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Methane dynamics in warming tundra of Northeast European Russia

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Abstract

Methane (CH₄) fluxes were investigated in a subarctic Russian tundra site in a multi-approach study combining plot scale data, ecosystem scale eddy covariance (EC) measurements and fine resolution land cover classification scheme for regional upscaling. The flux data as measured by the two independent techniques resulted in a seasonal (May–October 2008) cumulative CH₄ emission of 2.4 (EC) and 3.7 g CH₄ m⁻² (manual chambers) for the source area representative of the footprint of the EC instruments. Upon upscaling for the entire study region of 98.6 km², the chamber measured flux data yielded a regional flux estimate of 6.7 g CH₄ m⁻² yr⁻¹. Our upscaling efforts accounted for the large spatial variability in the distribution of the various land cover types (LCTs) predominant at our study site. In particular, wetlands with emissions ranging from 34 to 53 g CH₄ m⁻² yr⁻¹ were the most dominant CH₄ emitting surfaces. Emissions from thermokarst lakes were an order of magnitude lower, while the rest of the landscape (mineral tundra) was a weak sink for atmospheric methane. Vascular plant cover was a key factor in explaining the spatial variability of CH₄ emissions among wetland types, as indicated by the positive correlation of emissions with the leaf area index (LAI). As elucidated through a stable isotope analysis, the plant transport was the dominant CH₄ release pathway that discriminates against heavier δ¹³C-CH₄. The methane released from wetlands was lighter than that in the surface porewater and δ¹³C in the emitted CH₄ correlated with the vascular plant cover (LAI) implying that the plant-mediated CH₄ release dominates. A mean value of δ¹³C obtained here for the emitted CH₄, -68.2 ± 2.0‰, is within the range of values from other wetlands, thus reinforcing the use of inverse modeling tools to better constrain the CH₄ budget. Based on the IPCC A1B emission scenario, a temperature increase of 7 °C has been predicted for the tundra region of European Russia by the end of the 21st Century. A regional warming of this magnitude will have profound effects on the permafrost distribution leading to considerable changes in the regional landscape with a potential for an increase in the areal extent of methane emitting wet surfaces. We estimate that a

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projected increase in air temperature of 7 °C with a mere 10 % associated increase in the combined areal coverage of willow stands, fens and lakes in the region will lead to a 51 % higher amount of CH₄ being emitted into the atmosphere by the end of this century.

1 Introduction

The arctic tundra covers 9.2 million km², i.e., 8 % of the global land area (McGuire et al., 2012). These areas are important in climate change research, because they store nearly one third of the Earth's soil carbon (Schuur et al., 2015; Tarnocai et al., 2009) and thus possess a great potential via feedback mechanisms to alter the concentrations of CO₂ (carbon dioxide) and CH₄ (methane) in the atmosphere (Post et al., 2009). Top-down modeling results based on measurements of concentrations and stable isotope composition of CH₄ have already proved the importance of high-latitude wetlands as global CH₄ sources (Riley et al., 2011). For example, the increase in the global mean atmospheric CH₄ concentration in 2007 has been attributed to anomalously high summer temperatures experienced by these ecosystems during that year (Dlugokencky et al., 2011). Despite the large areal extent, the Russian tundra region is relatively less explored with respect to its ecosystem biogeochemical functioning. According to the latest estimates (McGuire et al., 2012; Schuur et al., 2015), presently, this region is considered to be a net carbon dioxide (CO₂) sink and a source of atmospheric CH₄. Although CO₂ flux represents the major component in the total C flow between tundra ecosystems and the atmosphere, CH₄ is equally important owing to its 25 times higher global warming potential (over a 100 year time horizon, IPCC, 2014).

In the arctic, CH₄ is mostly emitted from non-frozen wetlands (Heikkinen et al., 2004; Mastepanov et al., 2008) and from lakes and ponds (Walter et al., 2008). On the whole, there is a general consensus that the Arctic region is a moderate CH₄ source (19 Tgyr⁻¹) (McGuire et al., 2012). However, this estimate of the methane source strength is fraught with uncertainty ranging from 8 and 29 Tgyr⁻¹ (McGuire et al., 2012).

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This is attributed to the flux variability across time and space that is poorly characterized yet. Methane exchange is unevenly distributed across the landscape (hot spots) (Walter et al., 2006) and may occur during short periods of time (Mastepanov et al., 2008). For reliable estimates of CH₄ balance, measurements made across all important constituent land cover types at a high temporal resolution are required. The ideal way to achieve this is to apply chamber and eddy covariance techniques in parallel. Such an approach has, however, rarely been adopted in Arctic investigations (Parmentier et al., 2011; Sachs et al., 2008). Eddy covariance data, with a high temporal resolution and minimal disturbance to the ecosystem being studied, provides an ensemble average ecosystem source/sink strength, while chamber techniques aid in a proper characterization of the inherent spatial variability in the methane release. The two methods employed simultaneously help improve the accuracy of the regional flux estimates, as has been shown for carbon dioxide at this site (Marushchak et al., 2013).

In addition to increasing the accuracy of flux estimates, processes underlying CH₄ dynamics need to be better understood. This is important for developing process-based biogeochemical models with an ability to simulate present and future CH₄ fluxes (Riley et al., 2011). In this respect, stable isotope analyses of CH₄ have been useful as they provide valuable information on CH₄ sources and production mechanisms (Chanton, 2005; Chanton et al., 2005; Popp et al., 1999). Knowledge on the isotopic composition of CH₄ from various ecosystem types is also important for top-down modeling where the aim is to determine the relative contribution of different emission sources to the atmospheric CH₄ content (Riley et al., 2011). Data on isotopic composition of C in peatland CH₄ emissions are sparse, especially from the Russian tundra ecosystems (Sapart et al., 2012). A more detailed characterization of CH₄ emissions is highly relevant to better constrain global CH₄ sinks and sources, particularly in view of the growing importance of northern peatlands in global C cycle.

Present day trends have revealed that the permafrost temperatures have risen by 2 °C and the southern boundary of permafrost has retreated northwards in the Russian Arctic (Romanovsky et al., 2010). Changes in permafrost extent and active layer thick-

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ness affect composition (Christensen, 2004) and CH₄ flux (Johansson et al., 2006) from northern wetlands. In a study on permafrost dynamics of the Russian tundra (Anisimov, 2007), permafrost temperatures have been projected to increase by 2–3 °C by 2050 with a 15–25 % increase in the active layer thickness leading to a 25 % increase in the CH₄ emissions from the northern Russian wetlands. Such projections can be improved with a robust estimate of the magnitude of CH₄ fluxes, their spatial and temporal variability and underlying mechanisms.

Our aim here was to provide an estimate of CH₄ fluxes as measured by two independent measurement techniques in a subarctic Russian tundra region and to deepen our understanding of the factors regulating methane exchange in this environment, vulnerable to climate change. To investigate methane fluxes and underlying mechanisms in the Russian Arctic at various scales (from processes to landscape) we used a set of methodological tools including stable isotope investigations, EC and chamber based flux measurement techniques and regional upscaling by fine scale QuickBird satellite image based land cover classification scheme. We report here a full year of CH₄ measurements by static chambers and gas gradient methods. These methods were complemented by fluxes measured using the EC technique from early spring to autumn in 2008. Chamber measurements on dominant terrestrial surfaces and lake flux studies were used to evaluate the potential effect of changes in ecosystem composition on CH₄ exchange from the tundra. Based on the observed relationship between methane fluxes and controlling variables, we have projected the regional methane release by taking into account specific climate scenarios generated for this region by a regional climate model. Overall, to the best of our knowledge, this is one of the rare multi-level approaches on CH₄ dynamics over various temporal and spatial scales in an arctic environment.

2 Materials and methods

2.1 Site description

This study was conducted in the subarctic tundra of the Komi Republic, Northeast European Russia. The measurement site is located near the village Seida (67°03'21" N, 62°56'45" E, 100 m a.s.l.) and situated in the discontinuous permafrost zone just above the northern treeline. Based on the long-term air temperature data from the Vorkuta station (67°48' N, 64°01' E, 172 m a.s.l.) for the 1980–1999 period, the mean annual temperature in the region is -5.7°C , with January being the coldest month (mean temperature -20.1°C) and July the warmest one (mean temperature 12.8°C). The annual precipitation is 454 mm (long-term average precipitation for 1980–1999), based on the rainfall data from Salekhard station (66°32' N, 66°36' E, 66 m a.s.l.). A more detailed description of the site as well as information on permafrost and carbon storage of the tundra soils of this region can be found in Hugelius et al. (2011), Marushchak et al. (2011), Marushchak et al. (2013) and Biasi et al. (2013).

A high resolution QuickBird satellite image (Fig. 1) was used to map the distribution of the various land cover types (LCTs) of the study area of 98.6 km^2 (Hugelius et al., 2011; Marushchak et al., 2013). In terms of areal coverage, the tundra heath (58%) and tundra bog vegetation (24%) found especially on permanently frozen peat plateaus, are the dominant ecosystem types in the region followed by willow stands (9%), and various fen ecosystems (6%). The peat plateaus are spotted by unvegetated, patterned ground features (referred to hereafter as bare peat circles which have been studied by Repo et al., 2009, as they were found to emit large amounts of N_2O to the atmosphere). The willow stands are typically 0.5–1.5 m in height and grow on low-lying areas with water logged soils. The fens are found on littoral areas of thermokarst lakes and on the edges of the frozen peat plateau peatlands. They are mesotrophic and can be divided according to dominant vascular plant into *Eriophorum* and *Carex* fens. *Sphagnum* species dominate the ground layer and form a dense mat floating on

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the water together with vascular plant roots. Small lakes, mostly of thermokarst origin, cover a minor part of the landscape (1 %).

2.2 Instrumental setup and methodology

2.2.1 Plot-scale CH₄ flux measurements at terrestrial land cover types

5 Ten land cover types, each with three replicate measuring plots, were established for the determination of CH₄ fluxes from the soil surface, three of them on water-logged wetlands, three on peat plateau and four on upland tundra. Fluxes of CH₄ were determined using the methodology described in detail for nitrous oxide fluxes by Marushchak et al. (2011). Fluxes were measured by the static chamber technique 11–16 times during the snow-free season from early July to mid October 2007 and 16–21 times during the snow-free season from late May–early July until the beginning of October 2008. In addition, CH₄ fluxes were measured 2–5 times per plot during the snow cover period in January–June with a snow-gradient method (Merbold et al., 2013). The CH₄ concentrations in the collected gas samples were analyzed within three months from sampling using a gas chromatograph equipped with a flame ionization detector (Agilent 6890N, Agilent Technologies Deutschland, Böblingen, Germany). A leakage test with a high CH₄ concentration (15 ppm) showed that the reduction in gas concentration in the sample vials over two months was less than 1 % (data not shown). Flux calculation and criteria to accept or reject fluxes for further analysis are described in Marushchak et al. (2011). Water table level (WT), active layer depth (AL), soil temperature at 2 and 25 cm depths and vascular leaf area index (LAI; only in 2008) were monitored at different land cover types by manual and continuous measurements as described by Marushchak et al. (2011, 2013). The adjustment of moss surface to water table fluctuations on willow and fen microsites was monitored in 2008 by a measuring pole pushed through the peat profile down to the mineral soil.

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2.2.2 Lake methane emission measurements

Release of CH₄ by diffusion and ebullition pathways was studied in three thermokarst lakes from July to August 2007 (11 samplings between days 191–239) and from June to October 2008 (19 samplings between days 182–276). The area of the studied lakes was 0.03–3 ha with the maximum depth ranging from 2.0 to 2.6 m and surface water pH from 4.6 to 5.5. Diffusive CH₄ flux was calculated from CH₄ concentration in the surface water and local wind speed using the thin boundary layer (TBL) model (Liss and Slater, 1974). Surface water samples were collected during daytime (8 a.m.–19 p.m.). The determination of CH₄ concentration with a head space method and flux calculation were carried out as described in (Repo et al., 2007). Linear interpolation was used to obtain daily CH₄ concentrations. The hourly averaged wind speed measured at 2 m, normalized to 10 m using a logarithmic wind profile, was used to calculate hourly flux rates. Ebullitive CH₄ flux was monitored with permanently installed, submerged funnel gas collectors (Repo et al., 2007). Each lake had 6–7 replicate gas collectors (Ø 0.35 m), which were sampled concurrently with surface water sampling. Gas samples were stored and analyzed as described above.

2.3 Temporal extrapolation of plot-scale CH₄ fluxes

The temperature dependence of CH₄ flux was used to produce daily CH₄ exchange rates during the snow-free period for the land cover types with large CH₄ fluxes: willow stands, *Carex fen* and *Eriophorum fen*. Regression functions based on air temperature and peat temperatures at 2 and 25 cm were tested, and the best fit was obtained with temperature at 25 cm. Addition of a water table term improved the model fit in 2007 (helped explain 20 % additional variation in the flux data) and resulted in a more realistic seasonal pattern, so the following function was used:

$$\text{CH}_4 \text{ flux (gCH}_4\text{-C m}^{-2}\text{ d}^{-1}) = \alpha \times \beta^{(T-10/10)} \times \exp(\gamma \times \text{WT}) \quad (1)$$

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where T is the soil temperature at 25 cm ($^{\circ}\text{C}$) and WT is the water table level (cm). Model parameters were estimated for each measurement plot individually using the SPSS 14.0 statistical software. The regression functions explained 85 % of the overall variability in fluxes across the different vegetation types (Table 1; Fig. 2).

5 For the remaining terrestrial plots with low emissions and for lakes, CH_4 fluxes were integrated over time using linear interpolation for the days between the measurements as described by Marushchak et al. (2011). Linear interpolation was also used for wil-
10 lows and fens for the snow period when the water table levels were not monitored. The annual fluxes were calculated for the period from 6 October 2007 until the termination
15 of measurements on 5 October 2008.

2.4 Isotope analysis of emitted and porewater CH_4

The $\delta^{13}\text{C}$ values of the emitted and porewater CH_4 were determined during summer 2007 and 2008 from the three surface types with high water table and, thus, with a po-
15 tential for high CH_4 release: willow stands, *Carex* and *Eriophorum* fens. Gas samples were collected biweekly starting from mid-July until late August (total 5 times) in 2007
20 and twice in 2008, in late June and in early August. Five gas samples were collected for the isotopic analysis during the time of the chamber closure and injected into 35 mL
glass vials (Wheaton) topped with rubber septa and prefilled with N_2 gas. In addition,
25 pore water at 5 and 30 cm depths was sampled from gas collectors made out of perforated plastic tubes following Maljanen et al. (2003). A water sample of 30 mL was taken
in a 60 mL syringe, a similar volume of air was added and the syringe was then shaken
for 2 min, after which the gas phase was transferred to a glass vial (Labco Exetainer)
prefilled with pure N_2 . The 5 cm gas collector was occasionally above water table level,
in which case pore gas was sampled and transferred directly into a vial. Also ambient
gas samples were collected for isotopic analysis.

Isotope analyses of CH_4 were done at the laboratories of University of Eastern Finland by gas chromatography isotope ratio mass spectrometry (GC-IRMS; Thermo Finnigan Delta XP, Germany) equipped with a preconcentration unit (Precon, Thermo

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Scientific, Germany) (Dorodnikov et al., 2013). If needed, samples were diluted. Values are expressed as $\delta^{13}\text{C}$ relative to VPDB (Vienna Pee Dee Belemnite Standard) using a standard gas with known ^{13}C values. Standard error of five repeated measurements of isotope standard was less than 0.5 ‰ for CH_4 . Methane concentrations of all samples were separately analyzed by gas chromatography (Hewlett Packard 5890A) equipped with flame ionization detector (FID) for CH_4 (Mörsky et al., 2008). The Keeling plot method (Pataki et al., 2003) was used to determine the $\delta^{13}\text{C}$ value of emitted CH_4 . According to this method, the $\delta^{13}\text{C}$ value of the emitted CH_4 is obtained by plotting the measured $\delta^{13}\text{C}$ values against the inverse of CH_4 concentrations, where the intercept of the linear equation with the y axis is the $\delta^{13}\text{C}$ value of the emitted CH_4 .

2.5 EC measurements

The landscape scale CH_4 fluxes were measured by the EC technique during the period from mid-May to early October 2008. The CO_2 fluxes, measured simultaneously with the CH_4 fluxes data presented in this paper, have already been reported in Marushchak et al. (2013) and Kiepe et al. (2013). Fluctuations in the vertical wind speed were measured at a height of 2.75 m above the ground using a three-dimensional sonic anemometer (R3, Gill Instruments Ltd, UK). A quantum cascade laser (QCL) spectrometer was used for CH_4 concentrations (Aerodyne Inc., USA). The CH_4 fluxes were calculated and corrected for theoretical separation between instruments and attenuation of the CH_4 signal in the intake tube using the software package, AltEddy version 3.5 (Alterra, University of Wageningen, the Netherlands). Methane fluxes were further corrected for simultaneous flux of H_2O (Webb et al., 1980). Further data processing and quality control followed the standard methodology of Aubinet et al. (1999) and Foken et al. (2005). Calculation of the source area for the flux measurements followed the principles described in Soegaard et al. (2000) and Marushchak et al. (2013), where LCTs were based on a QuickBird satellite image classification.

2.6 Regional CH₄ emission

For area integration of the CH₄ fluxes to the landscape and regional level we used a land cover classification (Fig. 1; Hugelius et al., 2011; Marushchak et al., 2013) that was made based on a QuickBird satellite image acquired on 6 July 2007 (QuickBird ©2007, Digital Globe; Distributed by Eurimage/Pöyry). Classification procedure is explained in more detail in (Virtanen and Ek, 2014). High resolution of the satellite image (2.4 m pixel size, 4 channels) allowed accurate representation of the heterogeneous landscape, including fens that are distributed across the landscape as narrow stripes or patches (Virtanen and Ek, 2014). The hourly chamber fluxes of different land-cover types were weighted by their relative area contributions to estimate flux values for the EC footprint and for the whole QuickBird area. For rivers, we used a CH₄ emission value of 1 g C m⁻² during summer, estimated for a river in the same region by Heikkinen et al. (2004). A zero CH₄ balance was assumed for forest stands, sand and impacted tundra.

3 Results

3.1 Climatic conditions during the study period

Plot scale measurements of CH₄ fluxes on terrestrial sites and lakes covered the growing seasons 2007 and 2008 and, less frequently during the cold season in between (Fig. 3a and b). A detailed discussion of weather conditions during the study period can be found in Marushchak et al. (2011). In brief, mid-summer temperatures were higher than the long-term averages during both years, and July was hotter in 2007 (17.9°C) than in 2008 (15.8°C). The amount of precipitation received during the two growing seasons was comparable to the long-term regional precipitation. In 2008, a period from mid-May through early October was covered by simultaneous plot scale and eddy covariance measurements (Fig. 3c). In the beginning of this measurement cam-

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paign, there was still a 90 % snow cover, temperatures were below freezing point and there was no active layer above permafrost. By early October, the diurnal average air temperatures had again dropped close to zero and the maximum active layer thickness varied from 41 cm to greater than 120 cm depending on the land cover type.

3.2 Spatial variability in CH₄ fluxes

Based on the plot scale measurements, only the wetland sites (willow stands and fens) emitted high amounts of CH₄ to the atmosphere throughout the snow-free season (Fig. 3a). The CH₄ fluxes increased in the order: *Eriophorum* fen < *Carex* fen < willow stands, with LAI of vascular plants explaining 88 % of the differences in fluxes among the sites (Fig. 4). The annual CH₄ emissions from these wetland types were 11 ± 4.5, 37 ± 17 and 53 ± 8 g CH₄ m⁻², respectively. At willow and *Carex* fen sites, the floating *Sphagnum* mat followed the fluctuations in the ground water level. This dampened the amplitude of the water table level variation relative to the moss surface. While the absolute amplitude of the water table level at the fen sites in 2008 was 23 cm, this was reduced to about 10 cm relative to the moss surface as a result of the surface adjustment. Consequently, the fen sites remained submerged 5–10 cm below the water level even during the driest part of the growing season in July 2008. The willow LCT did not have a floating moss layer but the mean water table was still maintained close to the moss surface. The CH₄ fluxes from these sites showed a strong exponential dependence on temperature at the individual plot level. Moreover, a strong exponential relationship between CH₄ flux and soil temperature was also corroborated by EC measurements made on the landscape level (Fig. 5). The drier peatland habitats, the tundra bog and bare peat circles were smaller CH₄ sources (0.2 ± 0.2 and 0.7 ± 1.1 g CH₄ m⁻² yr⁻¹, respectively). The upland tundra types were at times small sinks for atmospheric methane during the season. When accumulated over the entire season, they were close to being neutral with the CH₄ emissions ranging from -0.03 to 0.13 g CH₄ m⁻².

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The annual CH₄ emissions from the thermokarst lakes varied from 2.1 to 5.3 g CH₄ m⁻² (mean 4.2 g CH₄ m⁻²) and thus, they were lower compared to wetland sites (Fig. 3b). The magnitude of total CH₄ emissions as well as the importance of diffusion vs. ebullition pathways varied strongly among the lakes. The contribution of the ebullitive flux ranged from 5 to 94 % and was the highest in the biggest of the lakes with the most intensive thermokarst processes occurring. The highest diffusive flux was observed in the smallest lake with the least open water area. The seasonal mean CH₄ concentration in the surface water was 0.3–3.7 μmol L⁻¹ in 2007 and 0.4–8.0 μmol L⁻¹ in 2008.

3.3 Isotopic signature of C-CH₄ in emission and porewater

The δ¹³C in CH₄ flux did not show much variability among the wetland types, years or sampling dates (Table 2, Fig. 6). In 2008, the *Eriophorum* fen was still partly frozen during the first sampling date. This presumably led to an anomalously high δ¹³C value, likely decreasing the average δ¹³C-CH₄ value for this site in 2008. The bulk average ±SD of δ¹³C in CH₄ emitted from different peatland types and years was -68.2 ± 2.0 ‰. Methane emitted from wetlands was lighter (δ¹³C more negative) than the porewater CH₄ at all wetland types and lighter CH₄ was found at 30 cm than at 5 cm (Fig. 6). A negative linear correlation was found between δ¹³C in CH₄ emission and vascular LAI across the wetland plots (Fig. 4, the higher the LAI, the lighter the CH₄; *P* < 0.0001).

3.4 Landscape scale and regional CH₄ balance

The fluxes of various land cover types were spatially extrapolated over the EC footprint area and further over the whole study region of 98.6 km² using the data on the land cover classification. When the plot scale measurements were scaled up to the EC footprint area, the CH₄ flux estimate (3.7 g CH₄ m⁻²) obtained was larger than the estimate by the EC technique (2.4 g CH₄ m⁻² for the whole EC measuring campaign, Fig. 3c).

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An LAI map produced for the area based on the QuickBird image showed that the fen plots selected for the chamber measurements had on average higher LAI (1.2) than the fens in the region (0.7). If the linear relationship between CH₄ flux and LAI presented in Fig. 4 is used to correct the CH₄ fluxes from fens to account for the lower LAI in the landscape, the CH₄ estimate was reduced to 2.8 gCH₄ m⁻². This is close to the estimate based on EC measurements (Table 2).

The regional CH₄ emission, without LAI correction for fen fluxes, was 5.6 gCH₄ m⁻² for the EC measurement period from May through September and 6.7 gCH₄ m⁻² for the whole year. Contribution of the non-growing season to this annual CH₄ flux was 30 %. The higher emission compared to the EC footprint area can be explained by higher coverage of wetlands in the whole study region (willow coverage 8.7 vs. 1.6 %). In the EC footprint area there were more tundra bog (39 %), fen (10 %) and lakes (9 %) and less tundra heath (41 %) and willows (2 %) than in the whole QuickBird area.

4 Discussion

In comparison with other studies of the Russian arctic tundra, the integrative landscape scale CH₄ emissions found in the present study are relatively low. A seasonal (May–September) emission of 2.4–2.8 gCH₄ m⁻² as revealed by eddy covariance measurements is less than what has been reported, e.g., for northeastern Siberia by Van Der Molen et al. (2007), who estimated an annual emission of about 4.0 gCH₄ m⁻² and by Corradi et al. (2005), who reported an even higher annual emission rate (16 gCH₄ m⁻²). The emissions reported in this study are also lower compared to the work of Jackowicz-Korczyński et al. (2010) in sub-arctic Scandinavia (25 gCH₄ m⁻²). Emission rates similar to the ones reported here were measured during the summer season by Friberg (2003) at a high arctic fen site in NE Greenland. The overall emission of CH₄ from this site seems to be relatively low, owing to a low coverage of high emitting wetlands (less than 20 %). Nevertheless, it is evident from our chamber measurements that the

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wet parts of the tundra ecosystem in the Seida area emit CH₄ at a rate equivalent or higher than what has been reported for similar tundra habitats in Russia (e.g., Heikkinen et al., 2004).

The area integrated chamber measurements in this study show somewhat higher fluxes than what is estimated by the EC technique (Table 3). This could be attributed to the disparity in the distribution of different land cover types within and outside the footprint of the EC tower and to the variability associated with the fluxes among various surface types as measured by the chambers. Variability among the surface types is relatively high and can, at least partly, explain the difference compared to the EC measurements. For example, the fen plots measured with chambers had higher LAI than the fens in the region in general. Based on the relationship between CH₄ flux and LAI, when we corrected the chamber CH₄ flux estimate for such a LAI variation, the CH₄ estimates based on the two independent methods were found to agree with each other. Without this correction, the seasonal CH₄ flux estimated based on the chamber method was higher for the region than based on the eddy covariance (2.4 g CH₄ m⁻²), but still lower as compared to other studies (referred to above) conducted at sites where wetlands are relatively more abundant.

To characterize the CH₄ source from the studied fens and willow stand, we employed stable isotope analysis and measured the $\delta^{13}\text{C}$ values of CH₄ in porewater and surface emissions. The overall mean $\delta^{13}\text{C}$ value of CH₄ released to the atmosphere was -68.2‰ and falls within the range of values reported for wetlands from the Arctic including Siberia (McCalley et al., 2014; Sriskantharajah et al., 2012). The $\delta^{13}\text{C}$ value of CH₄ from wetlands worldwide is $-59 \pm 6\text{‰}$ (McCalley et al., 2014). Generally, the isotope signal of CH₄ from wetlands appears to be rather constant and sufficiently distinct from other large sources, e.g. biomass burning (Monteil et al., 2011), supporting the use of isotopes to better constrain sources and sinks of atmospheric CH₄ by inverse modelling. We have shown here that the $\delta^{13}\text{C}$ emitted from the surface is lighter than the $\delta^{13}\text{C}$ dissolved in pore-water. This indicates that a large part of the emitted CH₄ is transported from peat to the atmosphere from deeper peat layers, likely via plant

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aerenchyma. Such a process leads to enhanced fractionation, thus depleting the $\delta^{13}\text{C}$ of methane (Chanton et al., 2005). Similar observations of depleted CH_4 in surface emissions compared to pore-water were made by others (e.g., Popp et al., 1999). It has been generally argued that plant-mediated transport accounts for a large share of CH_4 emissions in wetlands inhabited by vascular plants (Kutzbach et al., 2004; Riley et al., 2011; Van Der Nat et al., 1998). The assumption that plants significantly impact on the net CH_4 emissions from this site is further supported by the linear correlation between $\delta^{13}\text{C}$ of CH_4 and LAI, although this correlation may also indicate the influence of plant-derived C supply for methanogens (Riley et al., 2011). The observation that plants mediate CH_4 release is important in the context of climate change. This implies that a significant part of the CH_4 produced in the soil profile bypasses the oxic soil zones thus confounding the effect of water table variations.

Temperature records from the nearby Vorkuta station (75 km North of the field site) show that the average air temperature in the region rose by 0.9°C from 1980–1999 to 2000–08 (P. Kuhry, personal communication, 2010). A climate scenario for the northern part of the Komi Republic was developed as part of the CARBO-North project using the IPCC-SRES emission scenario A1B (Stendel et al., 2011). As per these projections, a 3.5°C regional warming relative to the present day climate is expected to occur by the end of the 21st century. For the northern part of the Komi Republic, the region within which the study site is situated, a temperature increase of nearly 7.0°C relative to the average over the period 1980–1999 is predicted by 2100.

Employing the temperature CH_4 flux relationship observed in this study (Table 1), a temperature increase of 7.0°C alone by 2100 relative to 1980–99 would lead to an increase of approximately 69% in the annual CH_4 emission. The floating peatland surface in fens typical of this area, adjusts to fluctuations in the water table. This implies that the fen types might remain water-logged, even if other tundra habitats would get drier. If the water table level remains within a range favorable for CH_4 production and its release to the atmosphere, the higher temperatures would enhance CH_4 emissions. Additionally, the isotope data suggest that CH_4 is released largely from deeper layers

of peat via plant roots thereby escaping its oxidation, implying relatively minor effects of water-table fluctuations. Moreover, the growth of willow stands in the study area has been reported to be higher owing to warmer temperatures (Forbes et al., 2010). Enhanced willow stand productivity may further lead to increased CH₄ emissions, also evidenced by the fact that plants control the net CH₄ and ¹³C-CH₄ release. Based on the positive correlation between LAI and CH₄ flux, we estimate that a 50% increase in the LAI would favor enhanced release of CH₄ to the extent of nearly 35% from tundra wetlands in the study region.

While less uncertainty is associated with the direct effects of temperature increase on the methanogenic processes, a high degree of uncertainty exists with respect to consequences of temperature increases on the geomorphological changes of the studied tundra landscape and their possible impact on vegetation. In addition to the direct enhancement of CH₄ fluxes by higher temperatures, warming of 6.1 °C by 2100 will evidently cause thawing of permafrost and result in landscape changes in the study region. Our measurements of active layer thickness over the season reveal that the seasonal active layer is deepest in the wettest (low laying) parts of the tundra, which are characterized by lakes, fens and willow wetlands. A possible consequence of the predicted warming could be that these wetland cover types become more prevalent in the future. Based on our results, fen sites are the strongest emitters of CH₄. Any landscape change leading to the formation and expansion of such wetland types owing to permafrost thaw would further increase CH₄ escape, thus providing a strong positive feedback to climate change in the region.

In view of the above, we have performed a scenario analysis to understand the potential impact of the warming temperature and consequent permafrost thaw leading to landscape change favoring wetland formation on the one hand and their expansion, on the other. Figure 7 (top panel) shows the annual CH₄ flux of the different methane emitting land cover types in the studied area. We assume here that the thawing of permafrost will primarily affect lowland ecosystem types, leading to relatively dry organic rich tundra bogs and palsas being converted into wet organic rich willows, fens and

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data, how these ecosystems will respond to the future climate is still uncertain. Therefore, with a view to understanding the future ecosystem responses better, regional studies aiming at a proper characterization of the atmosphere–biosphere greenhouse gas (GHG) exchange in the Arctic have been launched. To that end, the work presented in this paper serves to provide the much needed seasonal and annual methane flux estimates from the northwest Russian Siberia, a region not yet well represented in the Arctic studies. Flux data on other GHGs (CO₂ and N₂O) from this study site have already been reported in earlier publications (Repo et al., 2009; Marushchak et al., 2011, 2013).

Owing to the spatially heterogeneous nature of the studied ecosystem (Virtanen and Ek, 2014), this study segregated the site into several major land cover types employing a fine scale land cover classification scheme. Chamber techniques were used to measure CH₄ fluxes during 2007 and 2008 growing seasons from replicate plots on ten different LCTs. These data were useful in charactering the inherent variability in methane CH₄ flux at the studied site. To complement these plot scale measurements, the eddy covariance technique was also used to characterize this ecosystem's CH₄ source strength. Employing empirical modelling and vascular leaf area data, the up-scaled plot scale data agreed well with the seasonal CH₄ flux estimates obtained using EC technique. Soil temperature, water table level and leaf area were found to be the major factors controlling CH₄ release to the atmosphere. Growing season $\delta^{13}\text{C}$ -CH₄ isotopic analyses confirmed the active role of plants in transferring methane to the atmosphere. The seasonal/annual estimates reported here were employed to gain an insight into how the regional CH₄ flux would vary in the future with increasing air temperatures, associated permafrost thaw and plausible geomorphological changes in the landscape. Using the HIRHAM-4 RCM climate output, a scenario projecting the regional CH₄ flux to the end of the 21st century, informs us that a 10 % increase in the area of major methane emitting surfaces would lead to a 51 % increase in the regional CH₄ flux by the end of this century. The “what-if” analysis presented here is based solely on methane flux–temperature relationship observed at this study site.

Such observations, nevertheless, highlight the urgent need for well-planned, modelling and data based, detailed analyses of changes in vegetation structure and composition, hydrological readjustments and associated C flow patterns of the region in the days to come.

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Table 1. Summary of the empirical models used to generate the seasonal CH₄ flux estimates for the different wetland land cover types at the Seida study site. These seasonal estimates are based on chamber fluxes measured during the snowfree period. Models were fitted separately for each measurement plot.

Site	Year	α	β	γ	R^2
<i>Carex</i> fen	2007	0.11–0.26	2.1–7.4	–0.06–0.01	0.18–0.84
	2008	0.15–0.20	7.4–22.3	–0.02–0.04	0.78–0.83
<i>Eriophorum</i> fen	2007	0.04–0.11	3.3–3.7	–0.09 – –0.04	0.20–0.82
	2008	0.06–0.09	5.3–35.3	–0.01–0.09	0.62–0.66
Willow	2007	0.14–0.22	1.6–5.1	0.02–0.05	0.77–0.87
	2008	0.30–0.32	2.3–9.3	–0.01–0.07	0.79–0.94

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Table 2. Isotopic signature ($\delta^{13}\text{C}$) of CH_4 emission of various tundra wetland types and magnitude of CH_4 flux during isotope sampling. Data are growing season means \pm SD, $n = 3$.

		<i>Carex</i> fen	<i>Eriophorum</i> fen	Willow stand
$\delta^{13}\text{C}$ in CH_4 flux	2007	-66.8 ± 2.5	-70.8 ± 1.1	-70.4 ± 2.6
	2008	-66.6 ± 5.8	-64.3 ± 1.3	-70.5 ± 2.3
CH_4 flux, $\text{mgCH}_4 \text{ m}^{-2} \text{ d}^{-1}$	2007	10.1 ± 1.0	3.4 ± 2.8	9.1 ± 2.4
	2008	6.8 ± 1.3	1.5 ± 0.5	8.7 ± 0.2

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Table 3. Methane balance of the eddy covariance (EC) tower footprint area and the whole study region of 98.6 km² based on EC and area-integrated plot scale measurements. For the EC tower footprint area, chamber fluxes were corrected to account for the higher LAI on fen measurement plots (see text for more details on why such a correction was necessary).

CH ₄ balance, gCH ₄ m ⁻²	EC measuring campaign 2008 (days 139–279)	Annual (days 280/2007–279/2008)
EC footprint area		
EC	2.4	not determined
Plot scale measurements, with LAI correction	2.8 ± 1.2	3.4 ± 1.6
Plot scale measurements, without LAI correction	3.7 ± 1.5	4.4 ± 2.1
Study region of 98.6 km ²		
Plot scale measurements, without LAI correction	5.6 ± 1.3	6.7 ± 1.8

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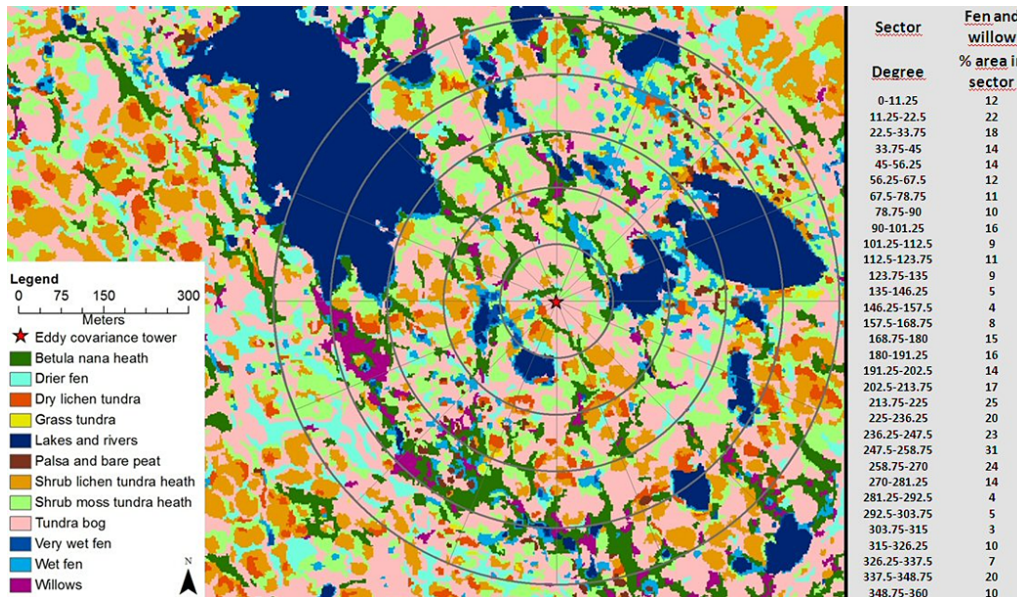


Figure 1. Land cover classification of the field site employing QuickBird satellite imagery. Eddy tower is indicated by a star, concentric lines drawn around the tower at 100 m intervals represent the EC footprint area. Areal coverage of fen and willow land cover types in different sectors from eddy tower is shown in a table to the right of the figure, zero refers to North.

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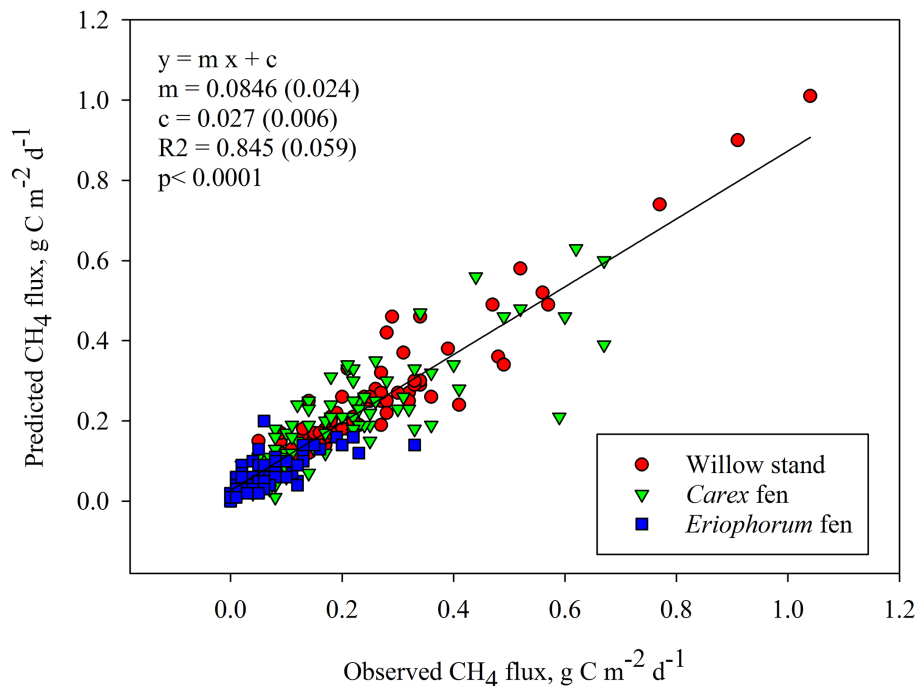


Figure 2. A comparison of observed and predicted CH_4 fluxes ($n = 254$) measured using chambers during 2007–2008 from different tundra wetland types in the Seida study site. The solid line represent the linear least squares fit of the data. Statistics from the linear regression analysis are also shown in the figure.

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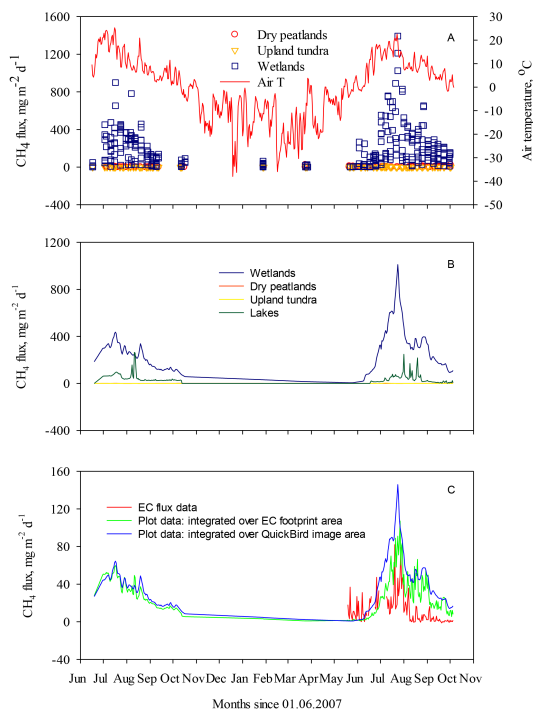


Figure 3. Seasonal distribution of daily values of chamber and EC measured CH₄ fluxes during the period from July 2007 to October 2008. Top panel: Raw data as measured by chamber method at dominant terrestrial land cover types (LCTs); Middle panel: Daily mean fluxes measured using chambers at terrestrial LCTs and lakes interpolated over the study period; Bottom panel: A comparison of the daily fluxes measured using EC technique with the plot scale chamber data integrated over the EC footprint area and over the QuickBird map area for the whole study region of 98.6 km².

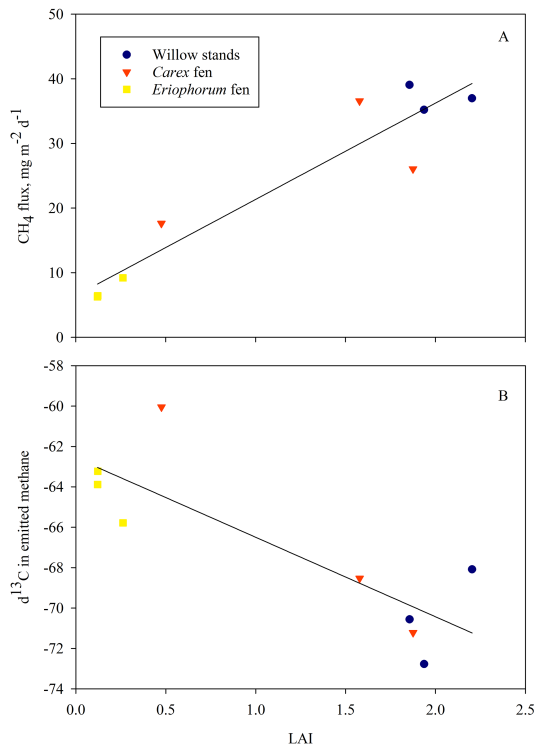


Figure 4. Correlation between cumulative seasonal CH₄ fluxes with **(a)** mean vascular LAI, **(b)** δ¹³C of CH₄ flux recorded in different wetland LCTs during the 2008 growing season.

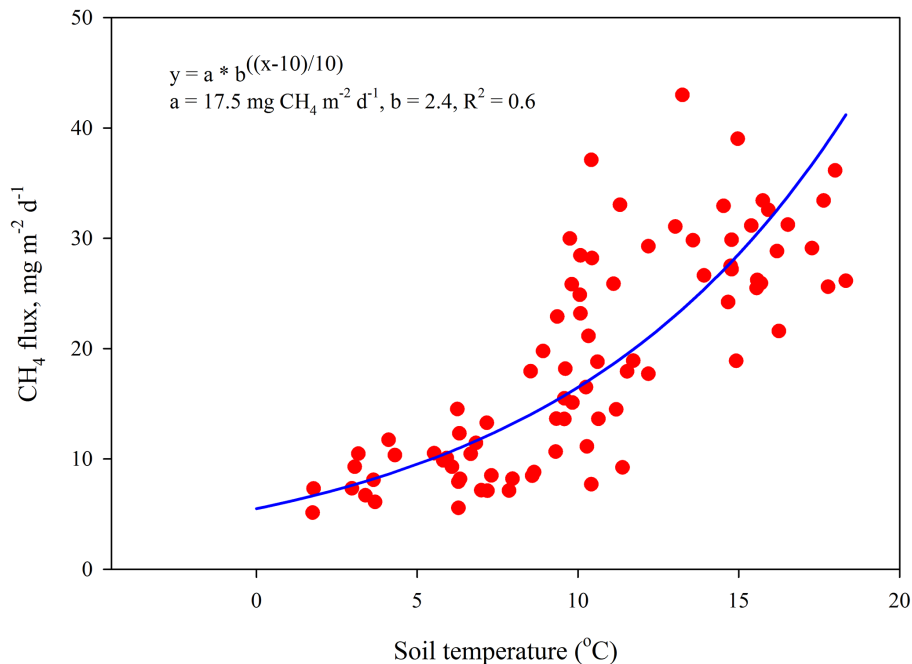


Figure 5. Dependence of CH₄ flux measured using EC technique during June until early October at fen surfaces on soil temperature. The solid line represents Q_{10} function fitted to the data using a nonlinear least squares fit (x is soil temperature, y is daily mean methane flux, a represents the base methane flux rate and b is the Q_{10} coefficient). The statistics generated from the regression analysis are also presented in the graph.

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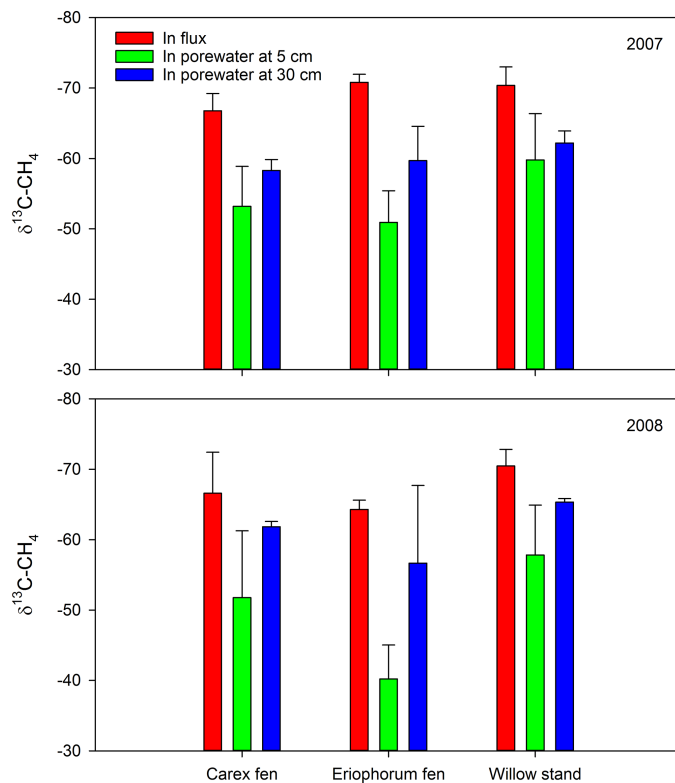


Figure 6. $\delta^{13}\text{C-CH}_4$ in emitted CH_4 (red bars) and in CH_4 contained in porewater samples collected from 5 cm (green bars) and 30 cm depths (blue bars) of methane emitting sites at the Seida site during 2007 and 2008 growing seasons.

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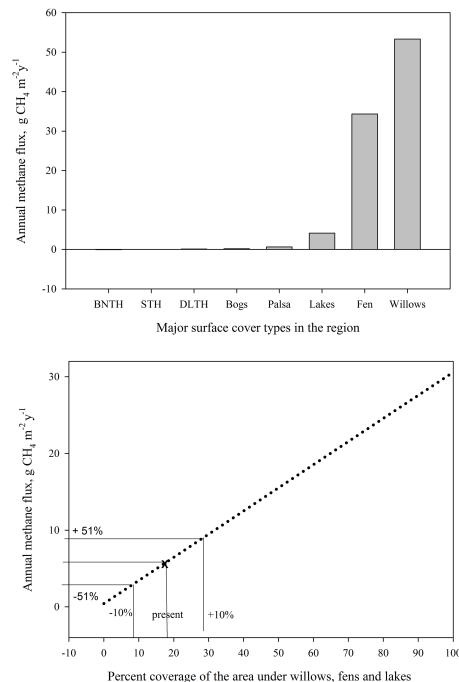


Figure 7. Top panel: Annual CH₄ flux from different major land cover types at the Seida study site. These annual estimates are obtained from plot scale chamber measurements. BNTH stands for *Betula nana* tundra heath, STH for shrub tundra heath, DLTH for dry lichen tundra heath. Bottom panel: A schematic diagram illustrating the effect of warming induced permafrost thaw on the land cover changes in the region. The x axis represents the percent coverage of the area under willows, fens and lakes and annual CH₄ flux is plotted as function of this percent coverage. The present day coverage and methane emitted from them is represented by an X mark on the dotted line. The figure shows that a 10% increase in the combined coverage of willows, fens and lakes (the major methane emitting surface at Seida) would lead to a 51% change in the annual CH₄ flux relative the present flux rate.