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Abstract

About 60% of the European wetlands are located in the European part of Russia. Nevertheless, data on methane emissions from wetlands of that area are absent. Here we present results of methane emission measurements for two climatically different years from a boreal peatland complex in European Russia. Winter fluxes were well within the range of what has been reported for the peatlands of other boreal regions before, but summer fluxes greatly exceeded the average range of $5–80\,\mathrm{mg\,CH_4\,m^{-2}\,d^{-1}}$ for the circumpolar boreal zone. Half of the measured fluxes ranged between 150 and $450\,\mathrm{mg\,CH_4\,m^{-2}\,d^{-1}}$. Extrapolation of our data to the whole boreal zone of European Russia shows that theses emissions could amount to up to $2.7 \pm 1.1\,\mathrm{Tg\,CH_4\,a^{-1}}$, corresponding to 69% of the annual emissions from European wetlands or 33% of the total annual natural European methane emission. In 2008, climatic conditions corresponded to the long term mean, whereas the summer of 2011 was warmer and noticeably drier. Counterintuitively, these conditions led to even higher CH_4 emissions, with peaks up to two times higher than the values measured in 2008. As Russian peatlands dominate the areal extend of wetlands in Europe and are characterized by very high methane fluxes to the atmosphere, it is evident, that sound European methane budgeting will only be achieved with more insight into Russian peatlands.

1. Introduction

Methane (CH_4) is a greenhouse gas that has significant impacts on the global climate and northern peatlands are one of the largest natural sources of CH_4 emissions to the atmosphere. Ground-based reliable budgets of these areas are particularly needed to verify atmospheric-based methane budgets. CH_4 emissions from tundra and boreal peatlands have previously been reported from North America (e.g. Turetsky *et al* 2002, Bubier *et al* 2005, Moore *et al* 2011), Scandinavia (e.g. Riutta *et al* 2007, Forbrich *et al* 2011), Russian tundra (e.g. Heikkinen *et al* 2004, Sachs *et al* 2010) and Siberia

(e.g. Friborg *et al* 2003, Glagolev *et al* 2008), but hardly any from boreal European Russia (e.g. Panikov 1994, Gažovič *et al* 2010). The European part of Russia includes approximately $129\,000\,\mathrm{km^2}$ of peatlands, which is about 3% of the European land surface (Joosten *et al* 2012), and about 80% of these peatlands are located within the boreal zone of European Russia. Nevertheless, wetland CH_4 emissions of boreal Russia appear to be underrepresented in the European greenhouse gas budget of Schulze *et al* (2009). Despite the sheer size of these wetland areas, virtually nothing is known about their methane fluxes. CH_4 flux from a boreal peatland site in Siberia were considerably

higher than those measured in Scandinavia and Northern America (Friborg *et al* 2003). Too few actual measurements are available from peatland ecosystems of boreal European Russia, which leaves a major gap to adequately address the European methane budget.

In order to start filling this knowledge gap, we measured methane fluxes at a boreal peatland in European Russia. The results were then extrapolated to larger spatial scales to assess the relative importance of these peatlands to the overall European methane budget. Without such conformational data, estimates for European methane budgets run the risk of remaining largely inaccurate.

2. Research site and methods

2.1. Site description and flux measurements

CH_4 emissions were studied from March 2008 to February 2009 and during the summer 2011 from a boreal peatland complex (Ust-Pojeg; 61°56′N, 50°13′E) in the Komi Republic, European Russia (detailed description of study site in Gažovič *et al* 2010, Schneider *et al* 2012, Runkle *et al* 2014). The long-term (1984–2013) mean annual temperature in the region is 1.3 °C and mean annual precipitation is 620 mm (RIHMI-WDC 2014). Our intensive study site consists of a *Sphagnum angustifolium* pine bog in the northern part and a *Sphagnum jensenii* fen in the Southern part of the peatland. On the basis of vegetation and microrelief, we selected seven microform types: hummocks, lawns and hollows in fen and bog, respectively, and *Carex* lawns in the transition zone between bog and fen. This peatland is representative of the majority of the European Russian peatlands. The largest part of the peatlands in European Russia is situated in the boreal zone and, depending on the data source the peatlands of the Komi Republic make up ¼ to ½ of all peatlands of the European Russia. The peatlands of Komi Republic consist of 48% bogs, 34% fen, and 18% mixed type peatlands (Alekseeva 1999).

CH_4 fluxes were measured once a week from 23 April to 12 October 2008 using a closed chamber approach (chamber dimensions: base 60 cm × 60 cm, height 25 cm). The chamber was equipped with a fan to ensure an even mixing of the air inside the chamber and with a venting tube to avoid under-pressure during gas sampling. This also allows the ambient pressure fluctuations to be transmitted into the chamber headspace. Additionally, measurements were conducted once a week from 20 May to 19 September 2011, nearly covering the entire growing season. A total of 18 measurement plots were established within the intensive study site in different microform types: two replicates each in ombrogenous hollows (OHO), lawns (OL) and hummocks (OH), and 3 replicates each in minerogenous hollows (MHO), lawns (ML) and hummocks (MH), and *Carex rostrata* lawns (CL). Six air samples were taken from the chamber

headspace during the 15–20 min chamber closure period using 60 ml plastic syringes. The air sample analysis was usually done within a day following field-sampling. Samples were analyzed with a gas chromatograph (GC, Hewlett Packard) equipped with a GFT PORAPAK a 80/100 (MESH-COND1900GC-015-9239, Hewlett Packard, USA) column and a flame-ionization detector. Flux rates were calculated from the change in the CH_4 concentration in the chamber headspace over time by fitting a linear function using least-squares regression. Measurements with unsteady concentration changes during chamber deployment were filtered out (9% of all measurements).

During the snow period, CH_4 fluxes were measured using a snow-gradient method. Here, 4–6 gas samples were taken per plot from different snow depths. In addition to the methane concentration measurements, profiles of snow density and temperature were measured. The diffusive fluxes were calculated from the CH_4 concentration gradient in the snow following Mc Dowell *et al* (2000). Fluxes were determined in March and April 2008 and in February 2009 (in total up to 10 times per plot). For the air sample analysis, the same gas chromatography system was used as for the samples from chamber measurements.

At each plot, soil temperature was measured at depths of 5, 10, 20 and 40 cm with a sampling frequency of 30 min (HOBO U12, HOBO, USA) in 2008. Ground water depth near the collars was measured manually each sampling date. Additionally, the green leaf area index was determined to describe the vegetation development during the growing season.

To get an individual flux estimate for each measurement plot for the whole investigation period 2008 to 2009, CH_4 fluxes were empirically modeled using the following exponential function:

$$FCH4 = a1 \times \exp(a2 \times T),$$

where T is soil temperature and $a1$ and $a2$ are fitting parameters.

We achieved best results using only soil temperature. The inclusion of further control parameters did not improve the modeling results. Modeling was solely used for filling measurement gaps, i.e. the daily emissions rates of non-measured days were modeled, which improved the annual estimates of the individual sites.

2.2. Upscaling of the fluxes

For calculating the intensive study site's overall CH_4 balance, the relative cover of the different microform types was determined along eight transects. A detailed explanation of the method is given in Schneider *et al* (2012). The annual emission of the study site is an area-weighted average using the relative land cover fractions of the microform types as weights. We used the method of maximum error estimation for the uncertainty analysis of the upscaled CH_4 fluxes. The

Table 1. Methane flux statistics for the different measurement periods and microform types: ombrogenous hollows (OHO), hummocks (OH) and lawns (OL), *Carex rostrata* lawns (CL), and minerogenous hollows (MHO), hummocks (MH) and lawns (ML).

Microform type	Daily CH_4 flux (mg CH_4 m^{-2} d^{-1})									Annual (2008) CH_4 flux (g CH_4 m^{-2} a^{-1})
	Winter			2008 (May–September)			2011 (May–September)			
	Mean	Range	N	Mean	Range	N	Mean	Range	N	
OHO	4	0.5–8	10	159	9–643	67	139	46–362	11	32.6 ± 2.1
OH	3	0.1–7	10	49	3–352	49	73	8–308	10	5.7 ± 0.5
OL	5	0.5–14	14	104	3–449	57	227	30–501	22	30.5 ± 2.5
CL	16	5–30	13	202	54–624	80	448	72–1582	20	29.5 ± 1.1
MHO	11	2–33	16	256	1–1020	98	193	75–260	11	39.0 ± 2
MH	7	3–18	8	101	0–600	78	72	16–150	12	15.5 ± 1.2
ML	8	2–20	14	166	2–722	96	ND	ND	ND	32.5 ± 1.1
Study site										25.6 ± 10.6

ND not determined.

error propagation routine for random errors is not suitable in our case, as the error of the area estimates for the different microforms cannot be considered as a random error (Schneider *et al* 2012). The mean flux of our study site was used to update the estimate of Grunwald *et al* (2012), in order to assess the new data's impact on the European CH_4 balance.

The new continental balance was calculated using the mean annual methane fluxes measured in this study for the Russian peatlands of the cold zone. For all other peatlands and land use types in Europe, including the rest of European Russia, the values given in Grunwald *et al* (2012) were applied. The mean methane fluxes of a certain land use type (forest, wetlands, agriculture and grasslands, water bodies) within a specific ecological zone (cold climates, temperate, Mediterranean or continental) was identified (via a literature review), and then multiplied by its area as derived from land cover products. Additionally, data from rice cultivation areas were incorporated. Different scenarios dealing with forest wetlands were calculated in Grunwald *et al* (2012). For this study, the scenario A3S2 was chosen, assuming 5.2% wet forests in the temperate zone and 13% in the cold climates, based on mean values given in Forest Europe (2011): we deemed these assumptions to be the most realistic for our calculation.

3. Results

The winter fluxes ranged between 0.1 and 33 mg CH_4 m^{-2} d^{-1} (table 1). The average daily fluxes during the vegetation period in 2008 differed between the different microform types, being highest at the minerogenous hollows (256 mg CH_4 m^{-2} d^{-1}) followed by Carex lawns (202 mg CH_4 m^{-2} d^{-1}). The lowest mean values were measured at ombrogenous hummocks (49 mg CH_4 m^{-2} d^{-1}) (figure 1, table 1).
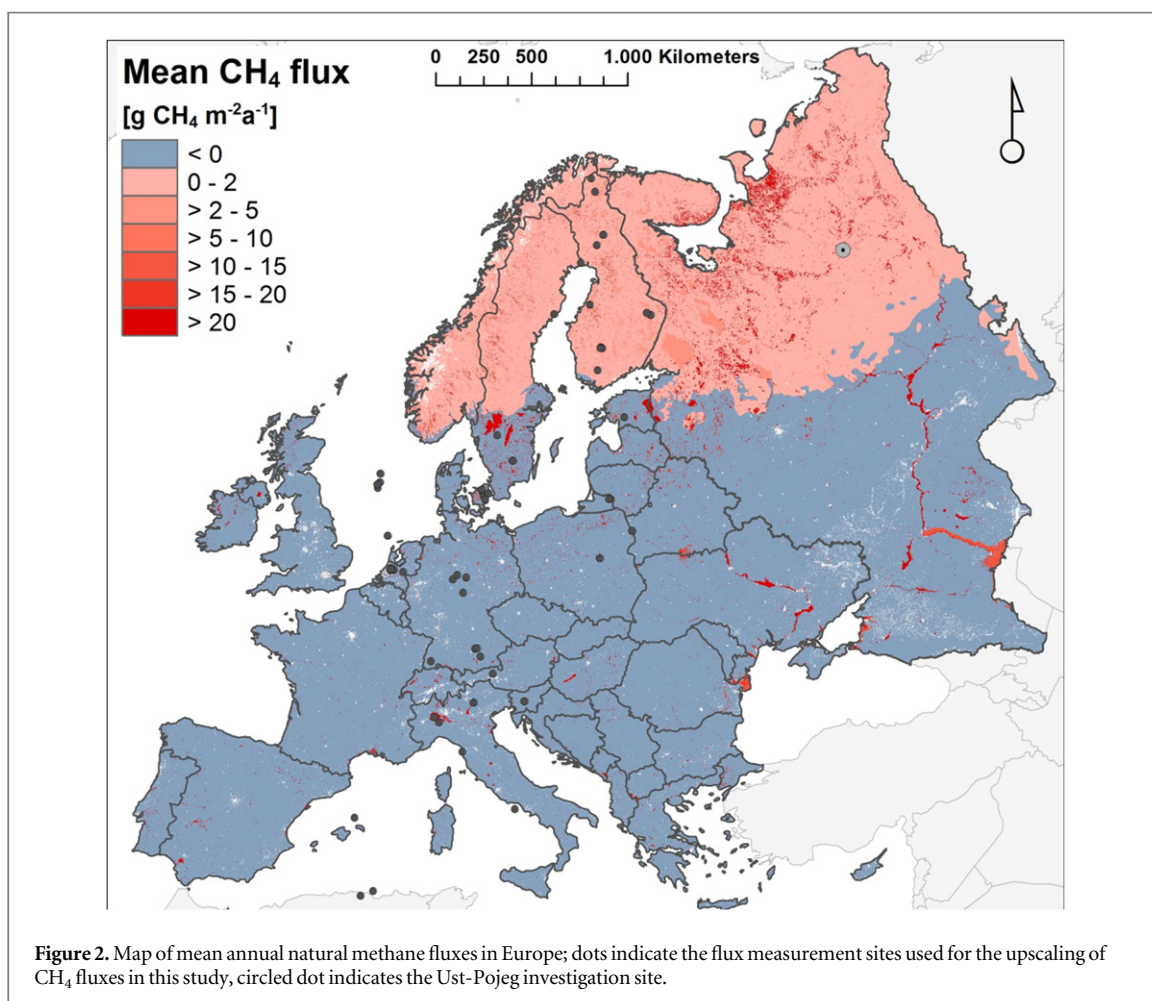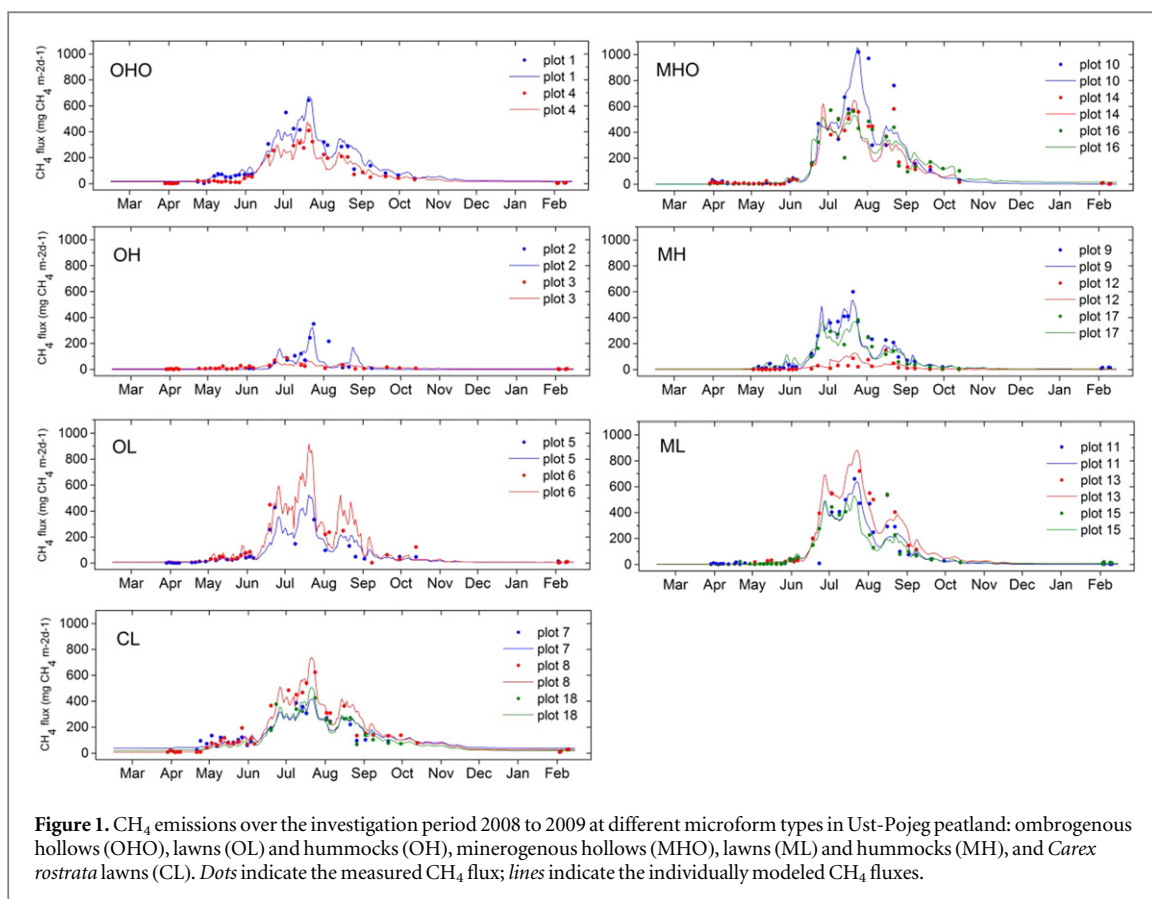
The CH_4 fluxes correlated well with individual soil temperatures, and therefore measurement gaps could be filled using regression models applied to the flux data from individual measurement plots (figure 1). The annual CH_4 fluxes for the year 2008 were estimated for each measurement plot using regression models. According to their topographic position, the flux rates ranked from highest at the minerogenous hollows (39 ± 2 g CH_4 m^{-2} a^{-1}) to the lowest at the ombrogenous hummocks (5.7 ± 0.5 g CH_4 m^{-2} a^{-1}) (table 1). As the peatland complex was well mapped, the area-weighted average annual emission was calculated as 25.6 ± 10.6 g CH_4 m^{-2} a^{-1}.

The natural European CH_4 budget was estimated using the land cover classification and literature survey of Grunwald *et al* 2012 (figure 2). The base map of Europe for this study includes five land use classes in four major ecozones (cold, temperate, continental and Mediterranean) (see the Methods section). We included the new estimate for Russian cold zone wetlands (i.e., boreal wetlands) from this study and calculated an annual natural European methane emission of 9.8 ± 2.2 Tg CH_4 and an uptake of 1.8 ± 0.7 Tg CH_4 resulting in a net balance of 8 ± 2.3 Tg CH_4 per year. The annual methane emission of the Russian boreal zone wetlands amounts up to 2.7 ± 1.1 Tg CH_4 a^{-1}, corresponding to 33% of the annual natural European methane emission.

4. Discussion

Russian peatlands must play a significant role in the overall methane budget of Europe based simply on their large surface area. The winter fluxes were well within the range of what has been reported before for the peatlands of boreal regions (Alm *et al* 1999, Rinne *et al* 2007). Fluxes during the vegetation period were twice as high as comparable sites in Scandinavia and North America (Turetsky *et al* 2014). Reasons for the high summer fluxes remain unexplained and have to be verified for other peatlands in European Russia. The most apparent difference in driving factors to

Figure 1. CH₄ emissions over the investigation period 2008 to 2009 at different microform types in Ust-Pojeg peatland: ombrogenous hollows (OHO), lawns (OL) and hummocks (OH), minerogenous hollows (MHO), lawns (ML) and hummocks (MH), and *Carex rostrata* lawns (CL). *Dots* indicate the measured CH₄ flux; *lines* indicate the individually modeled CH₄ fluxes.

Figure 2. Map of mean annual natural methane fluxes in Europe; dots indicate the flux measurement sites used for the upscaling of CH₄ fluxes in this study, circled dot indicates the Ust-Pojeg investigation site.

Scandinavia would be the continental climate and its possible effects on the driving factors and underlying processes. Temperature has an effect on methane emissions (e.g. Torn and Chapin 1993, Vicca *et al* 2009). It also most likely has an effect on substrate quality and quantity, which themselves influence the CH_4 flux (e.g. Joabsson *et al* 1999, Ström *et al* 2003). One main substrate for methane production is dissolved organic matter (DOM). During winter these substrates may be preserved due to very low temperatures reducing microbial processes. During higher temperatures in summer, a possible decrease in the size of DOM and a higher biodegradability of DOM may lead to higher CH_4 production (Bridgham *et al* 2013). Wet–dry cycles during the summer can also contribute to elevated DOM concentrations (Marschner and Kalbitz 2003). This climate type is characterized by pronounced freeze-thaw cycles in the winter–spring period, which increase the physical disruption of the organic soil, leading to higher fine root mortality. Both processes can result in higher dissolved organic carbon release, which might serve as easily available substrate for the anaerobic microbial food chain fostering CH_4 fluxes. Other known influencing factors are vegetation structure (e.g. Bubier 1995, Ström *et al* 2003, Lai *et al* 2014), ecosystem productivity (Ström *et al* 2015) and recently fixed carbon (Chanton *et al* 1995). A close connection exists between plant biomass and CH_4 transport capacity via aerenchyma tissues (Schimel 1995, King *et al* 1998). Generally, vascular plant production is considered an important control of CH_4 flux as a significant fraction of emitted CH_4 is derived from recently fixed carbon (Chanton *et al* 1995) and provides labile carbon compounds for hydrogenotrophic and acetoclastic methanogenesis (Updegraff *et al* 1995, Ström *et al* 2012). Laine *et al* (2015) showed that photosynthesis in European Russian bogs was more intensive than from bogs in Ireland and Finland. European Russian bogs had the highest photosynthesis parameter (maximal rate of photosynthesis per land surface area, maximal rate of photosynthesis per green leaf area, maximal rate of photosynthesis per total area of vascular plants and moss), which most likely translates to providing more recently fixed carbon to the rhizosphere. Thus, European Russia may supports higher CH_4 fluxes than in Scandinavia.

Another possible explanation for high flux rates at our study site is ebullition. We distinguish between two types of ebullition: episodic, which is mainly triggered by pressure alteration and occurs episodically and steady ebullition, which is described as a regular pattern with constant accumulation and release of bubbles (Baird *et al* 2004, Strack *et al* 2005). The process of steady ebullition is likely to take place at the Ust-Pojeg peatland due to water table draw-down caused by high temperatures during the summer. This could explain the higher fluxes found during the extreme summer in 2011. If so, a steady rather than an

irregular ebullition occurred at the Ust-Pojeg study site as evident by the CH_4 concentration increases within the chamber were mostly steady (91% of all measurements).

During the warmer and drier summer in 2011 (compared to 2008 and the long term average), mean fluxes were about 30% higher than the fluxes measured in 2008 (table 1), and two and a half times higher than peatland fluxes in Scandinavia and North America (Turetsky *et al* 2014). It is unclear if the warmer projected climatic conditions for this part of Europe in the 21st century will be counterbalanced by an appropriate amount of increase in precipitation (Kirtman *et al* 2013). Thus, our extraordinarily high flux rates measured under generally warmer climatic conditions might give a first insight into the future development of methane emissions for this large region. However, since only the ombrogenous part of the peatland responded with higher CH_4 fluxes under higher air temperatures, while the minerogenous part showed lower CH_4 fluxes (table 1, see also Turetsky *et al* 2014), the total methane fluxes will depend on the relative spatial proportion of each peatland type. This suggests that better spatial approximations of methane emitting ecosystems is still needed.

In the present study, we used a land cover map that comprises only a single wetland class for our upscaling. This aggregation might lead to uncertainties because differences in peatland and microform types are ignored. Other sources of uncertainty might occur from the accuracy of the land cover map itself, the date of production and the resolution of the underlying satellite data. Different authors already suggested spatially explicit global wetland databases that separate different wetland types (e.g. Matthews and Fung 1987, Aselman and Crutzen 1989, Lehner and Döll 2004). However, the data were produced at coarse spatial resolutions (5°–0.5°) and were mostly outdated and only partly validated. In our study, we relied on an up-to-date map (2009) at medium resolution (300 m) and we made use of comprehensive validation for the calculation of the uncertainty in the distribution of the respective land cover type. Our uncertainty assessment were built on the work of Olofsson *et al* (2013), who propose a method to obtain confidence intervals of land cover areas based on the error matrix. In total, the uncertainties resulting from the upscaling from one peatland complex to the total cold peatlands in European Russia remain uncalculatable. Despite all uncertainties, our study shows that a sound and complete greenhouse balance of Europe can only be achieved by including European Russia's peatlands. To do this, more data are needed from these peatlands. In this case, we also need to assess how representative our CH_4 flux measurements are, which may be achieved through detailed field and laboratory experiments.

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