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Comparison of methane fluxes of open and forested bogs of the southern taiga zone of Western Siberia

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Two bog ecosystems were compared by their ability to release CH_4 into the atmosphere during the warm season, and the influence of environmental factors (water table level and peat temperature) on CH_4 fluxes from the bog surface was studied. The studied bog ecosystems belong to the ombrotrophic bogs of the taiga zone of Western Siberia, but they differ significantly in vegetation cover, structure of peat deposits, hydrological conditions, and temperature of peat layers. Methane fluxes were measured using the close static chamber method. The results show that CH_4 emissions vary from site to site depending on the local hydrological regime and the type of vegetation cover. The mean±standard deviations of the CH_4 emission flux from the open and forested bogs were found to be 2.66±4.58 mg m^{-2} h^{-1} and 0.57±0.69 mg m^{-2} h^{-1}, respectively. The calculated total CH_4 flux shows that the amount of CH_4 released from open bog is on average 4.7× higher than from forested bog, despite the fact that the former cover an area 1.5× smaller than that covered by the latter. The seasonal dynamics of CH_4 fluxes in both bog ecosystems are characterized by a July maximum and are closely related to peat temperature, but are not connected with the water level. In open bogs, the average daily CH_4 emission variability was found to be 50% due to the influence of peat temperature at the depth of 10 cm, while in forested bogs it was found to be 39% due to peat temperature at the depth of 40 cm. The research results indicate a direct and very important link between the vegetation species composition and the hydrological regime of bog ecosystems in the estimates of the CH_4 flux from bog ecosystems in the region. This link causes high variability of the CH_4 fluxes at a small scale, which is often not accounted for when assessing CH_4 budgets of bogs and modelling responses of bog ecosystems to climate change.

Introduction

Western Siberia is the largest wetland region on the planet, and the bog ecosystems found here are exceptionally diverse. The bog ecosystems territory here exceeds 32 million hectares, and the bogginess of certain areas reaches 80% (Liss *et al.* 2001). However, the gas exchange of Siberian bogs is still poorly studied. Methane emission studies initiated here in 1992 were conducted in a few wetland areas located in the subzone of the southern taiga (Panikov *et al.* 1995;

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Glagolev and Smagin 2006; Inisheva and Sergeeva 2006; Naumov *et al.* 2007; Glagolev and Shnyrev 2008; Sabrekov *et al.* 2014a, Sabrekov *et al.* 2014b). The majority of the research results obtained are sporadic and there remains a lack of long-term monitoring observations. Field measurements are mainly focused on identifying the spatial dynamics of CH_4 fluxes, while seasonal dynamics are poorly investigated. The current state of knowledge is mainly constrained by the difficulties involved in organizing observations: no automation is possible, and observation stations are located in inaccessible areas. Thus, CH_4 fluxes are traditionally measured in natural conditions by the manual chamber method during the day over a period of a few days. By contrast, few papers are devoted to analyzing the time dynamics of CH_4 fluxes in the boreal zone of Western Siberia using automatic chambers (Davydov *et al.* 2018), manual chambers (Veretennikova and Dyukarev 2017) or the eddy covariance method (Fleischer *et al.* 2016).

Currently, the main objective of research is to estimate the total CH_4 flux into the atmosphere from the surface of Siberian bog ecosystems. The essence of these studies is to experimentally determine and then extrapolate the values of CH_4 fluxes from typical bog ecosystems. The main focus is on determining the areas of various types of wetland ecosystems using GIS mapping and high-resolution satellite images. The first estimate of global emissions from a bog in Western Siberia was 7.2±1.29 Tg CH_4 yr^{-1} (Glagolev 2010); the following year, this value was greatly reduced to 3.91±1.29 Tg CH_4 yr^{-1} (Glagolev *et al.* 2011). Many estimates of total CH_4 flux from the bogs of Western Siberia have been obtained since. For example, according to Kim *et al.* (2011), the CH_4 flux is 2.9–3.0 Tg CH_4 yr^{-1}. According to Bohn *et al.* (2015), the spread of the total CH_4 flux falls between 2.42 Tg CH_4 yr^{-1} and 11.9 Tg CH_4 yr^{-1}, depending on the model used. According to Makushev *et al.* (2016), the average flux rate for the period from 2003–2013 was 4.34 Tg CH_4 yr^{-1}. Estimates made by Thomson *et al.* (2017) range from 19.3 Tg CH_4 yr^{-1} to 19.9 Tg CH_4 yr^{-1}. Terentyeva *et al.* (2017) created a topological map of the wetlands in the southern taiga of Western Siberia based on high-resolution Landsat images. According to the researchers, the utilization of this map improved estimates of CH_4 flux from 0.84 Tg CH_4 yr^{-1} to 1.57 Tg CH_4 yr^{-1}. The fact that there is such a wide range of estimates indicates the problems and the insufficiency of existing studies of CH_4 fluxes in this area. Moreover, the lack of information on CH_4 fluxes obtained in field studies does not allow the contribution of Western Siberian bogs to global environmental processes to be objectively assessed.

Methane fluxes from bog ecosystems are characterized by significant spatial and temporal variability. In addition, this variability depends on various environmental factors, such as the temperature of the air and peat deposits (Brown *et al.* 2014; Lai *et al.* 2014; Rinne *et al.* 2018; Wang *et al.* 2018), soil moisture (Hu *et al.* 2015), bog water level (Glagolev and Smagin 2006; Laine *et al.* 2007; Moore *et al.* 2011; Sabrekov *et al.* 2014a), type of vegetation cover (Whiting and Chanton 1992; Joabsson *et al.* 1998; Ström *et al.* 2005; Green and Baird 2012) amongst others. Analysis of the above-mentioned studies shows that quantitative assessments of CH_4 flux from bog ecosystems in Western Siberia, as well as the impact of environmental factors on this process, constitutes an insufficiently studied topic. The initial data used to assess the contribution of the greenhouse gases produced by bog ecosystems to global climate change can represent the results of monitoring activities. Due to the scarcity of field observations, we do not yet know how future climate change will affect CH_4 emissions in the wetlands, what will be the magnitude and direction of the changes and when they will occur. This investigation examined two contrasting bog ecosystems (open and forested) located in the southern taiga zone of Western Siberia. The studied bog ecosystems are considered to be ombrotrophic, but they significantly differ in vegetation cover, structure of peat deposits, hydrological conditions, and temperature of peat layers. The first objective of the research was to compare the two bogs by their ability to release CH_4 into the atmosphere during the growing season. The second objective was to show the influence of environmental factors (groundwater level and peat temperature) on CH_4 fluxes. Based on the measurements of CH_4 fluxes combined with meteorological data, the

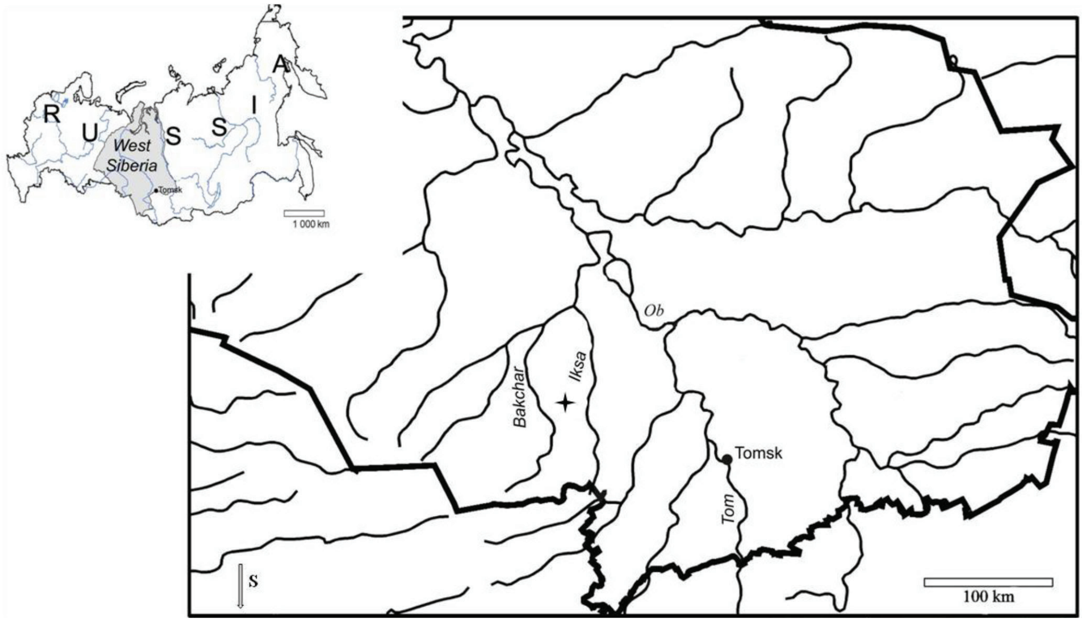

Fig. 1. Locations of the studied bog ecosystems.

summer CH_4 flux from the bogs under analysis was quantified.

Material and methods

Study Site

The research sites are located in the watershed of two small rivers — the Bakchar River and the Iksa River — which are part of the Chaya-Ob River system (Fig. 1). The watershed area belongs to the southern taiga subzone and comprises the northeastern part of the largest wetland system in the world, the Great Vasyugan Mires. Land cover classification based on Landsat 7 satellite images (Dyukarev *et al.* 2017) reveals that about 37.4% of the catchment area is occupied by bogs: 30% ombrotrophic and only 7.4% eutrophic. Open (15.0%) and forested (14.9%) bogs predominate among the ombrotrophic bogs.

For this research, we selected two ombrotrophic ecosystems most typical of the area that differ in their vegetation cover but that comprise the majority of bogs reserves in the area (Liss *et al.* 2001). The first bog is an open sedge-sphagnum bog (open bog — OB) (56°58′14.6′′N, 82°37′10.3′′E; Fig. 2a). It occupies up to 3.2%

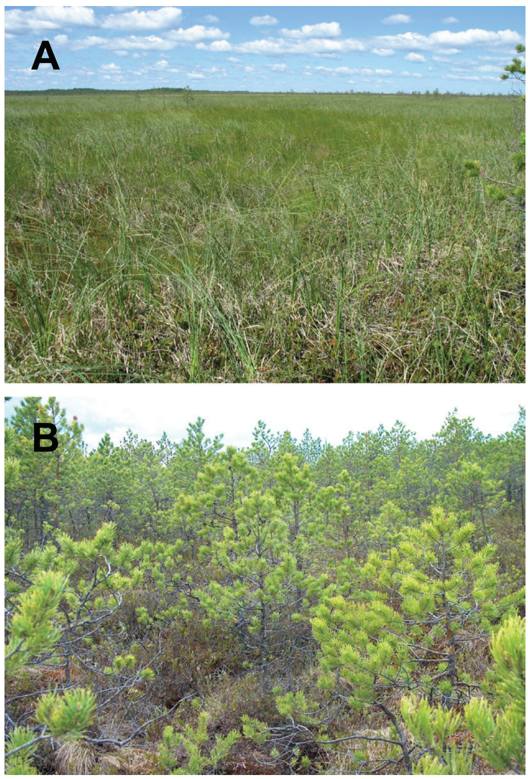

Fig 2. View of the (**A**) open sedge sphagnum bog — OB and the (**B**) forested pine schrub-sphagnum bog — FB.

from open type bog area or 46 348 ha. It is a sedge-sphagnum plant association, the vegetation cover of which is predominated by *Eriophorum vaginatum* and *Carex rostrata* (projective cover: 64%). The moss cover is represented by various types of sphagnum mosses (*Sphagnum fuscum*, *Sphagnum angustifolium*, and *Sphagnum magellanicum*), forming an uninterrupted cover. The degree of moss layer coverage is 100%. The microrelief of this bog is represented by small hummocks up to 20 cm high. The depth of the peat deposit reaches 3 m. The top layer of the deposit (0–100 cm) is mainly composed of sphagnum peat, followed by a layer of mesotrophic peat; the base of the deposit is underlain by eutrophic horsetail peat.

The second bog is a pine-shrub-sphagnum (forested bog — FB) (56°58′32.2′′N, 82°36′29.7′′E; Fig. 2b). It occupies up to 4.5% from forested type bog area or 65 812 ha. It is a pine-shrub-sphagnum association, the vegetation cover of which is predominated by *Pinus sylvestris*, (average tree height: 2–3 m). The shrub layer comprises of *Ledum palustre*, *Chamaedaphne calyculata*, *Andromeda polifolia*, *Vaccinium uliginosum*, and *Oxicoccus microcarpus*. The moss cover on hummocks and grassy patches is dominated by *Sphagnum fuscum* (95%), while *Sphagnum angustifolium* and *Sphagnum magellanicum* grow in between hummocks. The grass layer is poorly developed (vegetation cover: 5%) and is represented by clumps of *Eriophorum vaginatum*, *Rubus chamaemorus*, and *Drosera rotundifolia*. The bog is characterized by an undulating microrelief due to a significant number of large moss cushions with a height of about 30 cm and an average diameter of 3 m. The depth of the peat reaches 2 m. The upper 1 m layer of the peat deposit is represented by *Sphagnum sp*. (*Sphagnum magellanicum* and *Sphagnum fuscum*), followed by a thin layer of mesotrophic peat; at the base of the peat deposit there is a layer of mineral peat. Monitoring of CH_4 fluxes and environmental factors was carried out in different months of the 2012–2014 growing seasons at Vasyuganie field station of the Institute of Monitoring of Climatic and Ecological Systems of the Siberian Branch of the Russian Academy of Sciences. The field station is located in the southern taiga of Western Siberia, near the village of Polynyanka in the Bakcharsky district of the Tomsk region.

The climate of the research sites is distinctly continental, with long, cold winters and short, hot summers. The average annual temperature for the period from 1963 to 2015 was –0.3°C (Dyukarev 2015). The warmest month is July (18.1°C), and the coldest is January (–19.2°C). Average monthly air temperatures below 0°C are observed from November (–9.9°C) to March (–8.9°C). Annual precipitation is 468 mm, 45% of which occurs in the summer months, and 12% in the winter. The initial snow cover disappears under the influence of subsequent thaws. The disappearance of seasonal snow cover on average occurs by 20 April. The average duration of seasonal snow cover is 172 days (Kiselev *et al.* 2016).

Methods

Measurement of CH_4 emissions

The research was conducted in May, July, and September during the growing seasons of 2012, 2013, and 2014, with a sampling rate of eight times per day (at 07:00, 10:00, 13:00, 16:00, 19:00, 22:00, 01:00, and 04:00, local time). Observations of CH_4 fluxes were organized on similar dates: in 2012 from 15–18 May, 20–23 July, and 5–7 September; in 2013 from 21–23 May, 18–22 July, and 20–23 September; and in 2014 from 21–23 May, 21–24 July, and 21–23 September.

Methane emissions were measured using the dark static chamber method (for example, Pavelka *et al.* 2018). To reduce the spatial heterogeneity of fluxes, methane emissions were measured in triplicate. Six nontransparent cylindrical chambers with a volume of 16.6 l were installed in the studied bogs. They were placed on preinstalled basements with an area of 590 cm^2 and with a gutter for waterproofing. The basements were carefully placed into the peat to a depth of 20 cm each year in May, the day before the experiment commenced. Mixing of air in the chamber was ensured by a 12 V electric fan.

In the OB, three replicas of the chamber basements were installed for the entire season in the location representing plant communities predominated by *Carex* and *Eriophorum*. Three chamber basements were also installed in the FB site at moss cushions almost completely covered with *Sphagnum fuscum*. An independent temperature profile meters and a water pressure sensors were installed about 1 m from the chambers to record the water table level and the temperature of the peat. Wooden boardwalks were constructed over the vegetation cover at the research sites to minimize the impact on the area and to facilitate the chambers' deployment.

Air samples from each chamber were taken three times, on each occasion with a 1 ml plastic syringe immediately after the chamber was installed on the basement and after 15 (in the OB) or 30 minutes (in the FB) from the beginning.

After sampling, the syringes were tightly sealed and delivered to the laboratory (Institute of Monitoring of Climatic and Ecological Systems, Tomsk) for analysis within one week. The measurement of CH_4 concentration was carried out using a Shimadzu GC-14B gas chromatograph equipped with a flame ionization detector (FID), and a Carboxen-1000 packing column with a diameter of 2.1 mm and a length of 15 m; the carrier gas was helium. In the calculations of the CH_4 emission rate a best fit of data was achieved with linear regression (as opposed to non-linear regression). We tested this independently by taking samples more frequently over the 30 minutes incubation period (data not shown). The data were not corrected for water dilution to allow for proper comparison with other published data which do not take into account the effect of evaporation of water during chamber closure and a possible dilution of CH_4 concentration. However, based on our previous studies focusing on CO_2 fluxes the maximum error is estimated to be not more than 15% of the flux (Dyukarev 2017).

Change in CH_4 concentration (d_c, mg m^{-2} h^{-1}) in the chamber was calculated by the formula:

$$d_c = C_0 \times d_x \times P \times M / (R \times T), \qquad (1)$$

where $C_0 = 0.001$ (mg g^{-1} ppm^{-1}), P is the molar gas constant: 8.31 (J mol^{-1} × K), d_x is the change rate in the volume concentration of CH_4 in the chamber, (ppm h^{-1}), M is the molar mass of CH_4, 16.04 (g mol^{-1}) and T is the air temperature in the chamber (K). The specific flow (discharge rate) of CH_4 from the surface of the peat deposit was calculated using the formula:

$$F = d_c \times V / S, \qquad (2)$$

where F is the flux of CH_4, (mg m^{-2} h^{-1}); S is the chamber area at the surface, (m^2) and V is the chamber volume (m^3).

Registration of CH_4 fluxes was accompanied by additional measurements of environmental factors: air temperature, peat temperature, and water table level (WTL). Real-time monitoring of the depth of the WTL was carried out using a pressure sensor (HOBO Water Level Logger U20-001-04) submerged in water at a fixed level below the surface. The peat temperature was measured using an independent temperature profile meter designed to automatically record peat temperatures and accumulate measurement data over a long period of time. The peat temperature was recorded at centimetre depths of 2, 5, 10, 15, 20, 30, 40, 60, 80, 120, 160, and 240.

Statistical Analysis

Average CH_4 fluxes and standard deviation were calculated for three chambers at each research site. Subsequently, during the observation period, individual fluxes were averaged for each site. SigmaStat ver. 12 (Systat Software, USA) was used to analyze the data. Differences in average CH_4 emission values and environmental variables between bog ecosystem types were tested using non-parametric criteria (Mann-Whitney U test/Wilcoxon rank-sum test), which are used to test the null hypothesis when comparing both independent and dependent groups. The data were checked for normal distribution using the *t*-test. The peat temperatures and WTL were compared in a similar manner. Correlations of CH_4 fluxes with environmental variables were verified using the Spearman's correlation analysis. The data were analyzed on different time scales: per month; per season of 2012, 2013, and 2014, respectively; and per the three-year period.

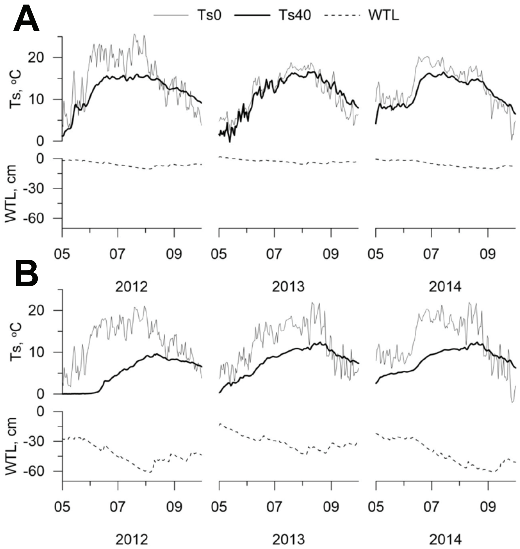

Fig 3. Time series of the two studied sites: (**A**) open bog and (**B**) forested bog. Measurements of soil temperature at 10 cm (Ts_{10}) and 40 cm (Ts_{40}) depth and the water table level (WTL) in the bogs for the growing seasons during 2012–2014 are shown.

Estimation of seasonal emissions of CH_4

Total CH_4 emissions during the growing season were calculated as the sum of average daily fluxes during the frost-free period. The frost-free period was estimated as the period with daily above-zero air temperatures. The average daily CH_4 fluxes were calculated using an exponential regression model, with peat temperature as input values. The exponential model parameters were estimated using SigmaStat for the entire observation period for each time series of daily peat temperatures at depths from 2–240 cm.

Results

Weather conditions during the research period

The winter and summer periods of 2012 were characterized by a prominent temperatures contrast. The lowest temperature was in December (average monthly temperature was –24.0°C), while the hottest month was July (average monthly temperature was 20.6°C). The summer of 2012 was abnormally hot, dry and windless (average temperature in June and August was 18.5°C). The average air temperature of the subsequent two years (2013 and 2014) did not exceed the average annual (1963–2015) values (16.1°C). The duration of the period with air temperatures above 0°C was 193 days in 2012, 213 days in 2013, and 192 days in 2014 (Kiselev *et al.* 2016).

WTL and peat temperature

The studied bogs significantly differed in WTL (Table 1). The results showed that in the OB, the average WTL was 5.13 cm below the surface (range from 2.5–10.3 cm). In the FB, the average WTL was 40.5 cm (range from 30.0–61.0 cm). The average seasonal WTL for 2012, 2013, and 2014 also differed significantly ($p < 0.001$). The

Table 1. The dominating plant species and mean values of WTL and peat temperatures for the growing seasons 2012–2014 at their respective study sites: OB (open bog) and FB (forested bog). T_s is the peat surface temperature, T_x is the peat temperature at a depth of x cm, and WTL is the water table level. The significant differences ($p < 0.001$) in environmental parameters between bogs are indicated in bold.

Bog	Dominating plant species	WTL	T_s	T_2	T_5	T_{10}	T_{20}	T_{30}	T_{40}	T_{60}	T_{80}	T_{120}	T_{160}	T_{240}
OB	*Eriophorum vaginatum*, *Carex rostrata*	**–40.5**	15.78	15.99	15.83	**15.61**	**14.86**	**14.27**	**13.40**	**9.66**	**9.20**	7.56	6.35	5.25
FB	*Pinus silvestrys*, *Ledum palustre*, *Chamaedaphne calyculata*, *Andromeda polifolia*, *Sphagnum fuscum*	–5.1	14.12	15.42	15.26	**14.54**	**10.42**	**8.32**	**9.92**	**7.69**	**8.98**	7.39	6.23	5.21

lowest WTL was observed in the dry 2012 (on average 7.0±1.2 cm and 48.2±4.8 cm below the surface in the OB and the FB, respectively). The highest WTL was recorded in the warm and wet 2013 (on average 3.4±0.4 cm and 33.5±1.7 cm below the surface). The 2014 season was dry and warm, with a lower WTL than in 2013 in both bogs, but a higher WTL than in 2012 (on average 5.0±0.8 cm and 39.9±3.1 cm below the surface, respectively). Fig. 3 depicts the WTL dynamics during vegetation periods. In 2012 and 2013, the WTL in both bogs changed simultaneously and had the same seasonal character: WTL growth was observed in May, decreased to a minimum in mid-summer (July), and after heavy rains in late summer and in September increased again, but did not exceed the May values. In the 2014 season, the WTL also peaked in May, but had a downward trend and reached its lowest level before the end of September.

During the research period, peat deposits in both bogs were characterized by a decrease in temperature from the surface to deeper layers. The OB was characterized by a higher temperature in the peat deposit at the depth of 10–80 cm ($p < 0.001$) compared to the FB (Table 1). Below 80 cm, the temperature of the bogs' peat was characterized by similar values.

Characteristics of CH4 fluxes from bog ecosystems

During the observation period, CH_4 emissions of the OB varied from –0.08–26.57 mg m^{-2} h^{-1}, and for the FB, from –0.08–4.86 mg m^{-2} h^{-1} (Table 2). Histograms clearly demonstrate that the density of the CH_4 flux distribution was characterized by a strongly pronounced left-hand asymmetry, i.e., the maximum number of observed fluxes corresponded to values below the arithmetic mean (Fig. 4). Both histograms have a so-called long tail, which indicates the presence of special cases of emission bursts that fit into individual fragments. The frequency of occurrence of such pulse fluxes was six and 1% of the number of observed values of CH_4 fluxes in the OB and the FB, respectively. Negative CH_4 fluxes were also registered; their share corresponded to six and 2.5% of the total number of observed fluxes in the OB and the FB, respectively. Given that the distribution of CH_4 fluxes did not fit into a normal distribution, median values were used in the data analysis along with standard arithmetic averages.

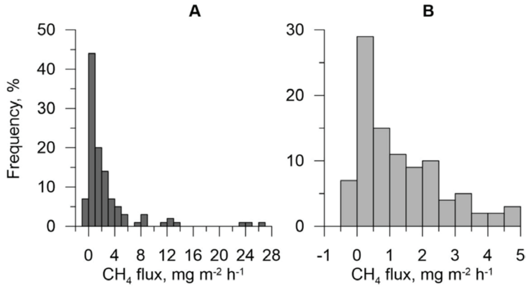

Fig 4. Probability densities of CH_4 fluxes from the (**A**) open bog and (**B**) forested bog sites.

The studied bogs differed in their ability to release CH_4 into the atmosphere: CH_4 emissions from the OB were three to six times higher than in the case of the FB. Furthermore, the difference in median values of CH_4 emissions between the bogs was statistically significant (Fig. 5). Table 3 summarizes the data on the CH_4 fluxes from the bogs under analysis, making it clear that the highest rates of CH_4 emissions were recorded in the hottest and driest year of 2012.

Table 2. The mean and median values of CH_4 fluxes (mg m^{-2} h^{-1}) from the studied bogs (*n* – number of measurements, *x* – mean, SD – standard deviation, Me – median).

Year	Open bog *n*	Open bog *x*±SD	Open bog Me	Forested bog *n*	Forested bog *x*±SD	Forested bog Me
2012	67	3.66±5.91	1.21	65	0.64±0.84	0.34
2013	78	1.47±1.24	1.40	78	0.47±0.40	0.34
2013	78	1.47±1.24	1.40	78	0.47±0.40	0.34
2012–2014	223	2.66±4.58	1.25	221	0.57±0.69	0.38

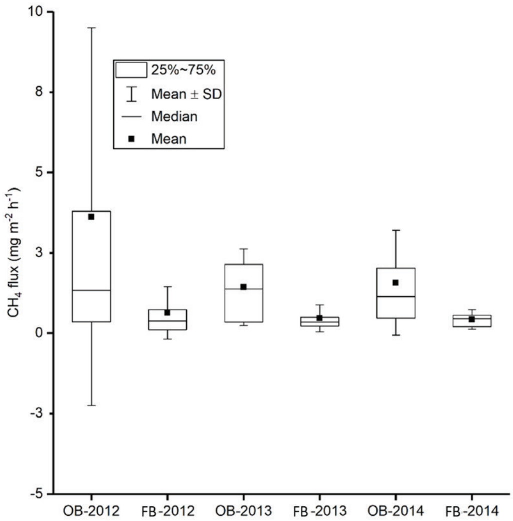

Fig 5. Box plot of CH_4 fluxes in the open bog (OB) and the forested bog (FB) over the growing seasons. The difference in the median values of CH_4 fluxes between bogs is statistically significant ($p < 0.001$ in 2012, $p = 0.003$ in 2013, and $p = 0.005$ in 2014).

Indeed, they exceeded those of the subsequent two years in the OB and the FB by about 1.5× and 1.3×, respectively. The median values did not differ statistically between the studied years ($p = 0.599$ and $p = 0.945$, respectively). It should be noted that there was a very wide range of flux variability in the growing season of 2012 compared to the two subsequent years, which is especially noticeable for the OB (Fig. 5). Methane fluxes during the growing seasons of 2013 and 2014 were characterized by similar average and median values.

In the OB, pronounced seasonal dynamics in all years with a maximum in July (Fig. 6) were observed. Fluxes in July differed statistically significantly ($p < 0.001$) from those in May and September (Table 3). Seasonal dynamics of CH_4 emissions from the FB were smoothed, but summer fluxes always exceeded spring-autumn fluxes by 1.5–2×. Nevertheless, the differences between these data were not statistically significant both for each year separately and for the three-year period as a whole.

Factors controlling CH_4 fluxes

Methane emissions from the studied bogs did not show a direct linear dependence on the changes in the WTL during the year and in separate months of the growing season (Table 4). Temperature, on the other hand, correlated with CH_4 fluxes in a number of ways.

In the OB, a correlation between CH_4 fluxes and peat temperature at depths from 2–20 cm was found on all time scales. As a rule, correlations with air and surface temperatures were lower than with deeper peat temperatures.

The greatest correlation between fluxes and temperature was observed in summer (July), and all these correlations were significant and best related to the temperature at the depth of 2 cm (Table 4). In May and September, there was no correlation between CH_4 flux and peat temperature, or it was very small. Focusing on the correlation between CH_4 fluxes and temperature on the seasonal time scale, dependence between these

Table 3. Seasonal dynamics of CH_4 emissions (mg CH_4 m^{-2} h^{-1}) from the studied bogs (*n – number of sites; x* – mean; SD – standard deviation).

Data of measurements	*n*	Open bog *x*±SD	Range	*n*	Forested bog *x*±SD	Range
15–18 May 2012	23	1.21±1.40	–0.02/5.57	21	0.44±0.45	–0.08/1.62
20–23 Jul. 2012	26	10.18±7.89	0.64/26.57	26	0.98±1.11	–0.05/4.86
5–7 Sep. 2012	18	1.22±1.43	0.07/5.23	18	0.37±0.52	–0.02/0.87
21–23 May 2013	18	0.40±0.16	–0.04/0.57	18	0.10±0.10	–0.02/0.24
20–22 Jul. 2013	32	1.43±1.24	–0.04/3.51	32	0.51±0.45	–0.06/1.55
20–23 Sep. 2013	24	0.64±0.48	0.04/1.86	24	0.36±0.30	–0.02/0.87
21–23 May 2014	20	0.22±0.20	–0.06/0.47	20	0.07±0.03	0.04/0.11
21–24 Jul. 2014	24	1.85±1.55	–0.05/5.89	24	0.51±0.31	–0.06/1.08
21–23 Sep. 2014	20	0.48±0.11	0.37/0.62	20	0.10±0.13	–0.01/0.36

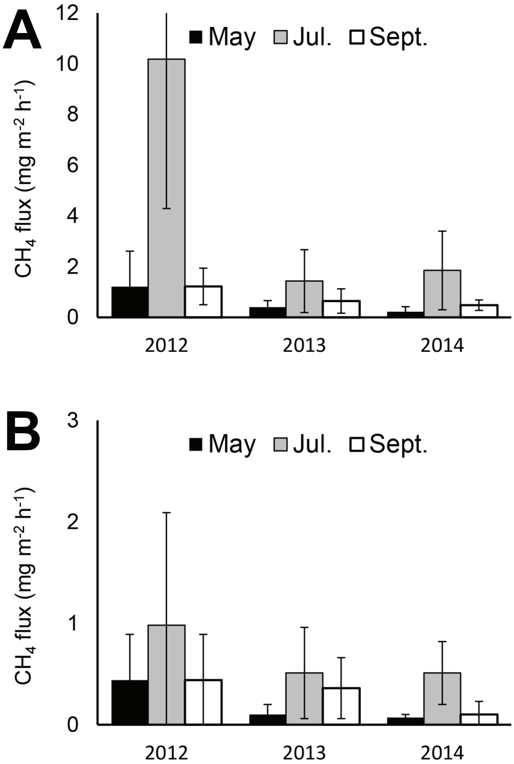

Fig 6. Average (±SD) monthly CH_4 fluxes in the (**A**) open bog and (**B**) forest bog sites.

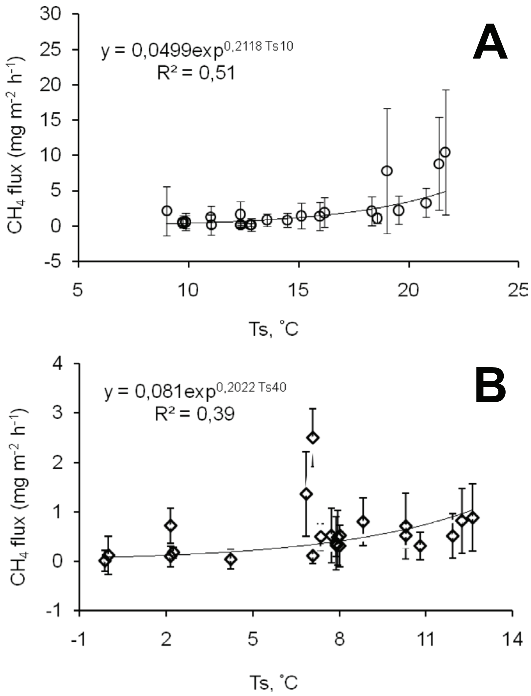

Fig 7. Relationship between the average daily CH_4 fluxes and the average daily peat temperature at (**A**) 10 cm depth in the open bog and at (**B**) 40 cm depth in the forest bog over the 2012–2014 growing seasons.

parameters decreased. The correlation between variables was even smaller when calculated for the three-year period. On the seasonal time scale, correlations worked best when the variables were averaged to daily values. In this case, the CH_4 flux was best correlated with the peat temperature at the depth of 10 cm. For the three-year period, a regression model was constructed. In accordance with it, the variability of the CH_4 flux during the growing season could be explained by the temperature at the depth of 10 cm ($r^2 = 0.51$) and be described by the exponential function (Fig. 7a).

In the FB, correlation analysis between fluxes and temperature at different time scales showed an insignificant correlation between the variables. First, no correlations in individual months of the growing season were discovered, or they were statistically insignificant. The exception was May 2012, when significant correlations were found between CH_4 fluxes and peat temperature at the depths of 20 cm and 30 cm (Table 4). On the seasonal time scale, a significant correlation between CH_4 fluxes and peat temperature at a minimum depth of 30 cm was found. The most significant was the correlation for the depth of 40 cm. The most remarkable dependencies of CH_4 fluxes on temperature were observed when considering the average daily values for the entire research period. According to the constructed exponential model, the seasonal dynamics of methane emissions by 39% could be explained by the temperature variability of peat deposits at the depth of 40 cm (Fig. 7b).

Estimation of total CH_4 fluxes during the growing season

The identified correlations between the temperatures of peat deposits and the CH_4 flux were used to estimate total CH_4 emissions during the 2012–2014 growing seasons (Table 5 and Fig. 8). It was found that the exponential equation best explains the average daily CH_4 fluxes for both of the bogs in the study. However, for the OB, the

Table 4. Correlation coefficient (*r*) between CH_4 flux and environmental variables during. T_{air} is air temperature, T_s is peat surface temperature, T_x is peat temperature at a depth of *x* cm, WTL is water table level and DAY is the daily average CH_4 from the years 2012–2014. Significant correlation ($p \leq 0.05$) is indicated in bold.

Season	T_{air}	T_s	T_2	T_5	T_{10}	T_{20}	T_{30}	T_{40}	T_{60}	T_{80}	T_{120}	T_{160}	T_{240}	WTL*
Open bog														
May 2012	0.13	–0.08	–0.06	–0.08	–0.10	–0.10	–0.16	–0.21	–0.02	–0.01	–0.01	–0.01	–0.01	–0.12
Jul. 2012	**0.51**	**0.59**	**0.76**	**0.72**	**0.70**	**0.67**	0.62	0.48	0.27	0.21	0.21	0.10	0.11	–0.24
Set. 2012	0.15	0.09	0.10	0.11	0.01	–0.09	–0.21	–0.51	–0.25	–0.24	–0.12	–0.15	–0.11	–0.10
May 2013	0.14	0.05	0.02	0.07	0.07	0.07	0.34	0.52	0.39	–0.12	–0.12	–0.10	–0.12	–0.12
Jul. 2013	**0.54**	**0.54**	**0.64**	**0.61**	**0.67**	0.08	–0.007	–0.08	–0.17	0.23	0.19	0.15	0.11	–0.58
Sept. 2013	0.70	0.60	–0.30	–0.51	–0.61	–0.72	–0.67	0.67	0.65	–0.67	–0.52	–0.42	–0.44	–0.21
May 2014	0.14	0.15	0.22	0.17	0.11	0.11	0.34	0.52	0.36	0.21	0.11	–0.22	–0.15	–0.36
Jul. 2014	**0.53**	**0.59**	**0.67**	**0.78**	**0.74**	**0.61**	0.28	0.18	0.29	0.34	0.33	0.31	0.21	–0.22
Sept. 2014	–0.03	–0.07	–0.03	–0.03	–0.03	0.12	0.13	0.58	0.41	–0.45	–0.49	0.11	0.12	–0.01
Year 2012	**0.44**	**0.41**	**0.41**	**0.42**	**0.52**	**0.49**	**0.40**	0.44	0.32	0.24	0.11	0.10	0.09	–0.52
Year 2013	**0.43**	**0.34**	**0.63**	**0.53**	**0.34**	0.24	0.08	0.20	0.01	0.02	0.01	–0.14	–0.15	–0.15
Year 2014	**0.40**	**0.46**	**0.73**	**0.66**	**0.74**	**0.68**	**0.57**	0.48	0.34	0.37	–0.28	–0.20	–0.44	–0.33
2012–2014	**0.47**	**0.35**	**0.38**	**0.38**	**0.42**	**0.35**	0.22	0.27	0.31	0.28	0.30	0.20	0.19	–0.42
DAY	**0.47**	**0.35**	**0.52**	**0.61**	**0.75**	**0.42**	0.62	0.66	0.25	0.34	0.35	0.41	0.14	–0.56
Forested bog														
May 2012	0.18	0.33	0.42	0.46	0.53	**0.54**	**0.65**	**0.41**	–0.02	–0.01	–0.01	–0.01	–0.01	–0.23
Jul. 2012	–0.14	–0.17	–0.20	–0.13	–0.11	–0.12	–0.06	–0.20	–0.19	–0.23	–0.22	–0.10	–0.15	–0.52
Sep. 2012	–0.10	–0.33	–0.33	–0.48	–0.50	–0.71	–0.42	–0.24	–0.24	–0.20	0.19	0.22	0.23	–0.12
May 2013	0.11	0.15	0.32	0.17	0.27	0.25	0.12	0.12	0.19	0.12	0.02	–0.10	–0.12	–0.03
Jul. 2013	0.33	0.36	0.31	0.30	0.19	0.03	–0.15	–0.23	0.27	0.27	0.22	0.35	0.36	–0.44
Sep. 2013	0.23	0.13	0.11	0.10	0.09	0.04	0.03	0.52	0.48	0.41	0.38	0.33	0.12	–0.24
May 2014	0.18	0.25	0.45	0.27	0.27	0.25	0.25	0.28	0.19	0.12	0.12	–0.35	–0.20	–0.15
Jul. 2014	–0.11	–0.09	–0.08	–0.03	0.03	0.14	0.19	0.21	0.24	0.24	0.21	0.11	0.12	–0.39
Sep. 2014	0.27	0.25	0.17	0.24	0.29	0.45	0.32	0.48	0.35	0.41	0.39	0.40	0.37	–0.22
Year 2012	0.43	0.50	0.50	0.54	0.54	0.44	**0.58**	**0.81**	**0.40**	0.41	0.22	0.42	0.48	–0.26
Year 2013	0.06	0.35	–0.06	0.09	0.09	**0.36**	**0.40**	**0.42**	0.45	0.18	0.21	0.32	0.33	–0.19
Year 2014	0.46	0.58	0.64	0.63	0.63	0.59	**0.37**	**0.65**	**0.52**	0.48	0.49	0.40	–0.26	–0.36
2012–2014	0.18	0.17	0.25	0.27	0.28	0.30	**0.38**	**0.34**	0.20	–0.20	–0.17	–0.19	0.11	–0.40
DAY	0.38	0.27	0.39	0.43	0.43	0.50	**0.42**	**0.65**	**0.36**	0.22	0.19	0.17	0.11	–0.42

*Negative WTL denotes water level below the peat surface maximum determination coefficient was obtained using the average daily peat temperature at the depth of 10 cm. By contrast, for the FB, the maximum was obtained using the equation with the peat temperature at the depth of 40 cm (Fig. 7a, b).

The calculations showed that 2013 and 2014 were characterized by similar values of total CH_4 flux for the season, despite the fact that the duration of the frost-free period in 2014 was significantly longer (about 50 days) than in 2013. The growing season of 2012 was a contrasting one: The maximum amount of CH_4 was released into the OB, while in the FB, an extremely warm year was characterized by minimal values of total CH_4 emissions.

According to the results of the extrapolation of CH_4 flux field measurements for the entire season (Fig. 8), the CH_4 flux from the OB exceeded the CH_4 flux from the FB by 4–5×. The exception was 2012, when the difference in fluxes was estimated at 11.2×. The maximum total flux for a season in the OB was observed in 2012 and amounted to 8 g CH_4. By contrast, the lowest total emissions were observed in the FB in the same year. Despite the hot summer of 2012, the soil of the FB at the depth of 40 cm warmed up only slightly due to the drying of the upper moss layers and the formation of a loose and dry thermal insulation layer. Thus, the estimate of the total CH_4 flux in the forested bog for 2012 was lower than for the warm but wet 2014, when total CH_4 emissions were 1.3 g CH_4.

Discussion

CH_4 emissions from bog ecosystems

Observations of CH_4 emissions have shown that the studied bog ecosystems emit different amounts of CH_4 into the atmosphere (Tables 2 and 3). Methane emissions from the OB are higher (three to six times) than from the FB. This observation is valid both for the entire measurement period as a whole and for each year in particular. The studied bog ecosystems differ significantly in the WTL. In the OB, the WTL is always higher than in the FB (Table 1). During the growing season, the average WTL is 5.13 cm and 40.5 cm below the surface in the OB and the FB, respectively. Thus, the aerobic layer in the FB is on average eight times thicker than in the OB, which initially offers more favorable conditions for CH_4 oxidation than in the OB. The observed differences in temperature between bogs in favor of the OB, especially at depths of 10–80 cm (Table 1), may be another reason for higher gas emissions in this ecosystem. In addition, the apparent differences in CH_4 fluxes between the two bog ecosystems may be explained by the differences in their vegetation cover (Table 1). According to previous studies, CH_4 fluxes are significantly lower in bogs with a predominance of *Sphagnum sp*. and negligible projective cover of vascular plants (Frenzel and Rudolph 1998; Greenup *et al.* 2000). By contrast, in bogs where vascular plants such as *Carex sp*., *Eriophorum sp*. and *Scheuchzeria* dominate in vegetation cover, CH_4 fluxes much be greater (Greenup *et al.* 2000; Ström *et al.* 2005; Glagolev and Smagin 2006). In our research, the effect of vegetation cover on the CH_4 flux rates was not specifically studied, but we believe that the predominance of sedge in the vegetation cover of the OB can increase the flux of CH_4 into the atmosphere. Therefore, the combination of these factors (closer location of the WTL to the surface and, as a result, a warmer upper part of the anaerobic layer, as

Table 5. Duration of the frost-free period (days), CH_4 emissions during the warm period (F, g CH_4 m^{-2}) and the total emission from all bogs of the study area (G, t CH_4); *S* indicates the bog area (km^2).

Year	Open bog (*S* = 463.48)			Forested Bog (*S* = 658.12)		
	Days	F, g CH_4 m^{-2}	G, t CH_4	Days	F, g CH_4 m^{-2}	G, t CH_4
2012	189	8.1	3754.2	192	0.7	460.7
2013	173	5.6	2595.5	185	1.2	789.7
2014	212	6.1	2827.2	235	1.3	855.6
Average	191	6.6	3059.0	204	1.1	702.0

well as specific vegetation cover) in our case was particularly more pronounced and by default caused a significant difference in CH_4 fluxes between the OB and the FB. The obtained data agree with previously obtained results in terms of CH_4 emissions, as well as in the fact that forested bogs emit less CH_4 into the atmosphere compared to open ones. For example, Glagolev and Shnyrev (2008) have shown that fluxes from forested bogs are always lower than in open bogs and vary from –0.39–7.40 mg CH_4 m^{-2} h^{-1} and from –4.73–24.39 mg CH_4 m^{-2} h^{-1}, respectively. Our results are most similar to the estimates by Sabrekov *et al.* (2014b): the median values of CH_4 fluxes obtained for bogs of similar types in the summer-autumn measurement period were 0.56–2.87 mg m^{-2} h^{-1}, respectively. Slightly higher values of CH_4 emissions have been given by Naumov (2007) for bogs of the central taiga (0.60–4.29 mg m^{-2} h^{-1}, for forested and open bogs, respectively), but the ratio in fluxes of bogs of different types is maintained.

The results are consistent with the data obtained for bog ecosystems in Canada. For example, open bog (La Grande River watershed) emits an average of 1.50±4.0 mg mg CH_4 m^{-2} h^{-1} according to Trudeau *et al.* (2012). A forested bog (Mer Blue), whose vegetation cover is dominated by *Chameadaphne*, on average emits between 0.78 mg CH_4 m^{-2} h^{-1} and 1.4 mg CH_4 m^{-2} h^{-1} depending on the year of research (Lai *et al.* 2014). Higher emission values (2.0–32.1 mg CH_4 m^{-2} h^{-1}) measured by eddy covariance have been observed from the surface of a shrub-sphagnum bog in Northern Quebec (James Bay) (Nadeau *et al.* 2013).

Therefore, the intensity of CH_4 fluxes into the atmosphere from the surface of the studied bog ecosystems generally coincides with the data obtained for similar bogs in other regions. However, there are also differences that may be caused by the structure of peat deposits in bogs, their hydrological regime, the research method used, and the weather conditions during the measurement period. In addition, differences in conditions are amplified by the variability of the flux over time, and values of the rate of CH_4 emissions from the same bog may change during the season and in different years of observation.

Methane emissions are characterized not only by significant variability between bogs, but also by variability within each bog. On some occasions, very intensive CH_4 fluxes are recorded in both bogs (for example, a maximum flux of 26.57 mg m^{-2} h^{-1} in the OB and 4.86 mg m^{-2} h^{-1} in the FB). The strongest dispersion of CH_4 emissions is typical for the OB, because the intensity of fluxes is several times higher and their number is twice as high as in the FB. This study identifies them as occasional extensive fluxes, the proportion of which is insignificant (2–6%; Fig. 4). A similar value has been attained by researchers of the vesicular transfer in Siikaneva bog in Finland during the summer (Männistö *et al.* 2019). Despite the fact that such extensive fluxes are quite rare, their exclusion from calculations can decrease the value of the total flux twofold compared to the original average. However, such powerful occasional local convective flows can carry out the main release of CH_4 into the atmosphere from bogs, sporadically discharging the gas reserves accumulated in peat deposits, as previously mentioned (Smagin 2005).

In addition, negative CH_4 fluxes were observed (for example, –0.08 mg m^{-2} h^{-1}). They were recorded in both studied bogs, i.e., the peat deposits received CH_4 from the atmosphere. Negative fluxes are associated with high rates of CH_4 oxidation by methanotrophic microorganisms, which are more abundant in bog ecosystems with a more aerated peat layer (Sundh *et al.* 1995). For example, this is typical of hummocks and ridges, which often act as atmospheric CH_4 sinks (Frenzel and Karofeld 2000). Our data show that negative fluxes occurred more frequently in the OB and accounted for 6.5% of the total number of measurements, while in the FB they were recorded much less frequently: about 2.5%. The more frequent occurrence of negative fluxes in the OB is quite difficult to interpret. It is probable that the reason is the presence of vascular vegetation, which on the one hand contributes to the release of CH_4 through the aerenchyma, bypassing the oxygen zones where CH_4 is usually oxidized (Joabsson *et al.* 1999; Greenup *et al.* 2000 Ström *et al.* 2005) but on the other hand, the same plants can increase the delivery of oxygen to the soil from the atmosphere, potentially leading to significant CH_4 oxidation in the rhizosphere (Popp *et al.* 2000). For example, Ström *et al.* (2005) have shown that 20–40% of CH_4 can be oxidized in the sedge rhizosphere. We think that the effect of CH_4 absorption in the OB can be partially explained by its oxidation due to the oxygen transported by undecomposed stems of vascular plants, but this mechanism and CH_4 emissions in such conditions require further research.

Seasonal variability of CH_4 fluxes

Methane emissions from the studied bogs are characterized by seasonal variability, which is expressed as an increase in CH_4 emissions in July relative to in May and September (Table 3 and Fig. 6). The most distinct seasonal variability was found in the OB. Our data found no significant empirical correlation between seasonal changes in CH_4 fluxes and the WTL. The lack of a direct relationship between CH_4 flux and the WTL has also been observed by other researchers (e.g., Rinne *et al.* 2007; Wang *et al.* 2018).

However, we noticed that in some cases the highest CH_4 fluxes were accompanied by the lowest WTL. A similar pattern was observed in the Mer Blue bog (Canada), when CH_4 fluxes were at their maximum while the WTL dropped to 40–45 cm (Brown *et al.* 2014). In our research, this phenomenon was especially evident in July 2012, when the largest CH_4 fluxes were recorded during a significant decrease in the water level. Emissions were almost ten times higher than the average over the three-year growing season. In 2012, most of the summer was very hot and dry, affecting the WTL. In the middle of the growing season, the surface of the peat deposit warmed from 20.2–29.7°C and from 24.4–42.2°C in the FB and the OB, respectively. Consequently, this increase in emissions was most likely caused by a combination of an unusually low WTL and high air and peat temperatures. We do not see evidence of such seasonal dynamics of CH_4 flux and WTL in similar bog ecosystems of Western Siberia in the reference literature; therefore, we regard the detected phenomenon as if not new, then at least not quite typical for CH_4 emissions. However, it is now known that during periods of extreme heat and drought and in the absence of wind, CH_4 fluxes can be quite ambiguous.

In fact, short-term phenomena of extremely high CH_4 fluxes have already been described, and have been associated with a decrease in hydrostatic pressure (Rinne *et al.* 2007) and the formation of bubbles containing CH_4 at concentrations below saturation in bog water (e.g., Baird *et al.* 2004). According to Glagolev and Smagin (2006), CH_4 is formed inside peat levels due to sorption and downward diffusion, and can be retained inside the peat deposit for a long time rather than being released into the atmosphere. The decrease in humidity observed with a significant drop in the WTL can lead to extremely high short-term bursts. This interpretation can convincingly explain the pattern we revealed of occasional bursts of emissions in July, when hot weather with a lack of precipitation caused a decrease in peat humidity alongside a decline in the WTL.

Our results show that soil temperature is the best predictor of CH_4 fluxes in both ecosystems. In the open bog, the seasonal average daily flux of CH_4 is best controlled by the temperature of the 10 cm layer, which is below the average WTL and its change limits. It is possible that this peat layer corresponds to the position where the most intensive activity of methanogenic microorganisms is concentrated, and the temperature of this layer is an average temperature condition (15.61°C, Table 1), favorable for the process of methanogenesis. In addition, given that considerable CH_4 emissions from the surface of the open bog were observed in mid-summer, the temperature of this layer may reflect a general seasonal trend of vegetation growth and development in the bog. For example, Saarnio *et al*. (1998) have shown that vascular vegetation participates in seasonal fluctuations in methane fluxes by increasing the supply of substrate for methanogenesis. At the same time, according to the authors the highest fluxes are observed at the peak of vegetation, when the sedge is most developed.

Based on this, it becomes clear why in September, with reduced temperature and the depletion of vegetation cover, there was a persistent decrease in the intensity of the CH_4 flux. After snow melting in May, bog water is diluted with thawed and atmospheric waters, leading to the formation of a water layer with a low concentration of dissolved CH_4. This slows down the diffusion of CH_4 through the peat matrix to the upper layers, because diffusion in water is slower than in air-filled pores (Rinne *et al.* 2018).

In the FB, the average daily CH_4 emissions expressed a correlation with peat temperature at the depth of 40 cm (Fig. 7b), reflecting similarly to the case of the open bog the overall seasonal trend in CH_4 production in the anaerobic layers. On the other hand, due to fluctuations in the WTL, the layer at the depth of 40 cm may correspond to the boundary of variable redox conditions, in which alternating oxidation or CH_4 generation occur (Blodau and Siems 2012). Our data on CH_4 fluxes from the FB are consistent with Lai *et al.* (2014) for similar peatlands (Mer Bleue, Canada). In this research, the temperature of the peat at the depth of 40 cm was the most important factor controlling the CH_4 flux, which according to the authors was associated with increased CH_4 production in this layer.

In addition, a connection between CH_4 emissions and peat temperature at the depth of 30 cm in the FB was found, explaining almost 50% of the flux variability in May 2012. During field observations in the spring of 2012, peat layers deeper than 20 cm were not completely thawed, and the temperature of the peat at the depth of 30 cm warmed only from –0.2 to 0.5°C. However, despite the relatively low temperatures of the peat deposit, CH_4 emissions were accompanied by slightly higher fluxes, which was not typical for subsequent years. The main reason might be the accumulation of CH_4 under frozen layers of peat deposits and ice in the winter, which is a well-known fact for wetland ecosystems with seasonal freezing, when ice obstructs the release of gases into the atmosphere from peat areas (e.g., Hargreaves *et al*. 2001; Hanis *et al.* 2013). When the peat deposit warms up completely in the spring, the accumulated CH_4 is released within a few days. We think that a similar relationship was detected in the spring of the subsequent years 2013 and 2014, but by the time the research began, all the layers of peat deposits were already sufficiently warmed up.

Total CH_4 emissions during the growing season

Total CH_4 fluxes (5.6–8.1 g m^{-2}) from the open bog are close to the fluxes observed in bogs in northeastern Canada (7.9 g m^{-2}; Trudeau *et al.* 2012) and Finland (7.6 g m^{-2}; Rinne *et al.* 2007). Total CH_4 fluxes from forested bog (0.7–1.3 g m^{-2}) are generally lower than those observed in forested bogs in Canada (James Bay Lowland) (4.8±2.3 g m^{-2}; Pelletier *et al.* 2007), northeastern Antabaska (3.2 g m^{-2}; Long *et al.* 2010), Northern Quebec (4.4 g m^{-2}; Nadeau *et al.* 2013), but similar to the results of the shrub-sphagnum bog of Western Newfoundland (1.9±0.08 g m^{-2}; Wang *et al.* 2018).

Taking into account the area occupied by the studied bog ecosystems within the Bakchar peatland and the total intensity of emissions during the growing season, the total CH_4 flux from the studied areas can be calculated. Total CH_4 emissions during the growing season from the studied bogs can be estimated at 3059 tons of methane from open sedge-sphagnum bogs with an area of 464 km^2 and only 702 tons of CH_4 from forested pine-shrub-sphagnum bogs with an area of 658 km^2. Despite the fact that the area of open sedge-sphagnum bogs here is 1.5× smaller than the area of forested pine-shrub-sphagnum in the watershed of the Bakchar and Iksa rivers, the total amount of CH_4 released from fist of them is on average 4.7× higher (from 3–8× higher, depending on the season) than from the surface of the latter (Table 3). In this regard, it is necessary to prioritize the study of open ecosystems with a high level of WTL and the predominance of vascular plants, as these ecosystems will eventually become more sensitive to changes in climate parameters. Therefore, a comprehensive assessment of the CH_4 regional budget should take into account the type of bog ecosystem, because the impact of environmental factors on each specific ecosystem will be individual.

Conclusions

This study has revealed the significant variability of CH_4 fluxes both in space and time. The spatial variability of fluxes is determined by the surface characteristics (microrelief, hydrological regime, and vegetation cover) of bogs. Indirectly, these parameters affect the spatial variability of the WTL, hence in terms of the spatial aspect, CH_4 fluxes are controlled by changes in the WTL, while there are no significant dependencies between the variability of CH_4 and the WTL during the growing season in each ecosystem. The temporal variability of CH_4 fluxes during the growing season is primarily determined by the temperature of the peat deposit. Significant regression dependencies (linear and exponential) between CH_4 fluxes and the temperatures of peat deposits are obtained. In addition, temperature — which controls processes of methanogenesis for the OB and the FB — approximately corresponds to the depth below the average position of the WTL. In our opinion, these simple empirical dependencies of CH_4 fluxes on temperature in the studied bogs are actually a reflection of complex and interrelated biochemical processes, the role of which is clearly manifested at the vegetation peak.

Total CH_4 fluxes in the warm season are more significant from open bog than from forested one, despite the fact that the area of the latter is 1.5× larger. In this regard, it is necessary to prioritize research on bogs with a high WTL and a predominance of vascular plants, as these ecosystems will eventually become more sensitive to changes in climate parameters.

In general, this research has highlighted a direct and crucial link between vegetation species composition and hydrological regime in estimates of CH_4 flux from bog ecosystems in the region. We believe that it is the frequent underestimation of these parameters when planning experiments that prevents researches from creating computational models in the search for true estimates of Western Siberian bogs' contribution to global climate change. Our estimates and patterns of CH_4 emissions are based on a larger sample of flux measurements and cover a much longer period of research than those previously presented for the given region, thereby offering a more objective view of variations in CH_4 flux during the warm period of the year. The authors consider the materials of this work an argument in favor of promoting further comprehensive research, including not only monitoring operations to clarify regional spatial and temporal models, but also analysis of patterns' causes in order to improve understanding of processes.

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