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Methane Emission from West Siberian Forest-steppe and Subtaiga Reed Fens

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Abstract—Methane emission from West Siberian forest-steppe and subtaiga reed fens (that is, fens dominated by *Phragmites australis*) observed in summer 2013, is considered using the static chamber method. The obtained medians of CH_4 fluxes varied from –0.08 to 2.7 mg CH_4/m^2 per hour. Eenvironmental factors affecting methane emission are analyzed. It was found that CH_4 emissions from the reed fens correlate only with the concentration of salt ions in the wetland water and with the plant community structure. The latter probably also depends on water salinity. It was revealed that in fens the ratio between fluxes of CH_4 and CO_2 does not depend on the water table level that contradicts the general pattern simulated by mathematical models of CH_4 emission. It was found that *Phragmites australis* fens and similar ecosystems should be considered as a separate wetland class from the point of view of methane emission study.

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Keywords: Effects of salt on methane emission, ecosystem respiration, *Phragmites australis* fens, forest-steppe, subtaiga, West Siberia

INTRODUCTION

The most significant contribution to the greenhouse effect formation is made by CO_2 and CH_4 (60 and 20%, respectively) [5]. The concentration of these gases in the atmosphere has considerably increased since the early 19th century and significantly exceeded mean values for the recent 800000 years [13]. Wetlands is the major factor in the cycle of carbonaceous gases, they function both as the net sink (carbon accumulation in the form of peat) and as the net source of atmospheric carbon (emission of carbon dioxide and methane from the surface).

In view of this, special attention is paid to West Siberia which is one of the most paludified regions in the world (there wetlands occupy the area of 68.5 Mha or 27.5% of the territory [20]). In the recent two decades more than 4000 measurements of CO_2 and CH_4 fluxes were carried out by the static chamber method in all climate zones in West Siberia (from forest-steppe to tundra), and their spatial and seasonal variability was assessed [4, 8, 15, 23].

However, fluxes of methane and carbon dioxide from West Siberian forest- steppe and subtaiga wetlands have been studied poorly till now [17, 20]. According to the data presented in [2, 16, 24], in these areas methane emission from fens is characterized by extremely high spatial variability. For example, the mean value of CH_4 flux for several forest-steppe fens varies from tenths to tens of milligrams of CH_4 per squared meter per hour (i.e., the range is equal to two orders of magnitude). Thus, these wetlands are to be studied in detail.

Emission of CH_4 and CO_2 from forest-steppe and subtaiga reed fens

Measurement site		WTL, cm	Temperature, °C				Flux, mg/(m^2 hour)			
Name; coordinates; date	Description; dominant species		air	soil at the depth, cm			CH_4		CO_2	
				5	15	45				
Forest-steppe zone										
Karm.Fen; 54.9485 N, 78.3745 E; July 9, 2013	Willow-hummocky-sedge fen; *Aus*; pH = 6.83	0	27.7	19.2	15.2	10	–0.04	0.69	53	44
							0.06	0.03	535	22
				18.8	15	10	0.07	0.05	652	36
							–0.08	0.51	513	18
Mal.Fen; 54.8283 N, 78.5503 E; July 10, 2013	Willow-hummocky-sedge fen; *Aus*, *Ves*; pH = 6.82	20	27.4	21.6	16	13	6.21	0.24	927	29
							–0.26	0.76	313	37
			27.6	21.8	16	13	1.20	0.04	574	18
							4.22	0.15	755	77
Mal.Fen2; 54.8111 N, 78.5746 E; July 10, 2013	Willow-hummocky-sedge fen; *Aus*; pH_{min} = 7.48; pH_{max} = 8.38	–20	26.3	18.5	17.5	14	0.03	0.04	189	15
							0.20	0.05	367	15
							0.22	0.08	825	29
							0.26	0.07	603	31
Kvash.Fen; 54.5545 N, 76.6794 E; July 11, 2013	Willow-hummocky-sedge fen; *Aus*; pH_{min} = 6.52; pH_{max} = 6.92	0	30.5	18	14.8	11	0.23	0.07	1531	121
							0.27	0.01	1670	51
							0.30	0.07	2378	51
							0.06	0.15	776	161
							–		1457	53
							–		1905	44
							–		2271	100
							–		751	23
NMikh.Grass; 55.0752 N, 76.0608 E; July 12, 2013	Meadow community; *Ulm*, *Sim*, *Ine*	–	30.6	–	–	–	0.03	0.03	1022	20
							0.11	0.04	690	92
							–0.06	0.64	1014	247
							0.03	0.08	1657	160
							–		1089	158
							–		391	58
							–		1148	80
							–		563	216
NMikh.Fen; 55.0747 N, 76.0633 E; July 12, 2013	Reed fen; *Aus*, *Bol*; pH = 7.19	0	33.1	28.2	18.9	12.5	–0.12	0.18	805	85
							–0.04	0.20	542	74
							–		1001	87
							–		1186	50
NMikh.BirFor; 55.0746 N, 76.0590 E; July 12, 2013	Birch community; *Pub*, *Cin*, *Pur*	–	23.6	–	–	–	–0.01	0.03	1389	230
							–0.05	0.02	969	133
							–		894	91
							–		971	143
Subtaiga zone										
Surguty.Fen; 56.0417 N, 78.5556 E; July 7, 2013	Marshy meadow; *Pur*, *Ces*, *Acu*; pH_{min} = 6.92; pH_{max} = 7.03	5	24.1	16	13.7	10.5	1.11	0.13	314	74
							1.70	0.20	389	80
							3.16	0.17	416	65
							3.55	0.12	831	122

Table. (Contd.)

Measurement site		WTL, cm	Temperature, °C				Flux, mg/(m^2 hour)			
Name; coordinates; date	Description; dominant species		air	soil at the depth, cm			CH_4		CO_2	
				5	15	45				
Borch.Fen2; 55.8792 N, 78.3885 E; July 8, 2013	*P. australis* fen; *Aus*, *Fes*, *Ath*; pH_{min} = 6.28; pH_{max} = 7.03	–5	25.3 25.3	16.9	16.5	11	2.68 5.88 2.31 1.59	0.36 0.04 0.08 0.08	447 866 666 533	29 18 20 21

Note: Here, *Cin* is *Salix cineria*; *Ves* is *Carex vesicaria*; *Pur* is *Calamagrostis purpureus*; *Aus* is *Phragmites australis*; *Ulm* is *Filipendula ulmaria*; *Sim* is *Thalictrum simplex*; *Ine* is *Bromus inermis*; *Bol* is *Bolboschoenus maritimus*; *Pen* is *Betula pubescens*; *Ces* is *Carex cespitosa*; *Acu* is *Carex acuta*; *Com* is *Comarum palustris*; *Fes* is *Scolochloa festucacea*; *Ath* is *carex atherodes*. The dash means the absence of data; negative values of water table level (WTL) correspond to the situation when water stands over the mean surface of moss cover.

It was interesting to determine the suitability of currently used classification of wetland types [21] and use it for estimating the regional methane flux. For this purpose the data are needed on the values of methane fluxes and on the effects of environmental factors on the emission for all types of wetlands. As a result, it will be possible to determine the expediency of the grouping of wetlands, i.e., to assess how close fluxes and the set of controlling factors are.

The present paper studies one of the most widely distributed type of wetlands in West Siberian subtaiga and forest-steppe, that is, fens dominated by *Phragmites australis*; also we considered two other environmentally similar wetland types (according to the data presented in [10]): reed-sedge fens and reedgrass fens.

RESEARCH SITES

The measurements were carried out in July 2013 in nine key areas of West Siberian forest-steppe and subtaiga on the territory of the Novosibirsk oblast (see the table). Measurement sites were chosen in a way that allowed embracing as many *P. australis* fens located in both subzones as possible.

To describe the climatic parameters, the observational data from Zdvinsk weather station (54 42 N, 78 40 E) were used [9]. Average annual air temperature in Zdvinsk is 1.4 C, the absolute minimum is –48.6 C, the absolute maximum is 36.1 C, and the average total amount of precipitation is 310 mm. During the measurement period the absolute minimum, mean, and absolute maximum temperature was equal to 11.7, 19.5, and 27.0 C, respectively; similar values for relative humidity were 23, 34, and 70%, respectively.

DATA AND METHODS

The fluxes of methane and carbon dioxide were measured by the static chamber method described in [15]. Gas was sampled from the chambers with syringes with the volume of 12 ml (for methane) and 20 ml (for carbon dioxide) at time moments t_0, t_1, t_2, and t_3 through the rubber stopper with the tube hermetically installed in the upper part of the chamber. The exposure time for CH_4 flux measurement ($t = t_3 - t_0$) was selected according to the microlandscape type (30–60 minutes). The exposure time for CO_2 flux measurement was equal to 15 minutes.

The syringes with the samples were pressurized by rubber stoppers, were put into the NaCl saturated solution (to reduce methane diffusion from the syringes), and were delivered to the laboratory. Methane concentration was measured by KhPM-4 gas chromatograph (produced in Russia) equipped with the flame ionization detector (the column length is 1 m, its diameter is 2.5 mm, sorbent is Sovpol, 80–100 mesh). Hydrogen was used as a carrier gas (the flow rate is 5 ml/minute). The methane–air gas mix with the concentration of CH_4 equal to 1.99, 5.00, and 9.84 ppm (National Institute for Environmental Studies, Japan) was used for calibration. The accuracy of these standards is 0.01 ppm.

The samples of carbon dioxide from opaque chambers were taken in a similar way simultaneously with the beginning of methane sampling. Vegetation was not removed during the measurements. The carbon dioxide–air gas mix with the concentration of CO_2 equal to 357 5 and 708 10 ppm (VNIIMEM, St. Petersburg) was used for the calibration. The concentration of carbon dioxide in the syringes was measured by DX-6100 infrared gas analyzer (RMT Ltd, Russia) in several hours after the sampling.

The following physical and chemical parameters were measured at each measurement site: temperature at the depth of 0, 5, 15, and 45 cm using THERMOCHRON iButton DS 1921G sensors (DALLAS Semiconductor, USA), pH and electric conductivity indicating the total content of ions in the mire water using SG8 pH-meter and SG7 conductivity meter (Mettler Toledo, USA), respectively. The flux was computed by the regression (in time–concentration coordinates): linear regression for the case of emission of CH_4 and CO_2 and nonlinear regression for the case of CH_4 consumption [2]. Positive values of fluxes indicate gas emission to the atmosphere, and negative values, its comsumption. To provide the statistical processing of the data (that included the comparison of mean values using the Wilcoxon test as well as linear and nonlinear one-dimensional regression and stepwise linear regression), MATLAB v. 7.0 (MathWorks, USA) interactive system was used. The median was used as an estimate of the mean value of fluxes because this estimate is robust that is quite essential when measuring methane emission from wetlands [6]. Due to the wetland soil properties, the researcher often has to press gas out manually when using the chamber method. The median estimate turns out to be more resistant to the effects of these sporadic emissions. However, the median coincides with the arithmetic mean for any symmetric distribution including the normal one.

RESULTS AND DISCUSSION

Emission of CH_4. The median of CH_4 fluxes for the investigated wetlands varied from –0.08 to 2.7 mg CH_4/m^2 per hour (see the table). These data do not enable assessing the temporal dynamics of emission from the fens under consideration as they were obtained during two weeks in summer; however, they allow assessing the spatial variability of emission. The analysis of the obtained dataset (except the parameters measured in the birch outlier and steppe meadow) demonstrated that the one-dimensional (single-factor) linear, quadratic, and exponential regression does not enable revealing reliable predictors for the medians of CH_4 fluxes. The obtained medians can be divided into two groups: the value of emission is equal to 0.1 0.14 mg CH_4/m^2 per hour (hereinafter, the arithmetic mean ± standard deviation is given) in the first group (Karm.Fen, Mal.Fen2, Kvash.Fen, and NMikh.Fen points) and 2.8 1.9 mg CH_4/m^2 per hour in the second group (Surguty.Fen, Borch.Fen2, and Mal.Fen points). The difference in values of CH_4 fluxes between these groups is statistically significant (according to the Wilcoxon test at the significance level of 0.001).

The separated groups considerably differ in two parameters which can affect methane emission. The first of them is electric conductivity: its mean value is 7920 S/cm for the first group and 820 S/cm for the second group. The differences are significant according to the Wilcoxon test at the significance level of 0.001, i.e., the smaller CH_4 flux corresponds to the higher concentration of salt. This also agrees with the results of measurements in other West Siberian *P. australis* fens presented in [3]. There the CH_4 flux for the wetland with the electric conductivity of water of 570 40 S/cm was equal to 3.4 2.2 mg CH_4/m^2 per hour, and the CH_4 flux for the wetland with the electric conductivity of water of 3900 100 S/cm was equal to 0.13 0.14 mg CH_4/m^2 per hour.

This can be explained by the fact that under anaerobic conditions in presence of SO_4^{2} , Fe^{3+}, and NO_3 ions, methanogenesis can be inhibited due to the development of microorganisms which use these electron acceptors and compete successfully with methanogens for common substrates as a result of more favorable thermodynamically microbe processes [1, 8, 14, 18]. Such microorganisms may include sulfate, iron, or nitrate reducers, respectively. Besides, the intermediates of nitrate reduction (NO_2 and NO) inhibit methanogenesis ferments [1]. Thus, along with other factors, the high concentration of salt in the ground water can be a reason for the smaller emission of methane from wetlands under study.

Besides, *P. australis* was the only higher plant (except NMikh.Fen where *Bolboschoenus maritimus* was present) at all points in the first group, whereas other higher plants in addition to *P. australis* were observed in the vegetation cover at all points in the second fen group. The relationship between high or low values of CH_4 emission and the presence or absence of concrete plant species and their biomass has been noted repeatedly by other researchers [16, 19]. However, in this case it can be an effect of the above difference in salt concentration in the ground water of wetlands: *P. australis* is the most resistant plant to the salinization conditions of West Siberian forest-steppe and subtaiga wetlands [7]; therefore, only this species forms single-species communities at the maximum content of salt in the water. This supposition

also allows explaining the above exception: *Bolboschoenus maritimus* is an extreme halophile growing in river estuaries [7].

The above dependence of CH_4 fluxes on environmental factors is unique for all investigated West Siberian wetlands because it is not typical of any data used in [15] or discussed in literature.

The uniqueness of *P. australis* fens and similar wetlands as methane sources can be assessed using the degree to which CH_4 emission follows the common pattern for all other mires which are present explicitly or implicitly in process-oriented mathematical models. This is representative because such mathematical models are also used to obtain regional estimates of emission [12]. One of such most common general patterns is the change in the ratio of processes of aerobic and anaerobic decomposition of organic matter depending on the water table level: the more watered the fen is, the larger (other conditions being equal) CH_4–CO_2 flux ratio is [11, 12, 19, 22]. This pattern is not typical of wetlands under study. Neither linear nor quadratic nor exponential dependencies of CH_4–CO_2 flux ratio on the water table level turned out to be reliable (even at the significance level of 0.2, $N = 6$). Thus, the simulation of such ecosystems requires a special approach taking into account the specific type of dependence of methane emission on different factors.

CONCLUSIONS

From the point of view of methane emission, *P. australis* fens and similar ecosystems should be considered as a separate type of wetlands. This is explained by the principally different origin of emission dependence on environmental factors. The emission volume from *P. australis* fens is controlled by the concentration of salt ions in the water and by the plant community structure that is perhaps associated with the degree of salinization of water. This is not typical of other West Siberian wetlands. Besides, the need in the separate consideration of *P. australis* fens is also indicated by the fact that the dependence of the ratio of CH_4–CO_2 fluxes on the fen water level that is common for all other wetland ecosystems, is not typical of *P. australis* fens.

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