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Methane and carbon dioxide fluxes in the waterlogged forests of south and middle taiga of Western Siberia

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Abstract. Field measurements of methane and carbon dioxide flux were carried out using portable static chambers in south (ST) and middle taiga subzones (MT) of Western Siberia (WS) from 16 to 24 August 2015. Two sites were investigated: Bakchar bog in the Tomsk region (in typical ecosystems for this area: oligotrophic bog/forest border and waterlogged forest) and Shapsha in Khanty-Mansiysk region (in waterlogged forest). The highest values of methane fluxes ($mgC \cdot m^{-2} \cdot h^{-1}$) were obtained in burnt wet birch forest (median 6.96; first quartile 3.12; third quartile 8.95). The lowest values of methane fluxes (among the sites mentioned above) were obtained in seasonally waterlogged forests (median -0.08; first and third quartiles are -0.14 and -0.03 $mgC \cdot m^{-2} \cdot h^{-1}$ respectively). These data will help to estimate the regional methane flux from the waterlogged and periodically flooded forests and to improve its prediction.

1. Introduction.

Soils play an important role in the balance of the most important greenhouse gases – carbon dioxide (CO_2) and methane (CH_4). On the one hand, the soils accumulate carbon through plants photosynthesis. On the other hand, several soil ecosystems (mainly wetlands) are one of the most important natural CH_4 sources. The ecosystem classification may help to predict total greenhouse gas budget, since the quantitative contribution of different ecosystems in CO_2 and CH_4 exchange is still undefined and is discussed by the experts [1, 2].

Significant efforts were made to quantify the different soil CH_4 sources such as mires, lakes, rice fields and landfills [3, 4, 5, 6]. However, from a theoretical point of view, the CH_4 emission may occur from any ecosystems with excessive water supply (for example, waterlogged forests and floodplains). Unfortunately, the data on the methane emission from these ecosystems are insufficient. Mostly such studies were carried out in tropics [7, 8, 9], but for other regions there is a lack of these data [10, 11, 12]. Some useful information is given in reviews [3, 13]. Nevertheless, there are not enough data for global, or at least, regional assessments. Some forests are flooded only on a certain interval of the season, being a source of CH_4 during these intervals, but the rest part of the season they will consume

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it from the atmosphere. It makes regional methane flux assessment more difficult. The same is relevant to the river floodplains.

The aim of this paper is to present preliminary results of CH_4 and CO_2 flux field measurements in WS south and middle taiga waterlogged forests (WF) obtained at two sites: close to the field station “Plotnikovo” (Bakchar district of Tomsk oblast) of the Institute of Soil Science and Agrochemistry of SB RAS and to the field station “Shapsha” (Khanty-Mansiysk Autonomous Okrug) of Yugorsky State University.

2. Materials and methods.

The CO_2 and CH_4 flux measurements were carried out in August 2015 in WS south and middle taiga subzones. In the south taiga subzone (near Plotnikovo, Tomsk oblast; indicated in Figure 1 as "Transect") four measurement sites were located on a transect from the open oligotrophic bog with dominance of pine (*Pinus sylvestris)* and mosses (*Sphagnum sp*.) to the border of waterlogged forest with dominance of birch (*Betula pendula*).

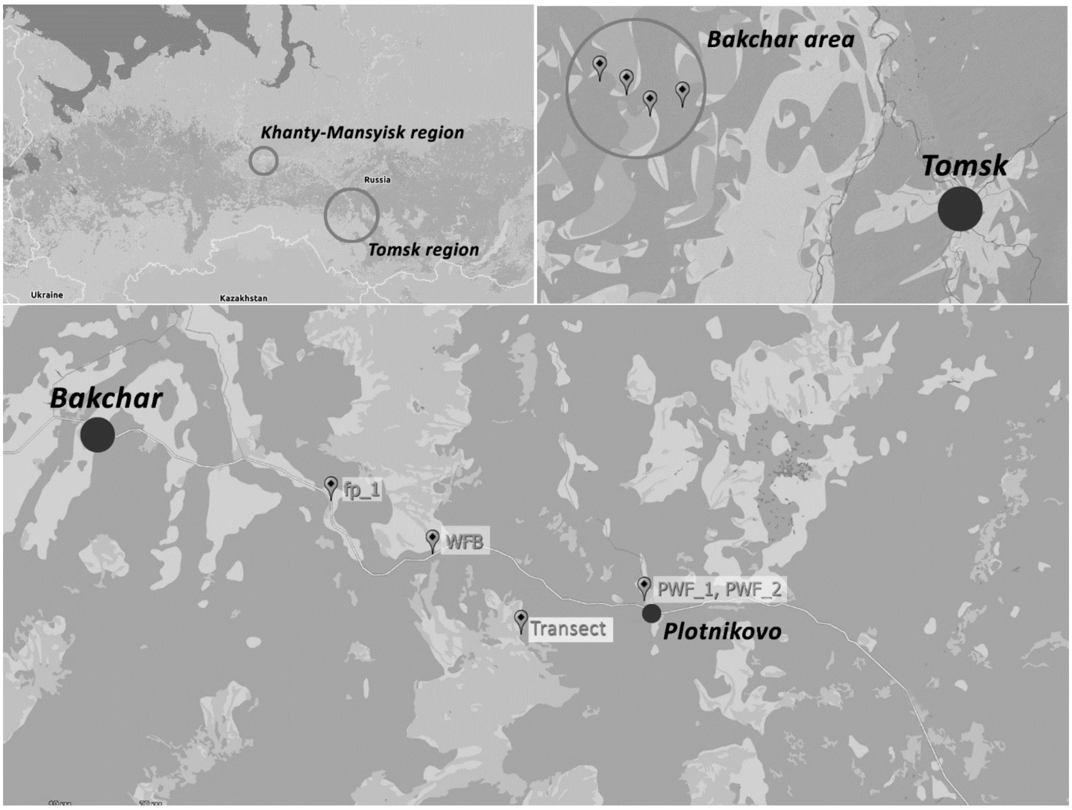

Figure 1. Location of test sites.

Thus, a wide range of soil moisture conditions and plant associations was studied. If possible the chambers were installed at hillocks and hollows (two points) at each microsite during the measurements. The first measurement point (Tr.PWF, 56°49.86800' N 82°51.16700' E) was located in a wet monodominant birch forest. The second one (Tr.WF/RB_2.1 and WF/RB_2.2, 56°49.88917' N 82°51.08000' E) and the third one (Tr.WF/RB_1, 56°49.90167’ N 82°51.07333’ E) in birch forest near the oligotrophic bog (“Bakchar wetland”) border with admixture of pine (*Pinus sylvestris*). The fourth point (Tr.Ryam, 56°49.91667' N 82°51.04500' E) was located in oligotrophic bog with admixture of birch (*Betula pendula*). The water table level (WTL) ranged from 21 to 46 cm below the surface of soil, the soil pH ranged between (4.2-5.2), the water conductivity did not exceed 100 µS/cm. In addition, the measurements were carried out in periodically wet birch-spruce forest (PWF_1.1, 56°51.74400' N, 83°4.28200' E and PWF_1.2, 56°51.74400' N, 83°4.27900' E) and in the burnt wet birch forest (WFB site, 56°54.596' N, 82°41.811' E), where the WTL was (-20 cm) above the soil surface. Note that the Bakchar wetland ecosystem has been studied in the last years and described in detail (see e.g., [14, 15, 16, 17]).

The studied middle taiga forest located in the central part of the first terrace above the floodplain of the river's Ob and formed mainly by spruce (*Picea obovata*) with minor admixture of birch and aspen (trees height near 20-25 m). Excessive water supply is caused by poor drainage and high precipitation/evapotranspiration ratio. There is a pronounced microrelief such as flooded depressions and dry elevations formed by tussocks of *Sphagnum magellanicum*. The depth of organic horizon does not exceed 0.5 m; the water pH is about 3.9; the electrical conductivity is 200 μS/cm.

CH_4 and CO_2 fluxes were measured by static chamber method [18, 19]. The chamber was small (size of 0.4 × 0.4 × 0.4 m^3) portable opaque plexiglas cube without the lower side with forced ventilation inside. The chamber was installed on a steel square collar (0.4×0.4 m^2) embedded into undisturbed soil before measuring. A water channel on the chamber rim acted as a lock against leaks into or out of the chamber. Gas sampling from the chamber was carried out using 12 ml (for CH_4) or 20 ml (for CO_2) syringes four times (t_0, t_1, t_2 and t_3) through a silicone tube entering the chamber through the rubber stopper hermetically installed in the hole of a chamber sidewall. The total exposure time (t_3) did not exceed 60 minutes (in case of CH_4 sampling) or 15 minutes (in case of CO_2); the vegetation inside the chamber remained intact. The analyses of CO_2 concentrations were made with infrared gas analyzer DX-6100 ("RMT Ltd", Russia) not later than six hours after air sampling from the chamber. The concentration of CH_4 was measured using a modified gas chromatograph "KhPM-4" (Chromatograph, USSR) equipped with a flame ionization detector (column length 1 m; diameter 5 mm; sorbent – Sovpol, 80-100 mesh; temperature of column 40 °C; hydrogen as a carrier gas with flow rate 5 ml/min). The chromatograph "Crystal-5000" (Chromatec, Russia) also was used (two flame ionization detectors; column length – 2 m; diameter – 2 mm; sorbent – Porapak Q, 80-100 mesh; column temperature 150 °C; nitrogen N_2 as the carrier-gas with flow rate 10 ml/min). The chromatograph was calibrated with "standard" gas mixtures (1.99±0.01, 5.00±0.01 and 9.84±0.01 ppmv methane in a synthetic air; National Institute for Environmental Studies, Japan). Following physical and chemical environmental parameters were measured simultaneously with the air sampling at the study sites: soil temperature at depths of 0, 5, 15, 45 cm (sensors "THERMOCHRON" iButton DS 1921G "DALLAS Semiconductor", US); electrical conductivity (ES) and soil water pH (Kelilong PHT-028 "Kelilong Electron", China) and soil moisture (by the gravimetric method [20]). The water electrical conductivity and pH were measured only in cases when the ground water table level (WTL) was not deeper than 50 cm below the surface (length of sampling tube). Botanical descriptions were made at the measurement sites. The fluxes were calculated by linear regression for CH_4 and CO_2 emission and by non-linear regression for CH_4 uptake [21]. Positive fluxes related to the emission from soil to the atmosphere and negative fluxes related to the emission from atmosphere to the soil. A positive value of WTL means the water level is below the soil surface, a negative value – above it.

3. Results and Discussion.

The median of all obtained CH_4 fluxes was 0.02 $mgC \cdot m^{-2} \cdot h^{-1}$ and the first and third quartiles were -0.03 and 0.36 $mgC \cdot m^{-2} \cdot h^{-1}$, respectively. The probability density distribution of CH_4 fluxes is shown in Figure 2. The WTL values varied from -20 to 46 cm (median is 0 cm). CH_4 fluxes on "transect", as expected, changed from consumption (Tr.PWF) to small emission (Tr.Ryam) (Table 1). The median of CH_4 flux at a plot Tr.PWF was (-0.08 ± 0.06) $mgC \cdot m^{-2} \cdot h^{-1}$, it is comparable with PWF_1(2) (-0.02 ± 0.05) $mgC \cdot m^{-2} \cdot h^{-1}$ (Table 2, periodically waterlogged spruce forest). The median of CH_4 flux on a plot Tr.Ryam was (0.30 ± 0.05) $mgC \cdot m^{-2} \cdot h^{-1}$ with changing from 0.03 in elevations (WTL = 56 cm) to 0.50 $mgC \cdot m^{-2} \cdot h^{-1}$ in depressions (WTL=37 cm). The highest value of the CH_4 flux (6.96±0.74) $mgC \cdot m^{-2} \cdot h^{-1}$ was observed in the burnt birch forest (WFB) (Table 2; located outside the site "transect") and probably associated with high groundwater level (WTL = -20 cm).

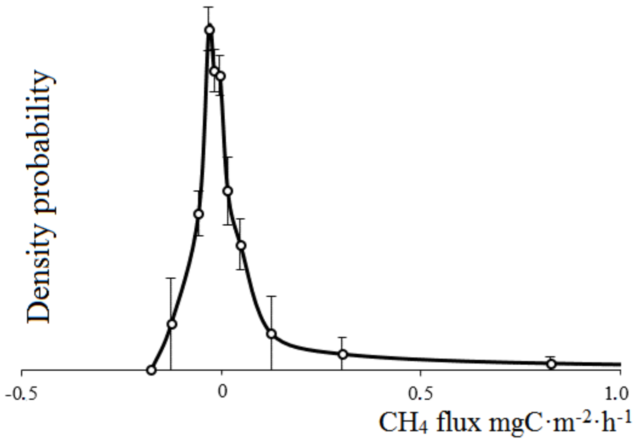

Figure 2. Probability density distribution of *CH_4* fluxes (all obtained fluxes).

In the middle taiga spruce forest, when soil moisture was high, CH_4 fluxes were changed from (0.08 ± 0.04) to (1.20 ± 0.05) $mgC \cdot m^{-2} \cdot h^{-1}$ when WTL was changed from 0 to -5 cm, median is 0.46 $mgC \cdot m^{-2} \cdot h^{-1}$ and 1st and 3rd quartiles are 0.25 and 0.82 $mgC \cdot m^{-2} \cdot h^{-1}$, respectively (Table 3).

It is known that the CH_4 fluxes strongly correlate with the soil moisture [11]. Therefore, the obtained small values of CH_4 fluxes are expectable. Firstly, the WTL was significantly below the soil surface for the majority of the investigated ecosystems, resulting in the inhibition of CH_4 formation and favorable conditions for its consumption. Secondly, the soil moisture in the periodically flooded forests is less stable than in the wetland due to the smaller height of peat horizon, which stores water. The recovery of the methanogenic activity is slow after the abrupt change of hydrological conditions (during subsequent periods of flooding and drought).

According to the literature data, CH_4 fluxes in wet forests (Table 4) may range from -0.67 to 17.1 $mgC \cdot m^{-2} \cdot h^{-1}$ depending on soil moisture and other factors (microtopography, season, type of ecosystems). For comparison, the CH_4 flux in the dry upland forests ranges from -2.26 ± 0.17 to -0.02 $mgC \cdot m^{-2} \cdot h^{-1}$ [11, 23, 24, 25, 26].

Moss-grass and soil respiration (MgSR), i.e. soil CO_2 fluxes without photosynthesis, ranged from (174±32) to (414±142) $mgC \cdot m^{-2} \cdot h^{-1}$ on a site (Tr.WF/RB_1). It should be noted, that the correlation between the CH_4 fluxes and MgSR was negative (Figure 3). The highest mean CH_4 flux was (6.96±0.7) $mgC \cdot m^{-2} \cdot h^{-1}$ on the site WFB where the mean MgSR was the lowest (68.6±8.9 $mgC \cdot m^{-2} \cdot h^{-1}$) (Table 3). On the contrary, on the site Tr.PWF the mean CH_4 flux was minimal (-0.08 ± 0.06 $mgC \cdot m^{-2} \cdot h^{-1}$), while the mean MgSR was the highest (414±142) $mgC \cdot m^{-2} \cdot h^{-1}$ (Table 3).

These values are in a good agreement with the published data. For example, in the spruce forest [28], in the similar ecosystems of the south taiga in the European part of Russia, MgSR measured in 1993 and 1995-1997 were respectively 207, 130, 217 and 104 $mgC \cdot m^{-2} \cdot h^{-1}$. For comparison, MgSR at the waterlogged spruce forest (Tr.PWF) with periodically excessive water supply had the same magnitude scope and ranged from (206 ± 6) to (533 ± 21) $mgC \cdot m^{-2} \cdot h^{-1}$. This difference can be explained by more intensive respiration of the soil and vegetation in the south taiga, by the small number of our measurements and inter-annual variability of the CO_2 emission.

The MgSR values from our sites do not differ considerably from the values obtained in tropical forests. For example, [8] presents data for forests in the basins of the river Congo and Ubangi (Central Africa): (110 ± 57) $mgC \cdot m^{-2} \cdot h^{-1}$ – for flooded soils, (93 ± 11) $mgC \cdot m^{-2} \cdot h^{-1}$ – for wet forests and (80 ± 9) $mgC \cdot m^{-2} \cdot h^{-1}$ – for dry forests. There are works of other researchers (cited in [8]) where MgSR is 108 and 176 $mgC \cdot m^{-2} \cdot h^{-1}$ for rain forests of the Amazon region.

Table 1. Methane and carbon dioxide fluxes in "transect" site (Bakchar wetland, south taiga subzone).

Temperature (°C)[a]					Flux ± error[b], mgC·m^{-2}·h^{-1}		WTL[e], cm	pH	EC[f], μS/cm
air	Depth from soil surface, cm								
	0	5	10	15	CH_4	CO_2			
plot Tr.PWF, birch forest with excessive water supply, (date: 9.08.2015), dominant: *Betula pendula*									
15.4/14.8	15.3/15.0	13.5/13.6	13	12.8/13.0	-0.041±0.045(a)	379±35(c)			
15.5/14.9	15.9/15.3	14.5	13	13.3/13.4	-0.111±0.057(a)	290±22(c)	*172(0)*		
14.8/15.1	14.6/14.7	13.5/13.5	13	12.5	-0.150±0.135(a)	489±41(c)	*353(5)*	Water table was too deep to take samples for analysis	
15.0/15.3	15.0/15.1	14.5	13	13.5/13.3	-0.031±0.028(a)	273±14(c)	*454(10)*		
14.4/14.5	14.3/14.4	13.6/13.5	13.2/13.0	12.9/12.6	-0.164±0.048(a)	509±26(c)	*503(15)*		
14.5	14.4/14.5	14.3/14.5	13.2/13.0	13.5/13.5	-0.031±0.070(a)	226±9(c)			
– "– (date: 16.08.2015)									
18.7/18.9	16.2/16.5	15	12.5	13	-0.073±0.190(a)	280±19(c)	n.d.		
18.7/18.9	16.2/16.5	15	12.5	13	-0.092±0.040(a)	399±122(c)	n.d.		
18.7/19.0	17	15.5/15.5	13	12.5	-0.040±0.024(a)	175±5(b, c)	n.d.	Water table was too deep to take samples for analysis	
20.2/19.6	17.2/16.7	15.9/15.1	13.2/12.5	13.6/13.0	-0.028±0.084(a)	566±181(c)	n.d.		
20.2/19.7	17.2/16.8	15.9/15.2	13.2/12.5	13.6/13.0	-0.153±0.250(a)	471±208(c)	n.d.		
20.4/19.9	17.9/17.5	15.9/15.5	13.8/13.0	13.2/12.5	-0.085±0.006(a)	429±163(c)	n.d.		
plot Tr.WF/RB_1, the periodically wet forest at the border of the pine-shrub-sphagnum community,(date: 16.08.2015)									
20.4/19.5	18.2/18.0	15.6/15.8	13.5/13.6	13	0.260±0.051(b)	374±20(c)	26.5	4.7	70
20.4/19.5	18.2/18.0	15.6/15.8	13.5/13.6	13	1.322±0.579(c)	491±16(c)	26.5	4.7	70
20.4/19.6	19.1/19.0	14.0/14.1	13.0/13.1	12.5	0.164±0.058(c)	172±48(c)	26.5	4.7	70
19.6/19.9	17.8/18.0	15.7/15.5	13.9/13.5	13.4/13.0	0.025±0.047(b)	304±28(c)	26.5	4.7	70
19.6/19.9	17.7/18.0	15.8/15.5	14.0/13.5	13.5/13.0	0.775±0.334(c)	479±97(c)	26.5	4.7	70
19.6/19.9	18.1/18.5	14.8/14.2	13.6/13	13.1/12.5	0.006±0.060(c)	338±11(c)	26.5	4.7	70
– "– (date: 18.08.2015)									
25.6/25.8	20.6/20.8	22.0/21.7	21.2[c]/21.0[c]	10.7[c]/11.0[c]	-0.017±0.107(a)	331±79(c)	21	4.4	40
25.5/25.8	20.6/20.8	22.0/21.7	21.2[c]/21.0[c]	10.7[c]/11.0[c]	-0.022±0.018(a)	149±32(c)	21	4.4	40
25.5/25.8	21.5/21.8	17.5/18.0	13.1[c]/13.2[c]	10.6[c]/10.9[c]	0.050±0.049(b)	622±152(c)	21	4.4	40
24.8/24.6	20	23.0/22.9	22.1[c]/22.0[c]	10.53	-0.029±0.081(a)	174±31(c)	21	4.4	40
24.8/24.5	20	23	22.1[c]/22.0[c]	10.53	-0.042±0.080(a)	130±24(c)	21	4.4	40
24.8/24.5	21	17	13.03	10.53	-0.001±0.092(a)	461±191(c)	21	4.4	40
plotsTr.WF/RB_2.1(2.2),the periodically wet forest near the border of the pine-shrub-sphagnum community,(date:08.08.2015)									
23.2/23.5	20.4/20.5	24	23.2[c]/23.1	11.8[c]/12.0[c]	0.167±0.039(c)	352±8(c)	37	4.9	45
23.2/23.5	21.0/21.1	19.3/19.5	15.0[c]/15.0	12.5[c]/12.5[c]	0.008±0.099(b)	311±4(c)	46	5.5	45
23.2/23.5	21.0/21.1	19.3/19.5	15.0[c]/15.0	12.5[c]/12.5[c]	0.060±0.032	236±81(c)	46	5.5	45
22.0/22.5	19.7/20.0	23.9/24.0	23.0[c]/23.0	11.53	0.079±0.046(b)	349±43(c)	37	4.9	45
21.9/22.4	20.18/20.5	19	15.0[c]/15.0	12.1[c]/12.3[c]	-0.017±0.089(a)	50±48(c)	46	5.5	45
20.8/21.0	19	23.4/23.5	23.0[c]/23.0	11.53	0.023±0.065(b)	213±46(c)	37	4.9	45
20.8/21.0	19.43/19.5	18.5	15.0[c]/15.0	12.03	-0.065±0.029(a)	441±90(c)	46	5.5	45
20.8/21.0	19.43/19.5	18.5	15.0[c]/15.0	12.03	0.134±0.106(b)	322±8(c)	46	5.5	45
– "– (date: 22.08.2015)									
12.0/11.2	12.0/11.2	13.0/13.1	14.0[c]/14.0	11.8[c]/12.0[c]	0.052±0.053(b)	630±299(c)	n.d.	n.d.	n.d.
12.1/11.2	12.1/11.2	13.2/13.7	14.3[c]/14.5	12.5[c]/12.5[c]	-0.021±0.018(a)	367±135(c)	n.d.	n.d.	n.d.
12.1/ n.d.	12.1/ n.d.	13.2/ n.d.	14.3[c]/ n.d.	12.5[c]/ n.d.	0.036±0.016(b)	n.d.	n.d.	n.d.	n.d.
12.5/12.3	12.42/12.1	12.9/13,0	13.4[c]/13.5	11.53	0.033±0.021(c)	299±36(c)	n.d.	n.d.	n.d.
12.5/12.3	11.5/11.5	12.9/13,0	14.0[c]/14.0	12.53	-0.029±0.054(a)	200±89(c)	n.d.	n.d.	n.d.
12.5/12.3	11.5/11.5	12.9/13,0	14.0[c]/14.0	12.53	-0.003±0.072(a)	190±25(c)	n.d.	n.d.	n.d.
plot Tr.Ryam, pine-shrub-sphagnum community, (date: 22.08.2015), dominant: *Pinus sylvestris*									
14.6/13.6	14.1/14.4	14	12.03	9.53	0.359±0.017(c)	194±96(c)	n.d.	n.d.	n.d.
14.6/13.6	14.1/14.4	14	12.03	9.53	0.495±0.184(c)	180±12(c)	n.d.	n.d.	n.d.
14.8/13.5	13.6/13.8	n.d.	13.53	10.7[c]/11.0[c]	0.162±0.036(b)	181±8(b)	n.d.	n.d.	n.d.
13.7/ n.d.	13.0/ n.d.	13.5/ n.d.	12.0[c]/ n.d.	9.0[c]/ n.d.	0.245±0.055(b)	n.d.	n.d.	n.d.	n.d.
13.7/14.2	13.0/13.1	13.5	12.0[c]/12.0[c]	9.03	0.503±0.208(c)	78±12(b)	n.d.	n.d.	n.d.
13.7/14.3	13.0/13.2	13.9/14.0	13.4[c]/13.5[c]	10.53	0.031±0.050(c)	186±46(c)	n.d.	n.d.	n.d.

[a, b, c, d, e] see notes of table 2.

Table 2. Methane and carbon dioxide fluxes in the forests with different soil moisture (south taiga).

Temperature (°C)[a]					Flux ± error[b], mgC·m^{-2}·h^{-1}		WTL[e], cm
air	soil depth						
	0 cm	5 cm	10 cm	15 cm	CH_4	CO_2	
PWF_1.1 and PWF_1.2, birch-spruce periodically waterlogged forest, site "Plotnikovo" (date: 5.08.2015), dominant species: *Betula pendula, Sorbus sibirica*							
15.9	17	16.1	16.7	n.d.	-0.013±0.193(a)	206±6(b)	n.d.
15.9	17	16.1	16.7	n.d.	-0.023±0.060(a)	227±15(c)	n.d.
15.9	17	16.1	16.7	n.d.	-0.065±0.081(a)	403±121(c)	n.d.
15.9	17	16.1	16.7	n.d.	-0.012±0.057(a)	428±36(c)	n.d.
18.4	18.6	16.5	16.5	n.d.	0.016±0.037(c)	227±33(c)	n.d.
18.4	18.6	16.5	16.5	n.d.	-0,064±0,031(a)	509±280(c)	n.d.
18.4	18.6	16.5	16.5	n.d.	-0.001±0.070(a)	351±15(c)	n.d.
18.4	18.6	16.5	16.5	n.d.	0.053±0.035(b)	315±10(c)	n.d.
15.5	16.7	16.5	16.5	n.d.	0.061±0.043(c)	353±11(c)	n.d.
15.5	16.7	16.5	16.5	n.d.	-0.041±0.063(a)	533±21(c)	n.d.
15.5	16.7	16.5	16.5	n.d.	-0.028±0.048(a)	471±31(c)	n.d.
15.5	16.7	16.5	16.5	n.d.	-0.065±0.058(a)	467±29(c)	n.d.
WFB, wet burnt birch forest, site "Bakchar bog" (date: 24.08.2015), dominant species: *Betula péndula, Calla palustris*							
17.9/18.8	14.6/14.9	14.5	12.5[c]/12.6[c]	11.6[c]/11.8[c]	6.839±1.155(b)	42±19(c)	-20
17.9/18.8	14.6/14.9	14.5	12.5[c]/12.6[c]	11.6[c]/11.8[c]	3.341±0.404(c)	40±10(c)	-20
17.9/18,8	15.3/15.5	14.8/15.0	13.6/13.8	11.5	9.419±3.442(c)	174±23(c)	-20
17.3/17.1	13.8/14.0	14	12.1/12.2	11.5	8.395±1.642(a)	152±41(a)	-20
17.3/17.1	13.8/14.0	14	12.1/12.2	11.5	1.599±0.132(c)	132±56(c)	-20
17.3/17.1	14.7/14.9	14.5/14.5	13.5/13.5	11.5	10.936±0.762(b)	116±6(c)	-20
17.3/17.1	14.7/14.9	14.5/14.5	13.5/13.5	11.5	8.945±1.499(c)	127±89(b)	-20
14.5/15.1	13.2	13.8/14	12	11.5	2.204±0.152(c)	25±8(c)	-20
14.5/ n.d.	13.2/ n.d.	13.8/ n.d.	12.0/ n.d.	11.5/ n.d.	5.623±0.356(c)	n.d.	-20
14.5/15.1	13.8/14.1	14.4/14.5	13.5/13.5	11.5	6.987±0.71	57±7(a)	-20
14.5/15.1	13.8/14.1	14.4/14.5	13.5/13.5	11.5	9.699±2.36(c)	118±48(c)	-20
10.1/11.6	12.5/12.9	13.2/13.5	12	11.5	7.174±0.851(c)	50±7(c)	-20
10.1/11.6	12.5/12.9	13.2/13.5	12	11.5	2.473±0.151(c)	80±41(c)	-20
10.1/11.6	13.0/13.3	13.9/14	13.5	11.5	6.925±2.157(b)	87±5(c)	-20
10.1/ n.d.	13.0/ n.d.	13.9/ n.d.	13.5/ n.d.	11.5/ n.d.	8.971±0.666(c)	174±23(b)	-20
fp_1, birch forest, site "Plotnikovo" (date: 14.08.2015), dominant species: *Betula pendula*							
19.4/19.5	16.6/16.5	15.5/15.6	14.8/15.0	13.5	0.130±0.060(a)	298±14(c)	*51(0)*
19.4/19.5	16.6/16.5	15.5/15.6	14.8/15.0	13.5	0.130±0.060(a)	298±14(c)	*38(5)*
18.9/19.0	16.4/16.5	15.5/15.5	14.5	13.5	0.053±0.045(a)	300±10(c)	*35(10)*
18.2/18.5	16.0/16.2	15.4/15.5	14.5	13.5	0.070±0.087(a)	271±96(c)	*35(15)*

[a] the temperature during the CH_4 flux measurement / the temperature during the CO_2 flux measurement (under the same temperature there was only one value);
[b] types of error: (a) – confidence interval at 95%; (b) – combined error, calculated according to [22]; (c) – standard deviation; (d) - standard deviation calculated with the weights which are inversely proportional to a variance of gas concentration;
[c] soil temperature measured at the depth of 45 cm;
[d] soil temperature measured at the depth of 25 cm;
[e] groundwater level WTL (positive values – below ground level, negative – above); in case where the values in this column are given in italics – it is a soil moisture (%) at depth (cm) specified in parenthesis (not WTL!);
[f] EC – electrical conductivity.

Table 3. CH_4 fluxes at "Shapsha" site (Sh.WFor.1.1-1.10, middle taiga, 27.8.2015).

Temperature (°C)[a]				flux± error[b], mgC·m^{-2}·h^{-1}	WTL[e], cm	pH
air	Soil depth					
	5 cm	10 cm	25 cm			
Spruce waterlogged forest, dominant species: *Picea obovata*, *Carex* sp., *Sphagnum magellanicum*						
11.1	9.5	9.0	8.5	0.238±0.017(d)	-3	3.9
11.1	9.5	9.0	8.5	0.600±0.022(d)	-3	3.9
10.6	9.4	8.8	8.4	0.081±0.042(d)	-3	3.9
10.6	9.4	8.8	8.4	0.890±0.008(d)	-3	3.9
10.3	9.3	8.8	8.4	0.235±0.017(d)	-5	3.9
10.3	9.3	8.8	8.4	0.563±0.030(d)	-5	3.9
9.6	9.0	8.8	8.4	1.152±0.025(d)	0	3.9
9.6	9.0	8.8	8.4	0.302±0.061(d)	3	3.9
8.8	8.7	8.8	8.4	1.201±0.051(d)	0	3.9
8.8	8.7	8.8	8.4	0.362±0.026(d)	3	3.9

[a, b, e] see notes to table 2.

Table 4. CH_4 flux in forests with excessive water supply.

Ecosystem	CH_4 flux, mgC·m^{-2}·h^{-1}	Source	Note
Flooded forests in the Amazon river basin.	3.4 6.0	Devol et al. Bartlett et al.	Data published in 1988 [8]
Forests in Central Africa in the Congo and Oubangui river basin	0.3 ÷ 17.1 0.04 ÷ 0.24 -0.03 ÷ -0.14	[8]	Flooded forests (WTL from -10 to -40 cm) Forests on moist soils (WTL from 10 to 20 cm) Forests on drained soils (WTL higher 1 m)
Forests in Central Africa to the SW and W from the Impfondo	0.19 or 0.67 (depends on method)	[8]	Measurements were performed in two variants of the gradient method (footprint ~ a few hundreds of m^2); fraction of flooded soil~1/3
Forests in Central Africa to the NE and N from Brazzaville	3.2 ÷ 6.5 2.4 ÷ 4.9	[8]	During the wet season (average from territory >> n·10^2 m^2) During the dry season (average from territory >> n·10^2 m^2)
Forest in Puerto Rico (18°18' N, 65°50' W)	3.1 ± 1.6[a] 0.010 ± 0.008[a] -0.015 ± 0.002[a]	[8]	*Tabebuia rigida* forest *Cyrilla racemiflora* forest *Dacryodes excelsa* forest
Spruce (*Picea abies L.*) forest, Denmark	from -0.001±0.005[a] to -0.030±0.004[a]	[10]	The data from Fig. 6 in the original publication
Pine forest (39°55'N, 74°35'W)	0.032 ± 0.008[b] -0.046 ± 0.007[b]	[11]	Elevation (WTL 7 m) Depression (WTL ± 5 cm)
Floodplain Alder forest (periodically flooded)	from -0.028 to 0.025	[27]	sites are located in Alaska, USA (64°45′N, 148°18′ W)
Floodplain Spruce Forest (periodically flooded).	-0.0121 ± 0.0008[c]		

[a] standard errors after «±».
[b] standard deviations after «±».
[c] there are no information about the type of error after «±».

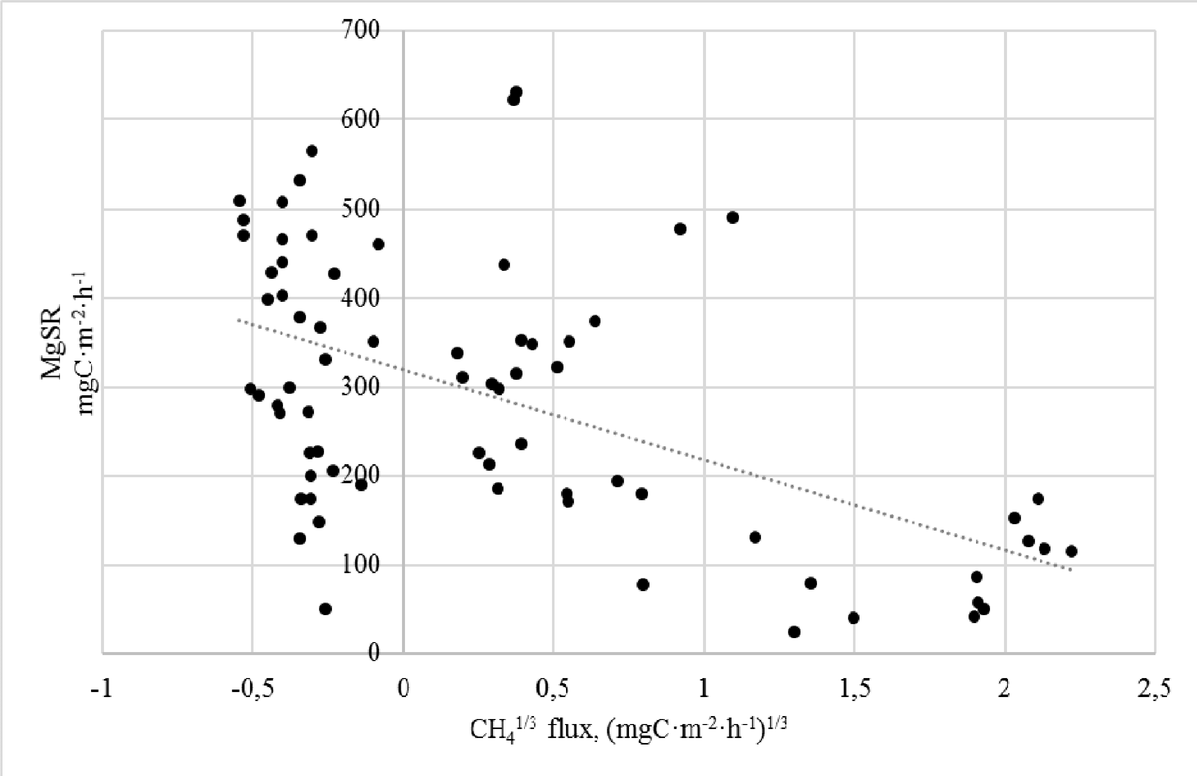

Figure 3. The relationship between CH_4 and CO_2 fluxes (without points Sh.WFor, where carbon dioxide fluxes were not measured). For better readability *x*-axis is not a CH_4 flux, but it is a cube root of it.

Ambus and Christensen [10] studied several ecosystems where temporary waterlogging was possible. They suggested the following important assumption: calculation of the total flux for the periodically waterlogging ecosystems should be performed with respect to the topography of the landscape. In this case, for correct estimation of gas flux using the chamber method it is necessary to take into account relative water levels during flooding (in addition to flux measurements at the flooded areas). Unfortunately, although these authors have studied waterlogged forests, in the end they did not include waterlogged forests in the list of ecosystems for which their assumption was relevant. Our results demonstrate both consumption and emission of methane in waterlogged forests. It allows us to extend this approach to forests, at least to those located on the border of wetlands.

To increase the accuracy of the flux prediction for these soils, it is necessary to make measurements with the highest possible spatial and temporal resolution [10]. Indeed, during a single measurements session in a season, the emission may be zero, but it does not mean that this site does not emit methane during the season. Apparently, if providing a detailed (in space and time) flux data is not possible, calculations may be a useful option. Knowing the topography and hydrology of for each point of a certain area it is possible to reveal how long and how often this point is relatively wet or dry.

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