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ECOLOGY

The Spatial Variability of Methane Emission from Subtaiga and Forest–Steppe Grass–Moss Fens of Western Siberia

A. F. Sabrekov[a, b], **I. V. Filippov**[a, c], **I. E. Terentieva**[d],
M. V. Glagolev[a, b, c, d], **D. V. Il'yasov**[a], **B. A. Smolentsev**[e], **and S. S. Maksyutov**[f]
[a] *Institute of Forest Science, Russian Academy of Sciences, Moscow oblast, Odintsovo raion, pos. Uspenskoe, ul. Sovetskaya 21, 143030 Russia*
[b] *Tomsk State University, prosp. Lenina 36, Tomsk, 634050 Russia*
[c] *Yugra State University, ul. Chekhova 16, Khanty-Mansiysk, 628012 Russia*
[d] *Faculty of Soil Science, Moscow State University, Moscow, 119992 Russia*
[e] *Institute of Soil Science and Agrochemistry, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent'eva 8/2, Novosibirsk, 630099 Russia*
[f] *National Institute for Environmental Studies, 305-8506 Japan, Ibaraki, Tsukuba-City, Onogawa 16-2*
e-mail: sabrekovaf@gmail.com

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Abstract—Methane emission from the grass–moss fens of the Western Siberia subtaiga was studied using a static chamber method. It was established that CH_4 flux median ± half of the interquartile range in the studied wetland ecosystems constituted 4.9 ± 2.9 mg of $CH_4/(m^2\ h)$. It was shown that such a high spatial variability of emission is caused mainly by the difference in the water table level. It was found that, in these observations, a higher water table level correlates with lower emission values. The causes of this phenomenon are discussed, and recommendations for conducting field studies for estimating the regional flux are given.

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INTRODUCTION

An estimation of the relative contribution of methane sources to the formation of the greenhouse effect is an important task within the framework of the issue of global warming (Heimann, 2011). The main natural sources of methane are mires. Their emission amounts to ~32% of the global methane emission from all sources, or 175 × 10^{12} g of CH_4/year (Ciais et al., 2014). Of them, according to different estimates, the mires located in the northern Hemisphere emit from 25 × 10^{12} to more than 65 × 10^{12} g of CH_4/year (Matthews and Fung, 1987; Aselmann and Crutzen, 1989; Fung et al., 1991; Zhu et al., 2013). Owing to this, special attention is paid to Western Siberia (WS), which is one of the most waterlogged regions in the world: mires cover 73 Mha, or 26% of the territory (Terentieva et al., 2015). In the last 20 years, in all natural zones of WS, from forest–steppe to tundra, >4000 CH_4 fluxes measurements have been made using the static chamber method, their spatial and seasonal dynamics were estimated (Panikov et al., 1993; Glagolev et al., 2011; Golubyatnikov and Kazantsev, 2013; Sabrekov et al., 2014).

However, the values methane fluxes from the WS subtaiga fens have remained sufficiently less studied until recently (Kim et al., 2011; Naumov, 2011). An analysis of the existing data shows, for example, that for the subtaiga fens, the fluxes range from tenths to tens of mg of $CH_4/(m^2\ h)$ (Glagolev et al., 2012). Thus, these wetlands require additional attention due to the high variability of the emission values.

According to the typological map of mires (Terentieva et al., 2014), poor fen and fen ecosystems occupy 46% of the wetlands of the entire zone; therefore, study of them is highly significant in the context of emission of greenhouse gases. We focused on those types of subtaiga fens that can be conditionally united as "grass–moss" ones: sedge–hypnum and sedge–sphagnum and sedge ones, birch–reed grass–sedge, birch–sedge–sphagnum, and pine–birch–sedge–sphagnum mires (Romanova et al., 1977).

Even if we exclude reed fens from consideration, the variability of CH_4 fluxes obtained for the grass–moss fens requires explanation. It could be caused by a lack of data, unsubstantiated unification of different (in terms of emission) types of fens into one category, or the natural spatial variability of emission.

The aim of this study is to identify the reasons for high variability of CH_4 fluxes in WS subtaiga and forest-steppe grass–moss fens. In order to accomplish this, we had to solve the following tasks: obtain measurements of CH_4 flux in the objects mentioned above and analyze the nature of the dependence of CH_4 fluxes on various environmental factors.

MATERIALS AND METHODS

The measurements were conducted in July 2013 at six sites in the subtaiga zone of WS. The plots were located along a transect that stretched for 100 km from the north to the south over the territory of Novosibirsk oblast (Table 1).

To describe the climatic characteristics of the subtaiga zone, the data of a weather station of the village of Severnoe (56°21′ N, 78°22′ E) were used. The mean annual temperature in Severnoe constitutes 0.8°C with the absolute minimum of –47.3°C and an absolute maximum of 34.1°C. The mean annual precipitation amounts to 490 mm/year. During the period of measurements (July 6, 2013—July 9, 2013), the temperature and relative humidity (absolute minimum/mean/absolute maximum) were 10.4/17.5/25.5°C and 32/48/76%, respectively.

Khob.Fen (a fen near the Khobotovo village). The inclusive landscape consists of birch forests, often overmoistened and waterlogged. The measurements were performed in a birch–sedge mire, which occupies a small (350 m) depression in the relief. The microrelief is differentiated into sedge (*Carex cespitosa*) tussocks 30–40 cm high and overmoistened, partly flooded with water. The tree layer is represented by birch *Betula pubescens*, 3–5 m high, the projective cover (PC) constitutes on average ~10% but some gaps occupied with willow (*Salix cinerea*, *S. pentandra*) can be found. In the grass tier, spots of *C. cespitosa* alternate with reed thickets (the average PC is 70%). Other types of vegetation that are present in the grass tier with a small PC but highly constant are *C. diandra*, *Kadenia dubia*, *Comarum palustris*, *Calamagrostis purpureus*, *Rumex aquaticus*, *Cardamine pratensis*, *Stellaria palustris*, *Lathirus palustris*, *Scutellaria galericulata*, *Lycopus europaeus*, and others. The moss tier is represented by *Plagiomnium ellipticum* and other green mosses.

NovTr.Fen (fen near the village of Novotroitskoe). The inclusive landscape consists of birch forests. The measurements were conducted in two vast (~1 km) open sedge fens, that were similar in terms of vegetation. The microrelief was not differentiated. At the first fen (NovTr.Fen.1), more moistened areas with open water prevail, while at the second (NovTr.Fen.2), drier ones are prevalent, with the bog water level (WTL) of 10 cm. In the previous season, a crown fire passed over the fen. In the grass tier, *C. acuta* (PC = 25–50%), *C. lasiocarpa* (PC = 3–10%), and *C. palustris* (PC = 3–20%) dominate, while *Naumburgia thyrsiflora*, *Equisetum fluviatile*, *Epilobium palustris*, *S. palustris*, and *Calamagrostis neglecta* are present as admixture. The moss tier is almost absent, with *Drepanocladus aduncus* present in some places, and remnants of dead *Sphagnum* sp. present in some spots in NovTr.Fen.2.

Potyuk.Fen (fen near the village of Potyukanovo). The inclusive landscape consists of humid galophile meadows in the river valley, the lowest spots of which are occupied by monodominant sedge swamps with *C. vesicaria*, in which the measurements were performed. The WTL was higher than the surface by 10 cm.

Borch.Fen (fen near the village of Borshchinskoe). The complex landscape consists of groups of birch trees and meadows (as well as deposits with various degrees of recovery), which are characteristic of the forest–steppe zone of WS. A vast depression (extending for more than 10 km) is occupied with a shallow, open, highly waterlogged mire of a complex structure: at the periphery, areas of reed thicket and monodominant sedge communities (*C. vesicaria*) alternate; deeper into the massif, sedge tufts with the domination of *C. cespitosa* appear. The measurements were performed at the Borch.Fen.1 plot with the absolute domination of the sedge *C. vesicaria*, where the WTL is higher than the surface by 30 cm, and at the plot Borch.Fen.3, which is a sedgy plot with a domination of *C. cespitosa* and codomination *Phragmites australis* and *Scolochloa festucacea*, where the WTL is also higher than the surface level by 20 cm.

Vag.Fen (a fen near the village of Borshchinskoe). The inclusive landscape consists of birch forests, small mires (with a diameter of up to 500 m), which occupy depressions in the relief. The measurements were performed in a sedge mire with domination of *C. lasiocarpa* and *C. omskiana*. The WTL is higher than the surface by 10 cm, and the microrelief contains weakly pronounced tussocks of *C. omskiana*.

Dun.Fen (a fen near the village of Dunaevka). The inclusive landscape consists of tilled lands, meadows, groups of birch trees, and rounded depressions. The latter are occupied with sedge tufts with *C. omskiana*, which are fringed at the periphery with willow swamps. The measurements were performed in *C. omskiana* sedge growth, and the microrelief was differentiated into flat tussocks (Dun.Fen.2) up to 50 cm high and flooded with water (WTL = 0 cm) spaces between them (Dun.Fen.1). In the shrub tier, *S. cinerea* is present, and in the grass tier, there are *C. palustris* and *Typha latifolia*. The presence of star duckweed *Lemna trisulca* and common bladderwort *Utricularia vulgaris* indicate that, for the most part of the year, the fen is overmoistened.

Methane and carbon dioxide fluxes were measured using the static chamber method (Glagolev et al., 2011). The gas was collected from the chambers using syringes 12 (for methane) and 20 (for carbon dioxide) mL in volume at the moments of time t_0–t_3 through a rubber stopper with a tube installed hermetically in the upper part of the chamber. The exposure time ($\Delta t = t_3 - t_0$) was selected according to the type of the mire ecosystem (it varied from 30 to 60 min for methane samples). When measuring CO_2 fluxes, the exposure time was 15 min. In most cases, the SF of CH_4 and CO_2 were measured simultaneously.

Table 1. Emission of CH_4 and CO_2 from the grass–moss fens of the subtaiga and forest–steppe of the Western Siberia (2013)

Sites, coordinates	Date	List of plant species	pH_{min}, pH_{max}	EC, μS/cm	WTL, cm	Temperature, °C				Flux	
						T_B	T_5	T_{15}	T_{45}	CH_4, mg of $CH_4/(m^2\ h)$	CO_2, mg of $CO_2/(m^2\ h)$
Subtaiga											
Khob.Fen, 56.2651° N, 78.3616° E	06.07	*Pub, Cin, Ces, Aus*	7.07, 7.15	336	–30	24.6	14	11	8	12.3 ± 0.4	845 ± 61
										3.4 ± 0.2	165 ± 16
										0.9 ± 0.1	85 ± 36
										3.1 ± 0.1	99 ± 11
						23.3		11		8.3 ± 0.1	748 ± 112
										3.1 ± 0.1	188 ± 36
						22.6		11		1.3 ± 0.1	98 ± 11
										1.6 ± 0.3	96 ± 23
						18.9		11.5		7.2 ± 0.3	743 ± 30
										1.9 ± 0.1	110 ± 17
										1.6 ± 0.2	94 ± 25
										2.1 ± 0.2	129 ± 18
NovTr.Fen, 56.1594° N, 78.4014° E	07.07	*Ves, Las, Ces*	6.16, 6.34	237	–10	29	15.5	14	8	5.6 ± 0.1	457 ± 193
										3 ± 0.1	626 ± 102
										5.4 ± 0.1	–
										2.2 ± 0.3	–
NovTr.Fen2, 56.1375° N, 78.3977° E	07.07	*Acu, Las, Com*	4.78, 5.27	71	10	29.5	17	13.8	9	0.1 ± 0.2	697 ± 136
										0.1 ± 0.2	259 ± 56
										–0.1 ± 5.1	558 ± 17
										0.3 ± 0.1	798 ± 70
Potyuk.Fen, 56.0604° N, 78.4438° E	07.07	*Ves*	7.03, 7.14	2004	10	29.5	16	13.8	8	13.5 ± 1.2	700 ± 29
										11.2 ± 0.7	1086 ± 70
										8.8 ± 0.2	635 ± 36
										11.1 ± 0.5	748 ± 21
Borch.Fen, 55.7789° N, 78.3887° E	08.07	*Ves*	6.28, 7.23	1051	–30	25.3	16.5	16	11.5	2 ± 0.3	363 ± 29
										3.5 ± 0.7	438 ± 64
						24.2				5.4 ± 0.3	584 ± 31
										1.9 ± 0.2	391 ± 33
Borch.Fen3, 55.7795° N, 78.3884° E	08.07	*Aus, Fes, Ces*	6.55, 7.26	749	–20	21	17	17	12.5	0.7 ± 0.2	296 ± 22
										0.2 ± 0.1	199 ± 15
										0.1 ± 0.1	259 ± 24
										7 ± 0.3	1118 ± 101

Table 1. (Contd.)

Site, coordinates	Date	List of plant species	pH_{min}, pH_{max}	EC, μS/cm	WTL, cm	Temperature, °C				Flux	
						T_B	T_5	T_{15}	T_{45}	CH_4, mg of $CH_4/(m^2\ h)$	CO_2, mg of $CO_2/(m^2\ h)$
Forest-steppe											
Vag.Fen, 55.8302° N, 78.4072° E	09.07	*Las, Aus*	6.65, 6.73	664	–10	19.8	17	16	11	5.9 ± 0.3	337 ± 13
										5.6 ± 0.2	246 ± 15
										9.1 ± 0.3	549 ± 39
										3.3 ± 0.2	170 ± 30
Dun.Fen, 55.2136° N, 78.2117° E	09.07	*Cin, Com, Lat*	6.36, 6.89	513	0	33.5	25.3	17.5	11	27.4 ± 5.3	411 ± 13
										30 ± 2.7	717 ± 34
										33.8 ± 0.6	505 ± 15
										30.7 ± 3.6	326 ± 65
Dun.Fen2, 55.2133° N, 78.2118° E	09.07	*Cin, Oms, Com*	6.43, 6.59	742	–20	27	17.5	15	11	–0.2 ± 0.3	369 ± 165
										0.1 ± 0.7	366 ± 26
										2.2 ± 0.6	–
										3.2 ± 0.7	–

(*Acu*) *Carex acuta*, (*Aus*) *Phragmites australis*, (*Ces*) *Carex cespitosa*, (*Cin*) *Salix cinerea*, (*Com*) *Comarum palustris*, (*Fes*) *Scolochloa festucacea,* (*Las*) *Carex lasiocarpa*, (*Lat*) *Typha latyfolia*, (*Oms*) *Carex omskiana*, (*Pub*) *Betula pubescens*, and (*Ves*) *Carex vesicaria*. ("–") No data.

* WTL < 0 and WTL > 0 are registered in the cases when the WTL is higher or lower than the mean moss cover surface, respectively.

The syringes with the samples were hermetized with rubber stopper, placed into a saturated solution of NaCl (in order to decrease the diffusion of methane from the syringes) and delivered to the laboratory. Methane concentrations were measured using a KhPM-4 modified gas chromatograph (Khromatograf, Moscow) equipped with a flame-ionization detector. The length of the column was 1 m, the diameter was 2.5 mm, and Sovpol (particles sized ≤0.15 mm) was used as the sorbent. Hydrogen was used as the carrier gas (the rate of the current 5 mL/min). Mixtures of gases methane/air with a concentration of CH_4 1.99 and 9.84 ppmv (National Institute for Environmental Studies, Japan) were used for calibration; the accuracy of these standards was ±0.01 ppmv.

From opaque chambers, air samples were taken in a similar way to determine the concentrations of carbon dioxide simultaneously with the beginning of sample collection to determine the concentration of methane. The vegetation was not removed from the samples during measuring. The carbon dioxide concentration in the syringes was measured using a DX-6100 infrared gas-analyzer (RMT Ltd., Russia) no later than several hours after the collection. For calibration of this device, we used carbon dioxide/air mixtures with a concentration of CO_2 357 ± 5 and 708 ± 10 ppmv (All-Russia Scientific Research Institute of Small Electric Machines, St. Petersburg).

The following parameters were also measured at each site: WTL (cm), air (°C) and soil temperature at the depths of 0, 5, 15, and 45 cm (T_A, T_0, T_5, T_{15}, and T_{45}, respectively) using a Thermochron iButton DS 1921G temperature sensor (DALLAS Semiconductor, United States), pH, and electrical conductivity (EC, μS/cm) using a SG8 pH-meter, and a SG7 conductometer (Mettler Toledo, United States), respectively. The flux was calculated by the regression (in the coordinates time–concentration): linear in the case of emission of CH_4 and CO_2 and nonlinear for consumption of CH_4, as described earlier (Glagolev et al., 2010). For statistical processing of the data (which included a comparison of the means using the Wilcoxon test, as well as linear and nonlinear one-dimensional and stepwise linear regressions), we used the MATLAB v. 7.0 interactive system (MathWorks, United States). If it is not indicated specifically, the threshold level of significance of statistical tests is 0.05.

RESULTS AND DISCUSSION

Emission of CH_4. The results of CH_4 flux measurements in the studied fen ecosystems are given in Table 1. Since these data were obtained in the course of one week of one year, they can help estimate both components of spatial variability of emission: variability within one fen and variability between the fens. The mean ± standard deviation of the first of these compo-

Table 2. Parameters of linear regression dependences found on different assumptions

No. of line	Independent variables	Points excluded from the analysis	R^2	Root mean square error, mg of $CH_4/(m_2\ h)$	Level of significance
1	T_{15}	–	0.49	4.6	0.012
2	T_{15}	Dun.Fen	0.24	2.6	0.127
3	pH, WTL	Dun.Fen	0.77	1.5	0.003
4	WTL	Dun.Fen	0.23	2.6	0.141
5	WTL	Dun.Fen and NovTr.Fen2	0.77	1.3	0.00079
6	CO_2 flux	Dun.Fen and NovTr.Fen2	0.44	2.1	0.037
7	WTL	NovTr.Fen2	0.39	5.1	0.039

The dependent variables are the medians of CH_4 flux for different mires. The independent variables are the enumerated ecological factors. R^2 is the determination coefficient, and "–" designates the absence of exceptions.

nents, calculated as the ratio of the standard deviation to the median for the entirety of measurements performed in one mire, constituted 0.34 ± 0.15. This value is very close to the values of spatial variability within one mire in the subtaiga (Sabrekov et al., 2014).

The spatial variability between the various mires can be estimated on the basis of a criterion proposed earlier (Sabrekov et al., 2014): the ratio of half of the interquartile range to the median (this is a nonparametric analogue of the variation coefficient) by a sampling of CH_4 flux values for separate mires from the medians. For the data obtained for the subtaiga zone, the median ± half of the interquartile range of CH_4 flux (the volume of sampling N is 12; the measurements taken on tussocks and in the spaces between them were perceived as different) constituted 4.9 ± 2.9 mg of $CH_4/(m^2\ h)$. Thus, the spatial variability value between the fens is ±0.61 (or ±61%). We did not find data for a similar estimation of any other zones or regions of Russia but it should be noted that the obtained knowledge exceeds all the existing values of variability of emission of other mire types for the WS (Sabrekov et al., 2014).

Influence of various ecological factors on methane emission. Stepwise linear regression, with both inclusion and exclusion of various ecological factors, allowed us to reveal the only reliable dependence between the medians of CH_4 flux for different mires and these factors (Table 2, line 1): the dependence on T_{15}. However, the regression error value for this dependence does not allow us to distinguish adequately the absolute majority of the obtained medians of CH_4 flux for separate mires. This dependence is subject to the strong influence of the median of CH_4 flux at the Dun.Fen point (31 mg of $CH_4/(m^2\ h)$). Exclusion of this point from the analysis results in the dependence of CH_4 flux on T_{15} becoming unreliable (Table 2, line 2).

Thus, the dependence of CH_4 flux on T_{15} is, apparently, an artefact of the high emission value at the point Dun.Fen and, for further analysis, this point has to be excluded. After the exclusion of this high value, which distorts the results, using multidimensional linear regression, we succeeded in obtaining the only reliable dependence of the medians of CH_4 flux for different mires, namely, the dependence on WTL and the mean pH value along the profile (Table 2, line 3). The appearance of pH as a factor significantly impacting the emission value leads to the necessity of analyzing whether the studied objects are similar or different in terms of geochemistry. This can serve as a basis for considering them separately as sources of methane. A comparison with the Wilcoxon test shows that the mean values of pH and EC along the profile for the point NovTr.Fen.2 significantly differ from all the respective values for all the other points. The exclusion of this point from the analysis leads to the dependence on the mean pH along the profile becoming unreliable when performing multiple regression. This can indicate that mires similar to NovTr.Fen2 should be considered separately from all other fens of the subtaiga. However, since there are no other such mires in our sampling, additional measurements should be conducted. The influence of WTL only on the CH_4 flux with the participation of the NovTr.Fen2 point in the regression proved to be statistically insignificant (Table 2, line 4). Thus, the dependence of the CH_4 flux on the WTL and the mean pH along the profile simultaneously is a consequence of the specific geochemical conditions at the NovTr.Fen2 point, and, for further analysis, this point must also be excluded from consideration. It is possible that, despite the vegetation, this fen should be considered oligotrophic on the basis of the geochemical parameters.

After the exclusion of the medians of CH_4 flux from the analysis at the DunFen and NovTr.Fen2 points, the multiple linear regression does not allow us to obtain reliable dependences of the emission on ecological factors. However, using one-dimensional regression, we succeeded in revealing a significant positive correlation between the CH_4 flux and WTL (Table 2, line 5):

$$CH_4 \text{ flux} = (0.187 \pm 0.036) \times \text{WTL} + (6.39 \pm 0.63).$$

The fact that the WTL correlates positively with the CH_4 flux requires a special explanation, as usually their connection has the opposite sign (Dise et al., 1993; Moore and Roulet, 1993; Glagolev et al., 2008). This is usually explained by the fact that the formation of methane occurs in anaerobic conditions in peat lower than the WTL, while in aerobic conditions, methane is oxidized. Therefore, the greater the part of the soil profile in anaerobic conditions, the higher the methane flux (Glagolev, 2012). However, in the papers mentioned above, the WTL is almost always lower than the surface, whereas in the fens studied by us, it is almost always higher; i.e., in our case, the change of the WTL has no influence on what part of the soil profile is submerged lower than the WTL (it is lower than the water surface in any case).

A positive correlation of the WTL with the CH_4 flux is noted only in a few papers (Moore et al., 1990; Treat et al., 2007). Glagolev (2012) considered the possible causes of this phenomenon. As in our case, it is the correlation with flux measured at approximately the same moment of time at different points of space, the most reasonable explanations seem to be the ones associated with the plants. The higher the waterlogging of the fen, the more the activity of plants is suppressed, and the lower their live biomass. Therefore, with an increase in the degree of waterlogging, the transport of methane associated with plants is decreased (in this case, it is not important whether it is passive or active), which, as a rule, carries the greater part of the entire transport of CH_4 (Kutzbach et al., 2004; Glagolev et al., 2008; Kao-Kniffin et al., 2010). This can be confirmed by the fact that the positive correlation between the CH_4 flux and CO_2 proved to be statistically significant (Table 2, line 6):

$$CH_4 \text{ flux} = (0.022 \pm 0.009) \times CO_2 \text{ flux} + (0.97 \pm 1.37).$$

Thus, the higher the respiration of plants and/or their biomass, the greater the emission of methane from the studied fens. Another cause of the positive correlation of the WTL with the CH_4 flux can be the fact that, at higher WTL, methane molecules have to pass a greater distance through the water. But as the contribution of the diffusion component into the methane transport does not exceed 10% (Schütz et al., 1989; Butterbach-Bahl et al., 1997; Kutzbach et al., 2004), this might not have any significant impact on the emission value.

On the basis of the analysis performed, the conclusion can be drawn that, excluding the geochemically different mire, all the other fens of the WS subtaiga demonstrate the same dependence of the CH_4 flux on the environmental factors, specifically, the WTL. This dependence is reliable even with the inclusion of the data of the Dun.Fen point (Table 2, line 7). Therefore, dividing these mires in the context of their classification as sources of methane appears inexpedient. The spatial variability revealed earlier is not an artefact of the small number of measurements but is of natural origin.

The great significance of spatial variability of emission between the various mires allows us to give some general recommendations on the most optimal method of measuring methane emission to obtain the regional estimates of emission. Taking into account the estimates of seasonal variability for poor fens (±30%) and fens (±10%) given earlier (Sabrekov et al., 2014), we can conclude that when studying fens, the spatial variability should be analyzed, as insufficient knowledge of it can lead to the most serious errors when assessing the regional flux estimate.

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