrophy in the topsoil. Additionally, a decrease in abundance of *E. angustifolium* reduced aerenchymous transport of CH_4.

However, drainage of permafrost wetlands is probably not an option for mitigating CH_4 fluxes. Drainage enhanced aerobic decomposition in the organic-rich soil (Kwon et al. 2016; Kittler et al. 2017). Before drainage, the area was a summer greenhouse gas source of 475 ± 253 g C-CO2-eq m^{-2}, which was reduced to 23 ± 26 g C-CO_2-equivalent m^{-2} shortly after drainage (Merbold et al. 2009). After 10 years of drainage, CO_2 uptake decreased, and CO_2 emission increased, resulting in a larger net GHG source (Kwon et al. 2016, 2017). An important cause of decreased CO_2 uptake is vegetation change: the decline in abundance of *E. angustifolium*, which is a high CH_4-emitting species, also contributes strongly to CO_2 uptake.

These experiments on anthropogenic manipulation of permafrost ecosystems show that there are no simple answers on how to mitigate CH_4 emission from permafrost ecosystems. However, the experiment by Nauta et al. (2014) points convincingly to protection of the vulnerable vegetation cover of permafrost ecosystems; increasing human activities without this protection may result in increased GHG emission.

5.6 BVOC

Oxidation by OH radicals is the main atmospheric sink for CH_4, but also for many organic compounds of natural (vegetation, wildfires) and anthropogenic origin. Non-methane volatile organic compounds (NMVOC) therefore compete with CH_4 for this atmospheric sink and have significant impact on the lifetime of CH_4 and global or regional CH_4 budget (e.g. O'Connor et al. 2010, Thonat et al. 2017). A major component of NMVOC are the biogenic volatile organic compounds (BVOCs), emitted by vegetation. BVOCs consist of thousands of volatile organic chemical species, e.g. isoprenes, terpenoids, alkanes, alkenes, alcohols, esters, carbonyls, and acids. However, only a few of these are emitted at quantities that may impact the atmosphere. The most important of these compounds are terpenoids, including isoprene and monoterpene which are the most studied compounds (Guenther 2013). Taiga forests such as those in Eastern Siberia are an important source of BVOC (Arneth et al. 2007).

With climate change the emission of these compounds may increase by higher temperatures, plant stress, and increasing leaf area (e.g. Arneth et al. 2007; O'Connor et al. 2010; Kramshøj et al. 2016), causing the atmospheric lifetime of CH_4 to become longer, resulting in a further increase of atmospheric CH_4 concentration. However, the emission of the important BVOC component isoprene is reduced at higher atmospheric CO_2 concentrations (Arneth et al. 2007), and furthermore BVOCs also result in the production of secondary organic aerosols that scatter and absorb radiation and act as cloud condensation nuclei (Arneth et al. 2010, 2016 and references therein), reducing solar radiation at the Earth's surface, complicating the effect of BVOC on climate.

Emission factors (E_s) for BVOCs are influenced by environmental parameters, such as light, temperature, and intercellular CO_2 concentration in leaves. Other drivers that can influence E_s are environmental stress, past environmental conditions, leaf age, and seasonality. In particular drought and heat stress are important, but also include the effects of air pollution such as ozone. For some compounds, e.g. isoprene, formation and emission is directly related to current environmental conditions of the plants, but other compounds like monoterpene can be stored in plants which complicates the relation of E_s with the environment by emission from storage (Niinemets et al. 2010).

In assessments of global BVOC emission, the huge Siberian forests have been severely under-sampled. Emission rates for terpenoids at the level of shoots were measured first by Kajos et al. (2013) in *Larix cajanderi* forest near Yakutsk (SPA station). They identified seven different monoterpenes, six different sesquiterpenes, linalool isoprene, and 2-methyl-3-buten-2-ol (MBO). Monoterpenes were dominant and contributed between 61% and 92% of the total emissions; the second important component was linalool isoprene. The emissions varied between 0.5 and 18.5 μg g_{dw}^{-1} h^{-1} and followed the daily cycles of temperature and photosynthetically active radiation. However, the differences among the studied trees were large, possibly because of mechanical stress and herbivore attack in the tree with the highest emissions. The monoterpene emission rates were best described by a model that involves emissions from a both storage pool and emissions directly after synthesis.

Unfortunately not much is known about BVOC emissions in the northern tundras in Eastern Siberia. Emissions of isoprene, methanol, acetone, and acetaldehyde measured above a mire in Northern Sweden measured with disjunct eddy correlation showed a large contribution from this wetland environment: isoprene emission rates were 329 μgC m^{-2} (Holst et al. 2010). Kramshøj et al. (2016) measured BVOC emissions from tundra plants (*Salix glauca* and *Empetrum hermaphroditum*) in a warming experiment in Greenland tundra. Warming by on average 3.1 °C resulted in a 260% increase of BVOC emission. These data demonstrate the need for further study in the large tundra area in Eastern Siberia.

Formaldehyde (HCHO) is a product in the oxidation of VOC from various sources (vegetation, wildfires, anthropogenic sources) and are therefore a proxy for BVOC sources. Satellite observations of atmospheric column formaldehyde concentrations, in combination with inverse modelling of sources (fire and vegetation isoprene emissions), indicate a strong increasing trend (3.8% per year) of isoprene emissions over Siberia (Bauwens et al. 2016; Fig. 5.7). This is attributed to increasing temperature and leaf area index.

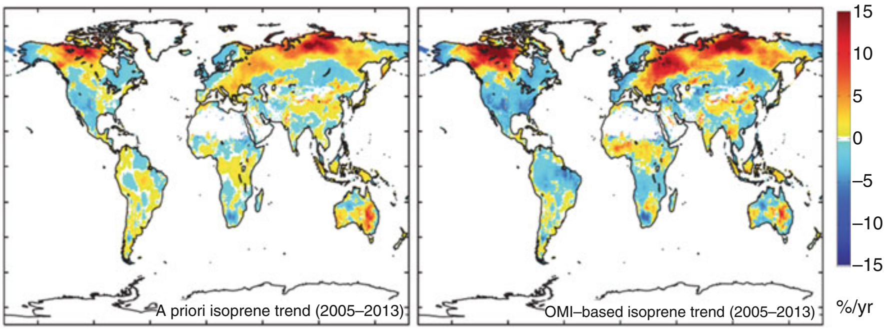

Fig. 5.7 Global distribution of annual isoprene emission trends over 2005–2013 according to an a priori model inversion of formaldehyde sources (left) and a top-down inventory from satellite formaldehyde data (right) expressed in percentage year. (From Bauwens et al. 2016)

Because of the complexity of interactions of BVOC emissions with greenhouse warming, Arneth et al. (2016) set up a modelling experiment for Eastern Siberia to assess these competing effects, including CO_2 emission from soil. The model experiment included the global vegetation model LPJ-GUESS and the ECHAM5.5-HAM2 climate model, with aerosol microphysics included. The emission factors for monoterpenes were taken from the minimum and maximum values measured in Siberia (Kajos et al. 2013), and CO_2 inhibition of BVOC formation was switched on and off in the models. Combined with CO_2 emission inhibition, BVOC emission decreased slightly by the end of this century. Without CO_2 inhibition, BVOC emissions almost tripled.

The model showed the importance of correctly predicting the effect of climate change on the leaf area index of tree species, since forest expansion would result in increasing BVOC emissions (although tundra emissions were not included). The effect on aerosol formation was considered small however, compared to the effects of aerosols from wildfires. The potential radiative effect of increasing BVOC emissions at the end of the century was a -0.2 W m^{-2} change on direct clear-sky radiation and an additional -0.5 W m^{-2} on the cloud radiative effect, but subject to large uncertainty. However, this modelling effort clearly shows the necessity of an integrative approach to the climate effect of BVOC emissions.

5.7 Conclusions

Field research based in Eastern Siberia has contributed significantly to process knowledge of the permafrost carbon feedback to climate change, in particular with respect to CH_4 emissions. However, more progress can be made. Winter emissions have shown to make up an important part of the yearly CH_4 budget of permafrost ecosystems; also spring thaw emissions from lake and pond ice can be substantial. Therefore, research efforts including the full winter season are urgently needed. Other CH_4 sources that need attention are:

- Spatial variabilities of ecosystem CH_4 emissions with attention to landscape-scale variation (lakes, drained thaw lake basins, floodplain wetlands).
- Transfer of old permafrost carbon to labile carbon compounds as substrate for methanogens.
- Potential emissions from deeper permafrost gas reservoirs in depth ranges that can be influenced by permafrost warming in the coming decades.
- Permafrost thaw and CH_4 emission resulting of human disturbance of ecosystems.
- Given the contribution of East Siberian ecosystems to global emission of BVOC and its effects on the oxidative OH sink of CH_4, also these emissions should be quantified better, in particular in the tundra regions of Eastern Siberia.

References

AMAP (2017) Snow, water, ice and permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo

Angle JC, Morin TH, Solden LM, Narrowe AB, Smith GJ, Borton MA, Rey-Sanchez C, Daly RA, Mirfenderesgi G, Hoyt DW (2017) Methanogenesis in oxygenated soils is a substantial fraction of wetland methane emissions. Nat Commun 8(1):1567

Archer D (2007) Methane hydrate stability and anthropogenic climate change. Biogeosci Discuss 4 (2):993–1057

Arneth A, Niinemets Ü, Pressley S, Bäck J, Hari P, Karl T, Noe S, Prentice I, Serça D, Hickler T (2007) Process-based estimates of terrestrial ecosystem isoprene emissions: incorporating the effects of a direct CO_2-isoprene interaction. Atmos Chem Phys 7(1):31–53

Arneth A, Sitch S, Bondeau A, Butterbach-Bahl K, Foster P, Gedney N, de Noblet-Ducoudré N, Prentice IC, Sanderson M, Thonicke K, Wania R, Zaehle S (2010) From biota to chemistry and climate: towards a comprehensive description of trace gas exchange between the biosphere and atmosphere. Biogeosciences 7(1):121–149

Arneth A, Makkonen R, Olin S, Paasonen P, Holst T, Kajos MK, Kulmala M, Maximov T, Miller PA, Schurgers G (2016) Future vegetation–climate interactions in Eastern Siberia: an assessment of the competing effects of CO_2 and secondary organic aerosols. Atmos Chem Phys 16 (8):5243–5262. https://doi.org/10.5194/acp-16-5243-2016

Babkina E, Khomutov A, Leibman M, Dvornikov Y, Kizyakov A (2017) Babkin E Paragenesis of thermal denudation with gas-emission crater and lake formation, Yamal Peninsula, Russia. EGU General Assembly Conference Abstracts, In, p 6026

Bastviken D, Ejlertsson J, Sundh I, Tranvik L (2003) Methane as a source of carbon and energy for lake pelagic food webs. Ecology 84(4):969–981

Bastviken D, Cole JJ, Pace ML, Van de Bogert MC (2008) Fates of methane from different lake habitats: connecting whole-lake budgets and CH4 emissions. J Geophys Res Biogeosci 113(G2)

Bauwens M, Stavrakou T, Müller J-F, Smedt ID, Roozendael MV, Werf GR, Wiedinmyer C, Kaiser JW, Sindelarova K, Guenther A (2016) Nine years of global hydrocarbon emissions based on source inversion of OMI formaldehyde observations. Atmos Chem Phys 16(15):10133–10158

Beermann F, Teltewskoi A, Fiencke C, Pfeiffer E-M, Kutzbach L (2015) Stoichiometric analysis of nutrient availability (N, P, K) within soils of polygonal tundra. Biogeochemistry 122 (2-3):211–227

Bergamaschi P, Houweling S, Segers A, Krol M, Frankenberg C, Scheepmaker RA, Dlugokencky E, Wofsy SC, Kort EA, Sweeney C, Schuck T, Brenninkmeijer C, Chen H, Beck V, Gerbig C (2013) Atmospheric CH4in the first decade of the 21st century: inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements. J Geophys Res Atmos 118(13):7350–7369. https://doi.org/10.1002/jgrd.50480

Berrittella C, van Huissteden J, Warnsloh JM, Dolman AJ (2017) Permafrost ecosystem: wetlands characteristics and their influence on CH4 emissions in a drained thaw lake basin, Northeastern Siberia. In: Berrittella C (ed) Wetland methane emissions during Last Glacial climate warming. PhD thesis edn. VU University, Amsterdam

Bhullar GS, Edwards PJ, Olde Venterink H (2013) Variation in the plant-mediated methane transport and its importance for methane emission from intact wetland peat mesocosms. J Plant Ecol 6(4):298–304. https://doi.org/10.1093/jpe/rts045

Bintanja R, Selten F (2014) Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. Nature 509(7501):479

Blok D, Heijmans MM, Schaepman-Strub G, Kononov A, Maximov T, Berendse F (2010) Shrub expansion may reduce summer permafrost thaw in Siberian tundra. Glob Chang Biol 16 (4):1296–1305

Blok D, Heijmans MMPD, Schaepman-Strub G, van Ruijven J, Parmentier FJW, Maximov TC, Berendse F (2011) The cooling capacity of mosses: controls on water and energy fluxes in a Siberian Tundra site. Ecosystems 14(7):1055–1065. https://doi.org/10.1007/s10021-011-9463-5

Boike J, Georgi C, Kirilin G, Muster S, Abramova K, Fedorova I, Chetverova A, Grigoriev M, Bornemann N, Langer M (2015) Thermal processes of thermokarst lakes in the continuous permafrost zone of northern Siberia – observations and modeling (Lena River Delta, Siberia). Biogeosciences 12(20):5941–5965. https://doi.org/10.5194/bg-12-5941-2015

Brouchkov A, Fukuda M (2002) Preliminary measurements on methane content in permafrost, Central Yakutia, and some experimental data. Permafr Periglac Process 13(3):187–197. https://doi.org/10.1002/ppp.422

Brouchkov A, Fukuda M, Fedorov A, Konstantinov P, Iwahana G (2004) Thermokarst as a short-term permafrost disturbance, Central Yakutia. Permafr Periglac Process 15(1):81–87. https://doi.org/10.1002/ppp.473

Bruhwiler L, Dlugokencky E, Masarie K, Ishizawa M, Andrews A, Miller J, Sweeney C, Tans P, Worthy D (2014) CarbonTracker-CH_4: an assimilation system for estimating emissions of atmospheric methane. Atmos Chem Phys 14(16):8269–8293

Budishchev A, Mi Y, van Huissteden J, Belelli-Marchesini L, Schaepman-Strub G, Parmentier FJW, Fratini G, Gallagher A, Maximov TC, Dolman AJ (2014) Evaluation of a plot-scale methane emission model using eddy covariance observations and footprint modelling. Biogeosciences 11(17):4651–4664. https://doi.org/10.5194/bg-11-4651-2014

Callaghan TV, Johansson M, Brown RD, Groisman PY, Labba N, Radionov V, Barry RG, Bulygina ON, Essery RLH, Frolov DM, Golubev VN, Grenfell TC, Petrushina MN, Razuvaev VN, Robinson DA, Romanov P, Shindell D, Shmakin AB, Sokratov SA, Warren S, Yang D (2012) The changing face of Arctic snow cover: a synthesis of observed and projected changes. Ambio 40(S1):17–31. https://doi.org/10.1007/s13280-011-0212-y

Chadburn SE, Krinner G, Porada P, Bartsch A, Beer C, Belelli Marchesini L, Boike J, Ekici A, Elberling B, Friborg T, Hugelius G, Johansson M, Kuhry P, Kutzbach L, Langer M, Lund M, Parmentier FJW, Peng S, Van Huissteden K, Wang T, Westermann S, Zhu D, Burke EJ (2017) Carbon stocks and fluxes in the high latitudes: using site-level data to evaluate Earth system models. Biogeosciences 14(22):5143–5169. https://doi.org/10.5194/bg-14-5143-2017

Christensen TR, Jonasson S, Callaghan TV, Havström M (1995) Spatial variation in high latitude methane flux-a transect across tundra environments in Siberia and the European Arctic. J Geophys Res 100(D10):21035–21045

Christensen TR, Ekberg A, Ström L, Mastepanov M, Panikov N, Öquist M, Svensson BH, Nykänen H, Martikainen PJ, Oskarsson H (2003) Factors controlling large scale variations in methane emissions from wetlands. Geophys Res Lett 30(7). https://doi.org/10.1029/2002gl016848

Corbett JE, Tfaily MM, Burdige DJ, Glaser PH, Chanton JP (2015) The relative importance of methanogenesis in the decomposition of organic matter in northern peatlands. J Geophys Res Biogeosci 120(2):280–293

Corradi C, Kolle O, Walter K, Zimov SA, Schulze ED (2005) Carbon dioxide and methane exchange of a north-east Siberian tussock tundra. Glob Chang Biol 11:1910–1925. https://doi.org/10.1111/j.1365-2486.2005.01023.x

Deutzmann JS, Stief P, Brandes J, Schink B (2014) Anaerobic methane oxidation coupled to denitrification is the dominant methane sink in a deep lake. Proc Natl Acad Sci 111 (51):18273–18278

Duguay CR, Flato GM, Jeffries MO, Ménard P, Morris K, Rouse WR (2003) Ice-cover variability on shallow lakes at high latitudes: model simulations and observations. Hydrol Process 17 (17):3465–3483. https://doi.org/10.1002/hyp.1394

Fedorov AN, Konstantinov PY (2009) Response of permafrost landscapes of Central Yakutia to current changes of climate, and anthropogenic impacts. Geogr Nat Resour 30(2):146–150

Fedorov A, Gavriliev P, Konstantinov P, Hiyama T, Iijima Y, Iwahana G (2014) Estimating the water balance of a thermokarst lake in the middle of the Lena River basin, eastern Siberia. Ecohydrology 7(2):188–196

Flessa H, Rodionov A, Guggenberger G, Fuchs H, Magdon P, Shibistova O, Zrazhevskaya G, Mikheyeva N, Kasansky OA, Blodau C (2008) Landscape controls of CH4fluxes in a catchment of the forest tundra ecotone in northern Siberia. Glob Chang Biol 14(9):2040–2056. https://doi.org/10.1111/j.1365-2486.2008.01633.x

Frenzel P, Karofeld E (2000) CH_4 emission from a hollow-ridge complex in a raised bog: the role of CH_4 production and oxidation. Biogeochemistry 51(1):91–112

Ganzert L, Jurgens G, Munster U, Wagner D (2007) Methanogenic communities in permafrost-affected soils of the Laptev Sea coast, Siberian Arctic, characterized by 16S rRNA gene fingerprints. FEMS Microbiol Ecol 59(2):476–488. https://doi.org/10.1111/j.1574-6941.2006.00205.x

Gauci V, Gowing DJ, Hornibrook ER, Davis JM, Dise NB (2010) Woody stem methane emission in mature wetland alder trees. Atmos Environ 44(17):2157–2160

Glagolev M, Kleptsova I, Filippov I, Maksyutov S, Machida T (2011) Regional methane emission from West Siberia mire landscapes. Environ Res Lett 6(4):045214. https://doi.org/10.1088/1748-9326/6/4/045214

Goovaerts A (2016) An explorative study of carbon sources and greenhouse gas emissions in thermokarst lakes and rivers using stable isotopes (Chokurdakh, Yakutsk, Russia). Master Thesis, KU Leuven, Facultei Bio-Ingenieurswetenschappen:122

Grosse G, Romanovsky V, Walter K, Morgenstern A, Lantuit H, Zimov S (2008) Distribution of thermokarst lakes and ponds at three yedoma sites in Siberia. In: 9th International conference on Permafrost, Fairbanks, 2008. Proceedings 9th International conference on Permafrost. pp 551–556

Grosse G, Harden J, Turetsky M, McGuire AD, Camill P, Tarnocai C, Frolking S, Schuur EAG, Jorgenson T, Marchenko S, Romanovsky V, Wickland KP, French N, Waldrop M, Bourgeau-Chavez L, Striegl RG (2011) Vulnerability of high-latitude soil organic carbon in North America to disturbance. J Geophys Res 116. https://doi.org/10.1029/2010jg001507

Grosse G, Jones B, Arp C (2013) 8. 21 Thermokarst lakes, drainage, and drained basins. 325–353. https://doi.org/10.1016/b978-0-12-374739-6.00216-5

Guenther A (2013) Biological and chemical diversity of biogenic volatile organic emissions into the atmosphere. ISRN Atmos Sci 2013:1–27. https://doi.org/10.1155/2013/786290

Gustafsson Ö, van Dongen BE, Vonk JE, Dudarev OV, Semiletov IP (2011) Widespread release of old carbon across the Siberian Arctic echoed by its large rivers. Biogeosciences 8 (6):1737–1743. https://doi.org/10.5194/bg-8-1737-2011

Hershey AE, Northington RM, Whalen SC (2013) Substrate limitation of sediment methane flux, methane oxidation and use of stable isotopes for assessing methanogenesis pathways in a small arctic lake. Biogeochemistry 117(2-3):325–336. https://doi.org/10.1007/s10533-013-9864-y

Hines ME, Duddleston KN, Kiene RP (2001) Carbon flow to acetate and C1 compounds in northern wetlands. Geophys Res Lett 28(22):4251–4254

Hodgkins SB, Tfaily MM, McCalley CK, Logan TA, Crill PM, Saleska SR, Rich VI, Chanton JP (2014) Changes in peat chemistry associated with permafrost thaw increase greenhouse gas production. Proc Natl Acad Sci USA 111(16):5819–5824. https://doi.org/10.1073/pnas.1314641111

Hoj L, Olsen RA, Torsvik VL (2008) Effects of temperature on the diversity and community structure of known methanogenic groups and other archaea in high Arctic peat. ISME J 2 (1):37–48. https://doi.org/10.1038/ismej.2007.84

Holst T, Arneth A, Hayward S, Ekberg A, Mastepanov M, Jackowicz-Korczynski M, Friborg T, Crill PM, Bäckstrand K (2010a) BVOC ecosystem flux measurements at a high latitude wetland site. Atmos Chem Phys 10(4):1617–1634

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson C (2001) Climate change 2001: the scientific basis. The Press Syndicate of the University of Cambridge, Cambridge

Houweling S, Krol M, Bergamaschi P, Frankenberg C, Dlugokencky EJ, Morino I, Notholt J, Sherlock V, Wunch D, Beck V, Gerbig C, Chen H, Kort EA, Röckmann T, Aben I (2014) A multi-year methane inversion using SCIAMACHY, accounting for systematic errors using TCCON measurements. Atmos Chem Phys 14(8):3991–4012. https://doi.org/10.5194/acp-14-3991-2014

Hugelius G, Strauss J, Zubrzycki S, Harden JW, Schuur EAG, Ping CL, Schirrmeister L, Grosse G, Michaelson GJ, Koven CD, O'Donnell JA, Elberling B, Mishra U, Camill P, Yu Z, Palmtag J, Kuhry P (2014) Improved estimates show large circumpolar stocks of permafrost carbon while quantifying substantial uncertainty ranges and identifying remaining data gaps. Biogeosci Discuss 11(3):4771–4822. https://doi.org/10.5194/bgd-11-4771-2014

Iijima Y, Fedorov AN, Park H, Suzuki K, Yabuki H, Maximov TC, Ohata T (2010) Abrupt increases in soil temperatures following increased precipitation in a permafrost region, central Lena River basin, Russia. Permaf Periglac Process 21(1):30–41. https://doi.org/10.1002/ppp.662

Jammet M, Crill P, Dengel S, Friborg T (2015) Large methane emissions from a subarctic lake during spring thaw: mechanisms and landscape significance. J Geophys Res Biogeosci 120 (11):2289–2305. https://doi.org/10.1002/2015jg003137

Johansson M, Callaghan TV, Bosiö J, Åkerman HJ, Jackowicz-Korczynski M, Christensen TR (2013) Rapid responses of permafrost and vegetation to experimentally increased snow cover in sub-arctic Sweden. Environ Res Lett 8(3):035025. https://doi.org/10.1088/1748-9326/8/3/035025

Jones BM, Grosse G, Arp C, Jones M, Walter Anthony K, Romanovsky V (2011) Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. J Geophys Res Biogeosci 116(G2):G00M03. https://doi.org/10.1029/2011JG001666

Jørgenson JC, Lund Johansen KM, Westergaard-Nielsen A, Elberling B (2014) Net regional methane sink in High Arctic soils of northeast Greenland. Nat Geosci 8(1):20–23. https://doi.org/10.1038/ngeo2305

Jorgenson MT, Shur Y (2007) Evolution of lakes and basins in northern Alaska and discussion of the thaw lake cycle. J Geophys Res Earth Surf 112(F2):F02S17. https://doi.org/10.1029/2006JF000531

Jorgenson MT, Shur YL, Pullman ER (2006) Abrupt increase in permafrost degradation in Arctic Alaska. Geophys Res Lett 33(2). https://doi.org/10.1029/2005gl024960

Kajos M, Hakola H, Holst T, Nieminen T, Tarvainen V, Maximov T, Petäjä T, Arneth A, Rinne J (2013) Terpenoid emissions from fully grown east Siberian Larix cajanderi trees. Biogeosciences 10(7):4705

Karlsson J, Lyon S, Destouni G (2014) Temporal behavior of lake size-distribution in a thawing permafrost landscape in Northwestern Siberia. Remote Sens 6(1):621–636. https://doi.org/10.3390/rs6010621

King J, Reeburgh W, Thieler K, Kling G, Loya W, Johnson L, Nadelhoffer K (2002) Pulse-labeling studies of carbon cycling in Arctic tundra ecosystems: the contribution of photosynthates to methane emission. Glob Biogeochem Cycles 16(4):1062. https://doi.org/10.1029/2001GB001456

Kip N, van Winden JF, Pan Y, Bodrossy L, Reichart G-J, Smolders AJP, Jetten MSM, Damsté JSS, Op den Camp HJM (2010) Global prevalence of methane oxidation by symbiotic bacteria in peat-moss ecosystems. Nat Geosci 3(9):617–621. https://doi.org/10.1038/ngeo939

Kirpotin S, Polishchuk Y, Zakharova E, Shirokova L, Pokrovsky O, Kolmakova M, Dupre B (2008) One of the possible mechanisms of thermokarst lakes drainage in West-Siberian North. Int J Environ Stud 65(5):631–635. https://doi.org/10.1080/00207230802525208

Kirpotin SN, Polishchuk Y, Bryksina N (2009) Abrupt changes of thermokarst lakes in Western Siberia: impacts of climatic warming on permafrost melting. Int J Environ Stud 66(4):423–431. https://doi.org/10.1080/00207230902758287

Kirpotin S, Polishchuk Y, Bryksina N, Sugaipova A, Kouraev A, Zakharova E, Pokrovsky OS, Shirokova L, Kolmakova M, Manassypov R, Dupre B (2011) West Siberian palsa peatlands: distribution, typology, cyclic development, present day climate-driven changes, seasonal hydrology and impact on CO_2 cycle. Int J Environ Stud 68(5):603–623. https://doi.org/10.1080/00207233.2011.593901

Kirschke S, Bousquet P, Ciais P, Saunois M, Canadell JG, Dlugokencky EJ, Bergamaschi P, Bergmann D, Blake DR, Bruhwiler L (2013) Three decades of global methane sources and sinks. Nat Geosci 6(10):813

Kittler F, Heimann M, Kolle O, Zimov N, Zimov S, Göckede M (2017) Long-term drainage reduces CO2 uptake and CH4 emissions in a Siberian permafrost ecosystem. Global Biogeochem Cycles 31 https://doi.org/10.1002/2017GB005774

Knoblauch C, Zimmermann U, Blumenberg M, Michaelis W, Pfeiffer E-M (2008) Methane turnover and temperature response of methane-oxidizing bacteria in permafrost-affected soils of northeast Siberia. Soil Biol Biochem 40(12):3004–3013

Knoblauch C, Spott O, Evgrafova S, Kutzbach L, Pfeiffer EM (2015) Regulation of methane production, oxidation, and emission by vascular plants and bryophytes in ponds of the northeast Siberian polygonal tundra. J Geophys Res Biogeosci 120(12):2525–2541

Kobabe S, Wagner D, Pfeiffer EM (2004) Characterisation of microbial community composition of a Siberian tundra soil by fluorescence in situ hybridisation. FEMS Microbiol Ecol 50(1):13–23. https://doi.org/10.1016/j.femsec.2004.05.003

Kraev GN, Schultze ED, Rivkina EM (2012) Cryogenesis as a factor of methane distribution in layers of permafrost. Dokl Earth Sci 451(2):882–885. https://doi.org/10.1134/s1028334x13080291

Kramshøj M, Vedel-Petersen I, Schollert M, Rinnan Å, Nymand J, Ro-Poulsen H, Rinnan R (2016) Large increases in Arctic biogenic volatile emissions are a direct effect of warming. Nat Geosci 9(5):349–352

Kutzbach L, Wagner D, Pfeiffer E-M (2004) Effect of microrelief and vegetation on methane emission from wet polygonal tundra, Lena Delta, Northern Siberia. Biogeochemistry 69 (3):341–362

Kutzbach L, Schneider J, Sachs T, Giebels M, Nykänen H, Shurpali N, Martikainen P, Alm J, Wilmking M (2007) CO_2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression. Biogeosciences 4(6):1005–1025

Kwon MJ, Heimann M, Kolle O, Luus KA, Schuur EAG, Zimov N, Zimov SA, Göckede M (2016) Long-term drainage reduces CO_2 uptake and increases CO_2 emission on a Siberian floodplain due to shifts in vegetation community and soil thermal characteristics. Biogeosciences 13 (14):4219–4235. https://doi.org/10.5194/bg-13-4219-2016

Kwon MJ, Beulig F, Ilie I, Wildner M, Kusel K, Merbold L, Mahecha MD, Zimov N, Zimov SA, Heimann M, Schuur EAG, Kostka JE, Kolle O, Hilke I, Gockede M (2017) Plants, microorganisms, and soil temperatures contribute to a decrease in methane fluxes on a drained Arctic floodplain. Glob Chang Biol 23(6):2396–2412. https://doi.org/10.1111/gcb.13558

Langer M, Westermann S, Walter Anthony K, Wischnewski K, Boike J (2015) Frozen ponds: production and storage of methane during the Arctic winter in a lowland tundra landscape in northern Siberia, Lena River delta. Biogeosciences 12(4):977–990. https://doi.org/10.5194/bg-12-977-2015

Lara MJ, McGuire AD, Euskirchen ES, Tweedie CE, Hinkel KM, Skurikhin AN, Romanovsky VE, Grosse G, Bolton WR, Genet H (2015) Polygonal tundra geomorphological change in response to warming alters future CO_2 and CH_4 flux on the Barrow Peninsula. Glob Chang Biol 21 (4):1634–1651. https://doi.org/10.1111/gcb.12757

Larmola T, Tuittila E-S, Tiirola M, Nykänen H, Martikainen PJ, Yrjälä K, Tuomivirta T, Fritze H (2010) The role of Sphagnum mosses in the methane cycling of a boreal mire. Ecology 91 (8):2356–2365

Larmola T, Leppänen SM, Tuittila E-S, Aarva M, Merilä P, Fritze H, Tiirola M (2014) Methanotrophy induces nitrogen fixation during peatland development. Proc Natl Acad Sci 111(2):734–739

Leibman MO, Kizyakov AI, Plekhanov AV, Streletskaya ID (2014) New permafrost feature–deep crater in Central Yamal (West Siberia, Russia) as a response to local climate fluctuations. Environ Sustain 4:68–80

Li B, Heijmans MMPD, Blo D, Wang P, Karsanaev SV, Maximov TC, Van Huissteden J, Berendse F (2017) Thaw pond development and initial vegetation succession in experimental plots at a Siberian lowland tundra site. Pant Soil 420:147–162. https://doi.org/10.1007/s11104-017-3369-8

Liebner S, Zeyer J, Wagner D, Schubert C, Pfeiffer EM, Knoblauch C (2011) Methane oxidation associated with submerged brown mosses reduces methane emissions from Siberian polygonal tundra. J Ecol 99(4):914–922

Liljedahl AK, Boike J, Daanen RP, Fedorov AN, Frost GV, Grosse G, Hinzman LD, Iijma Y, Jorgenson JC, Matveyeva N, Necsoiu M, Raynolds MK, Romanovsky VE, Schulla J, Tape KD, Walker DA, Wilson CJ, Yabuki H, Zona D (2016) Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. Nat Geosci 9(4):312–318. https://doi.org/10.1038/ngeo2674

Mastepanov M, Sigsgaard C, Dlugokencky EJ, Houweling S, Strom L, Tamstorf MP, Christensen TR (2008) Large tundra methane burst during onset of freezing. Nature 456(7222):628–630. https://doi.org/10.1038/nature07464

Mastepanov M, Sigsgaard C, Tagesson T, Ström L, Tamstorf MP, Lund M, Christensen T (2013) Revisiting factors controlling methane emissions from high-Arctic tundra. Biogeosciences 10 (7):5139

McGuire AD, Christensen TR, Hayes D, Heroult A, Euskirchen E, Kimball JS, Koven C, Lafleur P, Miller PA, Oechel W, Peylin P, Williams M, Yi Y (2012) An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. Biogeosciences 9(8):3185–3204. https://doi.org/10.5194/bg-9-3185-2012

Melton JR, Wania R, Hodson EL, Poulter B, Ringeval B, Spahni R, Bohn T, Avis CA, Beerling DJ, Chen G, Eliseev AV, Denisov SN, Hopcroft PO, Lettenmaier DP, Riley WJ, Singarayer JS, Subin ZM, Tian H, Zürcher S, Brovkin V, van Bodegom PM, Kleinen T, Yu ZC, Kaplan JO (2013) Present state of global wetland extent and wetland methane modelling: conclusions from a model inter-comparison project (WETCHIMP). Biogeosciences 10(2):753–788. https://doi.org/10.5194/bg-10-753-2013

Merbold L, Kutsch WL, Corradi C, Kolle O, Rebmann C, Stoy PC, Zimov SA, Schulze ED (2009) Artificial drainage and associated carbon fluxes (CO2/CH4) in a tundra ecosystem. Glob Chang Biol 15(11):2599–2614. https://doi.org/10.1111/j.1365-2486.2009.01962.x

Metje M, Frenzel P (2007) Methanogenesis and methanogenic pathways in a peat from subarctic permafrost. Environ Microbiol 9(4):954–964. https://doi.org/10.1111/j.1462-2920.2006.01217.x

Mi Y, van Huissteden J, Parmentier FJW, Gallagher A, Budishchev A, Berridge CT, Dolman AJ (2014) Improving a plot-scale methane emission model and its performance at a northeastern Siberian tundra site. Biogeosciences 11(14):3985–3999. https://doi.org/10.5194/bg-11-3985-2014

Morgenstern A, Grosse G, Günther F, Fedorova I, Schirrmeister L (2011) Spatial analyses of thermokarst lakes and basins in Yedoma landscapes of the Lena Delta. Cryosphere 5 (4):849–867. https://doi.org/10.5194/tc-5-849-2011

Morgenstern A, Ulrich M, Günther F, Roessler S, Fedorova IV, Rudaya NA, Wetterich S, Boike J, Schirrmeister L (2013) Evolution of thermokarst in East Siberian ice-rich permafrost: a case study. Geomorphology 201:363–379. https://doi.org/10.1016/j.geomorph.2013.07.011

Morishita T, Hatano R, Desyatkin RV (2003) CH4flux in an alas ecosystem formed by forest disturbance near Yakutsk, Eastern Siberia, Russia. Soil Sci Plant Nutr 49(3):369–377. https://doi.org/10.1080/00380768.2003.10410022

Nakagawa F, Yoshida N, Nojiri Y, Makarov V (2002) Production of methane from alasses in eastern Siberia: implications from its 14C and stable isotopic compositions. Glob Biogeochem Cycles 16(3)

Nakano T, Kuniyoshi S, Fukuda M (2000) Temporal variation in methane emission from tundra wetlands in a permafrost area, northeastern Siberia. Atmos Environ 34(8):1205–1213

Nauta AL, Heijmans MMPD, Blok D, Limpens J, Elberling B, Gallagher A, Li B, Petrov RE, Maximov TC, van Huissteden J, Berendse F (2014) Permafrost collapse after shrub removal shifts tundra ecosystem to a methane source. Nat Clim Chang 5(1):67–70. https://doi.org/10.1038/nclimate2446

Niinemets Ü, Arneth A, Kuhn U, Monson RK, Peñuelas J, Staudt M (2010) The emission factor of volatile isoprenoids: stress, acclimation, and developmental responses. Biogeosciences 7 (7):2203–2223. https://doi.org/10.5194/bg-7-2203-2010

O'Connor FM, Boucher O, Gedney N, Jones CD, Folberth GA, Coppell R, Friedlingstein P, Collins WJ, Chappellaz J, Ridley J, Johnson CE (2010) Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: a review. Rev Geophys 48 (4). https://doi.org/10.1029/2010rg000326

Ohta T, Maximov TC, Dolman AJ, Nakai T, van der Molen MK, Kononov AV, Maximov AP, Hiyama T, Iijima Y, Moors EJ, Tanaka H, Toba T, Yabuki H (2008) Interannual variation of water balance and summer evapotranspiration in an eastern Siberian larch forest over a 7-year period (1998–2006). Agric For Meteorol 148(12):1941–1953. https://doi.org/10.1016/j.agrformet.2008.04.012

Overland JE, Wang M, Walsh JE, Christensen JH, Kattsov VM, Chapman WL (2011) Climate model projections for the Arctic. In: Snow, water, ice and permafrost in the Arctic (SWIPA). Arctic Monitoring and Assessment Programme (AMAP), Oslo

Parmentier FJW, van Huissteden J, Kip N, Op den Camp HJM, Jetten MSM, Maximov TC, Dolman AJ (2011a) The role of endophytic methane-oxidizing bacteria in submerged *Sphagnum* in determining methane emissions of Northeastern Siberian tundra. Biogeosciences 8 (5):1267–1278. https://doi.org/10.5194/bg-8-1267-2011

Parmentier FJW, van Huissteden J, van der Molen MK, Schaepman-Strub G, Karsanaev SA, Maximov TC, Dolman AJ (2011b) Spatial and temporal dynamics in eddy covariance observations of methane fluxes at a tundra site in northeastern Siberia. J Geophys Res 116(G3). https://doi.org/10.1029/2010jg001637

Parmentier F-JW, Christensen TR, Sørensen LL, Rysgaard S, McGuire AD, Miller PA, Walker DA (2013) The impact of lower sea-ice extent on Arctic greenhouse-gas exchange. Nat Clim Chang 3(3):195–202. https://doi.org/10.1038/nclimate1784

Parmentier FW, Zhang W, Mi Y, Zhu X, van Huissteden J, Hayes DJ, Zhuang Q, Christensen TR, McGuire AD (2015) Rising methane emissions from northern wetlands associated with sea ice decline. Geophys Res Lett 42(17):7214–7222. https://doi.org/10.1002/2015GL065013

Petrescu A, Van Huissteden J, Jackowicz-Korczynski M, Yurova A, Christensen T, Crill PM, Maximov T (2007) Modelling CH_4 emissions from arctic wetlands: effects of hydrological parameterization. Biogeosci Discuss 4(5):3195–3227

Petrescu A, Van Beek L, Van Huissteden J, Prigent C, Sachs T, Corradi C, Parmentier F, Dolman A (2010) Modeling regional to global CH_4 emissions of boreal and arctic wetlands. Glob Biogeochem Cycles 24(4)

Plug LJ, Walls C, Scott B (2008) Tundra lake changes from 1978 to 2001 on the Tuktoyaktuk Peninsula, western Canadian Arctic. Geophys Res Lett 35:L03502. https://doi.org/10.1029/2007GL032303

Pokrovsky OS, Shirokova LS, Kirpotin SN, Kulizhsky SP, Vorobiev SN (2013) Impact of western Siberia heat wave 2012 on greenhouse gases and trace metal concentration in thaw lakes of discontinuous permafrost zone. Biogeosciences 10(8):5349–5365

Raghoebarsing AA, Pol A, van de Pas-Schoonen KT, Smolders AJ, Ettwig KF, Rijpstra WI, Schouten S, Damste JS, Op den Camp HJ, Jetten MS, Strous M (2006) A microbial consortium couples anaerobic methane oxidation to denitrification. Nature 440(7086):918–921. https://doi.org/10.1038/nature04617

Rivkina E, Friedmann E, McKay C, Gilichinsky D (2000) Metabolic activity of permafrost bacteria below the freezing point. Appl Environ Microbiol 66(8):3230–3233

Rivkina E, Gilichinsky DA, McKay C, Dallimore S (2001) Methane distribution in permafrost: evidence for an interpore pressure methane hydrate. In: Permafrost response on economic development, environmental security and natural resources. Springer, Dordrecht, pp 487–496

Rivkina E, Shcherbakova V, Laurinavichius K, Petrovskaya L, Krivushin K, Kraev G, Pecheritsina S, Gilichinsky D (2007) Biogeochemistry of methane and methanogenic archaea in permafrost. FEMS Microbiol Ecol 61(1):1–15. https://doi.org/10.1111/j.1574-6941.2007.00315.x

Sachs T, Giebels M, Wille C, Kutzbach L, Boike J (2008a) Methane emission from Siberian wet polygonal tundra on multiple spatial scales: vertical flux measurements by closed chambers and eddy covariance, Samoylov Island, Lena River Delta. In: 9th international conference on permafrost, Fairbanks, pp 1549–1554

Sachs T, Wille C, Boike J, Kutzbach L (2008b) Environmental controls on ecosystem-scale CH4emission from polygonal tundra in the Lena River Delta, Siberia. J Geophys Res 113. https://doi.org/10.1029/2007jg000505

Sachs T, Giebels M, Boike J, Kutzbach L (2010) Environmental controls on CH4 emission from polygonal tundra on the microsite scale in the Lena river delta, Siberia. Glob Chang Biol 16 (11):3096–3110

Schädel C, Bader MK-F, Schuur EA, Biasi C, Bracho R, Čapek P, De Baets S, Diáková K, Ernakovich J, Estop-Aragones C (2016) Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. Nat Clim Chang 6(10):950

Schirrmeister LHM, Wetterich S, Siegert C, Kunitsky VV, Grosse G, Kuznetsova TV, Derevyagin AY (2008) The Yedoma Suite of the Northeastern Siberian Shelf Region: characteristics and Concept of Formation. Proceedings Ninth International Conference On Permafrost 2:1595–1600

Schirrmeister L, Grosse G, Wetterich S, Overduin PP, Strauss J, Schuur EAG, Hubberten H-W (2011) Fossil organic matter characteristics in permafrost deposits of the northeast Siberian Arctic. J Geophys Res 116. https://doi.org/10.1029/2011jg001647

Schirrmeister L, Froese D, Tumskoy V, Grosse G, Wetterich S (2013) Yedoma: late Pleistocene ice-rich syngenetic permafrost of Beringia. In: Encyclopedia of quaternary science, 2nd edn. Elsevier, Amsterdam, pp 542–552. https://doi.org/10.1016/b978-0-444-53643-3.00106-0

Schuur EA, Bockheim J, Canadell JG, Euskirchen E, Field CB, Goryachkin SV, Hagemann S, Kuhry P, Lafleur PM, Lee H (2008) Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. Bioscience 58(8):701–714

Schuur EA, McGuire AD, Schadel C, Grosse G, Harden JW, Hayes DJ, Hugelius G, Koven CD, Kuhry P, Lawrence DM, Natali SM, Olefeldt D, Romanovsky VE, Schaefer K, Turetsky MR, Treat CC, Vonk JE (2015) Climate change and the permafrost carbon feedback. Nature 520 (7546):171–179. https://doi.org/10.1038/nature14338

Segers R (1998) Methane production and methane consumption: a review of processes underlying wetland methane fluxes. Biogeochemistry 41(1):23–51

Shakhova N, Semiletov I (2007) Methane release and coastal environment in the East Siberian Arctic shelf. J Mar Syst 66(1-4):227–243. https://doi.org/10.1016/j.jmarsys.2006.06.006

Shkolnik I, Pavlova T, Efimov S, Zhuravlev S (2017) Future changes in peak river flows across northern Eurasia as inferred from an ensemble of regional climate projections under the IPCC RCP8.5 scenario. Clim Dyn. https://doi.org/10.1007/s00382-017-3600-6

Sidorova OV, Siegwolf RT, Saurer M, Naurzbaev MM, Vaganov EA (2008) Isotopic composition ($\delta^{13}C$, $\delta^{18}O$) in wood and cellulose of Siberian larch trees for early Medieval and recent periods. J Geophys Res Biogeosci 113:G02019. https://doi.org/10.1029/2007JG000473

Smith LC, Sheng Y, MacDonald G, Hinzman L (2005) Disappearing arctic lakes. Science 308 (5727):1429–1429

Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) (2013) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Strauss J, Schirrmeister L, Grosse G, Wetterich S, Ulrich M, Herzschuh U, Hubberten HW (2013) The deep permafrost carbon pool of the Yedoma region in Siberia and Alaska. Geophys Res Lett 40(23):6165–6170. https://doi.org/10.1002/2013GL058088

Ström L, Ekberg A, Mastepanov M, Røjle Christensen T (2003) The effect of vascular plants on carbon turnover and methane emissions from a tundra wetland. Glob Chang Biol 9 (8):1185–1192

Ström L, Mastepanov M, Christensen TR (2005) Species-specific effects of vascular plants on carbon turnover and methane emissions from wetlands. Biogeochemistry 75(1):65–82

Ström L, Falk JM, Skov K, Jackowicz-Korczynski M, Mastepanov M, Christensen TR, Lund M, Schmidt NM (2015) Controls of spatial and temporal variability in CH_4 flux in a high arctic fen over three years. Biogeochemistry 125(1):21–35

Sugimoto A, Wada E (1993) Carbon isotopic composition of bacterial methane in a soil incubation experiment: contributions of acetate and CO_2H_2. Geochim Cosmochim Acta 57(16):4015–4027

Takakai F, Desyatkin AR, Lopez CML, Fedorov AN, Desyatkin RV, Hatano R (2008) CH_4 and N_2O emissions from a forest-alas ecosystem in the permafrost taiga forest region, eastern Siberia, Russia. J Geophys Res Biogeosci 113(G2). https://doi.org/10.1029/2007jg000521

Tarnocai C, Canadell JG, Schuur EAG, Kuhry P, Mazhitova G, Zimov S (2009) Soil organic carbon pools in the northern circumpolar permafrost region. Glob Biogeochem Cycles 23(2). https://doi.org/10.1029/2008gb003327

Thonat T, Saunois M, Bousquet P, Pison I, Tan Z, Zhuang Q, Crill PM, Thornton BF, Bastviken D, Dlugokencky EJ (2017) Detectability of Arctic methane sources at six sites performing continuous atmospheric measurements. Atmos Chem Phys 17(13):8371–8394

Turetsky MR, Kotowska A, Bubier J, Dise NB, Crill P, Hornibrook ER, Minkkinen K, Moore TR, Myers-Smith IH, Nykanen H, Olefeldt D, Rinne J, Saarnio S, Shurpali N, Tuittila ES, Waddington JM, White JR, Wickland KP, Wilmking M (2014) A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands. Glob Chang Biol 20 (7):2183–2197. https://doi.org/10.1111/gcb.12580

Van der Kolk H-J, Heijmans MMPD, van Huissteden J, Pullens JWM, Berendse F (2016) Potential Arctic tundra vegetation shifts in response to changing temperature, precipitation and permafrost thaw. Biogeosciences 13(22):6229–6245. https://doi.org/10.5194/bg-13-6229-2016

Van der Molen M, Van Huissteden J, Parmentier F, Petrescu A, Dolman A, Maximov T, Kononov A, Karsanaev S, Suzdalov D (2007) The growing season greenhouse gas balance of a continental tundra site in the Indigirka lowlands, NE Siberia. Biogeosciences 4(6):985–1003

Van Hardenbroek M, Lotter AF, Bastviken D, Duc N, Heiri O (2012) Relationship between δ13C of chironomid remains and methane flux in Swedish lakes. Freshw Biol 57(1):166–177

Van Huissteden J. The permafrost carbon cycle. Springer. (in preparation)

Van Huissteden J, Dolman AJ (2012) Soil carbon in the Arctic and the permafrost carbon feedback. Curr Opin Environ Sustain 4(5):545–551. https://doi.org/10.1016/j.cosust.2012.09.008

Van Huissteden J, Maximov TC, Dolman AJ (2005) High methane flux from an arctic floodplain (Indigirka lowlands, eastern Siberia). J Geophys Res Biogeosci 110(G2). https://doi.org/10.1029/2005jg000010

Van Huissteden J, Maximov TC, Kononov AV, Dolman AJ (2008) Summer soil CH4 emission and uptake in taiga forest near Yakutsk, Eastern Siberia. Agric For Meteorol 148(12):2006–2012. https://doi.org/10.1016/j.agrformet.2008.08.008

Van Huissteden J, Maximov TC, Dolman AJ (2009) Correction to "High methane flux from an arctic floodplain (Indigirka lowlands, eastern Siberia)". J Geophys Res Biogeosci 114(G2). https://doi.org/10.1029/2009jg001040

Van Huissteden J, Berrittella C, Parmentier F, Mi Y, Maximov T, Dolman A (2011) Methane emissions from permafrost thaw lakes limited by lake drainage. Nat Clim Chang 1(2):119

Van Huissteden J, Vandenberghe J, Gibbard PL, Lewin J (2013) Periglacial fluvial sediments and forms. In: Encyclopedia of quaternary science, 2nd edn. Elsevier, Amsterdam, pp 490–499. https://doi.org/10.1016/b978-0-444-53643-3.00108-4

Vaughn LJ, Conrad ME, Bill M, Torn MS (2016) Isotopic insights into methane production, oxidation, and emissions in Arctic polygon tundra. Glob Chang Biol 22(10):3487–3502. https://doi.org/10.1111/gcb.13281

Vile MA, Wieder RK, Živković T, Scott KD, Vitt DH, Hartsock JA, Iosue CL, Quinn JC, Petix M, Fillingim HM (2014) N2-fixation by methanotrophs sustains carbon and nitrogen accumulation in pristine peatlands. Biogeochemistry 121(2):317–328

Vonk JE, Mann PJ, Davydov S, Davydova A, Spencer RGM, Schade J, Sobczak WV, Zimov N, Zimov S, Bulygina E, Eglinton TI, Holmes RM (2013) High biolability of ancient permafrost carbon upon thaw. Geophys Res Lett 40(11):2689–2693. https://doi.org/10.1002/grl.50348

Wagner D, Liebner S (2009) Global warming and carbon dynamics in permafrost soils: methane production and oxidation. In: Permafrost soils. Springer, pp 219–236

Wagner D, Kobabe S, Pfeiffer EM, Hubberten HW (2003) Microbial controls on methane fluxes from a polygonal tundra of the Lena Delta, Siberia. Permafr Periglac Process 14(2):173–185

Walter Anthony KM, Anthony P, Grosse G, Chanton J (2012) Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers. Nat Geosci 5(6):419–426. https://doi.org/10.1038/ngeo1480

Walter Anthony KM, Zimov SA, Grosse G, Jones MC, Anthony PM, Chapin FS 3rd, Finlay JC, Mack MC, Davydov S, Frenzel P, Frolking S (2014) A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. Nature 511(7510):452–456. https://doi.org/10.1038/nature13560
Walter KM, Zimov SA, Chanton JP, Verbyla D, Chapin FS, 3rd (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature 443 (7107):71–75. https://doi.org/10.1038/nature05040
Walter KM, Edwards ME, Grosse G, Zimov SA, Chapin FS 3rd (2007a) Thermokarst lakes as a source of atmospheric CH4 during the last deglaciation. Science 318(5850):633–636. https://doi.org/10.1126/science.1142924
Walter KM, Smith LC, Chapin FS, 3rd (2007b) Methane bubbling from northern lakes: present and future contributions to the global methane budget. Philos Trans A Math Phys Eng Sci 365 (1856):1657–1676. https://doi.org/10.1098/rsta.2007.2036
Walter K, Chanton J, Chapin F, Schuur E, Zimov S (2008) Methane production and bubble emissions from arctic lakes: isotopic implications for source pathways and ages. J Geophys Res Biogeosci 113:G00A08. https://doi.org/10.1029/2007JG000569.
Walvoord MA, Kurylyk BL (2016) Hydrologic impacts of thawing permafrost—a review. Vadose Zone J 15 (6):0. https://doi.org/10.2136/vzj2016.01.0010
Wik M, Crill PM, Bastviken D, Danielsson Å, Norbäck E (2011) Bubbles trapped in arctic lake ice: potential implications for methane emissions. J Geophys Res Biogeosci 116(G3)
Wik M, Thornton BF, Bastviken D, MacIntyre S, Varner RK, Crill PM (2014) Energy input is primary controller of methane bubbling in subarctic lakes. Geophys Res Lett 41(2):555–560
Wille C, Kutzbach L, Sachs T, Wagner D, Pfeiffer E-M (2008) Methane emission from Siberian arctic polygonal tundra: eddy covariance measurements and modeling. Glob Chang Biol 14 (6):1395–1408. https://doi.org/10.1111/j.1365-2486.2008.01586.x
Worden JR, Bloom AA, Pandey S, Jiang Z, Worden HM, Walker TW, Houweling S, Röckmann T (2017) Reduced biomass burning emissions reconcile conflicting estimates of the post-2006 atmospheric methane budget. Nat Commun 8(1):2227
Yakushev V, Chuvilin E (2000) Natural gas and gas hydrate accumulations within permafrost in Russia. Cold Reg Sci Technol 31(3):189–197
Zalman C, Meade N, Chanton J, Kostka J, Bridgham S, Keller J (2018) Methylotrophic methanogenesis in Sphagnum-dominated peatland soils. Soil Biol Biochem 118:156–160
Zimov S, Voropaev YV, Semiletov I, Davidov S, Prosiannikov S, Chapin FS, Chapin M, Trumbore S, Tyler S (1997) North Siberian lakes: a methane source fueled by Pleistocene carbon. Science 277(5327):800–802
Zimov SA, Davydov SP, Zimova GM, Davydova AI, Schuur EAG, Dutta K, Chapin FS (2006) Permafrost carbon: stock and decomposability of a globally significant carbon pool. Geophys Res Lett 33(20). https://doi.org/10.1029/2006gl027484
Zona D, Gioli B, Commane R, Lindaas J, Wofsy SC, Miller CE, Dinardo SJ, Dengel S, Sweeney C, Karion A, Chang RY, Henderson JM, Murphy PC, Goodrich JP, Moreaux V, Liljedahl A, Watts JD, Kimball JS, Lipson DA, Oechel WC (2016) Cold season emissions dominate the Arctic tundra methane budget. Proc Natl Acad Sci USA 113(1):40–45. https://doi.org/10.1073/pnas.1516017113