doi: 10.25750/1995-4301-2019-3-012-020

Carbon dioxide, heat and water vapor exchange in the boreal spruce and peatland ecosystems

© 2019. S. V. Zagirova[1] ORCID: 0000-0002-3304-4160,
O. A.Mikhailov[1] ORCID: 0000-0002-6044-6528, Ju. Schneider[2] ORCID: 0000-0002-2790-8487,
[1]Institute of Biology of the Komi Science Centre of the Ural Branch of RAS,
28, Kommunisticheskaya St., Syktyvkar, Russia, 167982,
[2]Institute for Environmental Sciences, University of Koblenz-Landau,
7, Fortstrase, Landau, Germany, 76829,
e-mail: zagirova@ib.komisc.ru

The mass and energy exchange between the terrestrial ecosystem and the atmosphere depends on the structure and functioning of vegetation and soil cover. The aim of the work was to compare the ecosystem CO_2, heat and water vapor exchange in the old-growth spruce forest and meso-oligotrophic peatland, typical ecosystems of the middle taiga landscapes on the European Russia. The study was made by using the eddy-covariance method. In the warm period of the year, the spruce forest ecosystem was characterized by higher values of the net radiation (R_n) and turbulent heat exchange (*H*) than the peatland. In the peatland, the latent heat flux (*LE*) in July represented more than the half of the net radiation. Net ecosystem exchange CO_2 (*NEE*) from 1st April to 31st August was -327 gC/m^2 in the spruce forest and -40 gC/m^2 in the peatland, and the total evapotranspiration (*ET*) was 324 mm and 300 mm, respectively. A close correlation was established between *NEE* and *ET* in daily dynamics (R^2 = 0.7–0.9). The average daily values of net exchange CO_2 in spruce forests are closely correlated with the net radiation (R^2 = 0.63) and turbulent heat exchange (R^2 = 0.57). For the meso-oligotrophic peatland, heat transfer factors turned out to be less significant (R^2 = 0.38–0.45). The obtained data can be used to predict carbon exchange processes and water vapor fluxes in terrestrial ecosystems due to expected climate changes in the region.

Keywords: spruce forest, peatland, carbon dioxide exchange, heat exchange, evapotranspiration.

УДК 630*187:582.475:556.56:55.584.4

Обмен диоксида углерода, тепла и влаги в экосистемах ельника и болота таёжной зоны

© 2019. С. В. Загирова[1], д. б. н., зав. отделом, с. н. с.,
О. А. Михайлов[1], к. б. н., н. с.,
Ju. Schneider[2], докторант,
[1]Институт биологии Коми научного центра Уральского отделения РАН,
167982, Россия, Республика Коми, г. Сыктывкар, ул. Коммунистическая, д. 28,
[2] Институт экологических наук, Университет Кобленц-Ландау,
76829, Германия, г. Ландау, Форстрасе 7,
e-mail: zagirova@ib.komisc.ru

Обмен веществ и энергии между наземной экосистемой и атмосферой зависит от структурно-функциональной организации растительного и почвенного покровов. Цель работы состояла в сравнении экосистемного обмена CO_2, тепла и влаги в старовозрастном ельнике и на мезо-олиготрофном болоте, типичных экосистем для среднетаёжных ландшафтов европейской части России. Для измерения потоков вещества и энергии в приземном слое атмосферы использован метод микровихревых пульсаций. Согласно полученным данным, в тёплый период года ельник характеризовался более высоким радиационным балансом и турбулентным теплообменом с атмосферой, чем болото. В экосистеме болота более половины радиационного баланса в июле составили затраты на эвапотранспирацию. В тёплый период года ельник и болото выполняли функцию стока атмосферного диоксида углерода. Суммарный нетто-обмен CO_2 (*NEE*) в апреле–августе соответствовал -327 гС/м^2 в ельнике и -140 гС/м^2 на болоте, а суммарное испарение влаги (*ET*) – 324 и 300 мм. Для исследованных типов экосистем установлена тесная связь *NEE* и ET в суточной динамике (R^2 = 0,7–0,9). Среднесуточные значения нетто-обмена CO_2 в ельнике тесно коррелированны с радиационным балансом (R^2 = 0,63) и турбулентным теплообменом (R^2 = 0,57). Для мезо-олиготрофного болота факторы теплообмена оказались менее значимыми (R^2 = 0,38–0,45). Полученные данные могут быть использованы при прогнозировании процессов углеродного обмена и потоков влаги в таёжных экосистемах в связи с ожидаемым изменением климатических условий в регионе.

Ключевые слова: ельник, болото, обмен диоксида углерода, теплообмен, эвапотранспирация.

Boreal forest and peatland ecosystems play a key role in the global carbon and water cycle. Boreal forests occupy an area of 1135 • 10^6 ha and accumulate annually 0.5 • 10^{15} g of carbon. This is about 20% of all carbon stored in forests worldwide [1]. Peatland ecosystems area cover a much smaller area compared to forests, but they contain almost one-third of the global soil carbon [2]. Global temperature increase of the past decade has led to an enlargement in carbon stock in forests of the European Russia [1] and productivity of northern peatlands in recent decades due to climate change [3]. However, a further rise of temperature and the degradation of permafrost will turn large areas of forest and peatland in Subarctic to a carbon source by the end of this century [4, 5].

Forest and peatland ecosystems differ in the mass and energy exchange with the atmosphere. The amount of absorbed energy and its distribution to the turbulent heat and water vapor fluxes in the atmospheric boundary layer is largely dependent on the vegetation and wetting of the underlying surface [6, 7]. In turn, the carbon exchange of forest and peatland ecosystems is closely related to heat exchange [8–10].

In the European Northeast of Russia, dark coniferous forests predominate in the vegetation, the area of mires is about 8% [11]. According to climate predictions in this region, temperature and precipitation will be increasing up to the middle of this century [12], which may affect the energy and mass exchange of terrestrial ecosystems. However, to predict possible changes in the ecological functions of forest and peatland landscapes due to climate change, data from long-term stationary observations are needed. For the boreal ecosystems of Russia, such data are rare [13–15]. The purpose of this work was to compare the ecosystem CO_2, heat and water vapor exchange in boreal old spruce forest and meso-oligotrophic peatland during the snow free period. We assumed that structure of vegetation (botanic composition, height and biomass of plants) and degree of soil moisture will influence on energy participation and carbon dioxide and water vapor exchange in spruce and peatland ecosystems.

Methods and study sites

The investigation of CO_2 and H_2O exchange between the peatland or spruce forest and atmosphere was carried out using the eddy covariance method (EC), which determines the exchange rate of the gas across the interface between the atmosphere and the plant canopy by measuring the covariance between fluctuations in vertical wind velocity and the mixing ratio of the gas being studied [16].

There are two EC systems established for measuring energy and mass exchange in the European North-East of Russia: one in spruce forest at the Lali forest station of the Institute of Biology of Komi Science Center (62°16' N, 50°41' E) and the second at the mesooligotrophic peatland Medla-Pev-Nyur (61°56' N, 50°13' E), situated in the northern direction from Syktyvkar. The distance between them is about 40 km. A bilberry-grass spruce, a bilberry sphagnum spruce and a mixed coniferous stand develop within the forest area. Their more detailed characteristics are presented in [17, 18]. Spruce stand is dominated by *Picea obovata* Ledeb., there are also *Pinus sylvestris* L., *Abies sibirica* Ledeb., *Betula pubescens* Ehrh., *Populus tremula* L. The height of spruce trees is 22 m, their age varies from 80 to 215 years. The measurement area of mesooligotrophic peatland is dominated by the following plant communities: oligotrophic pine-shrub-cotton grass-sphagnum type, mesotrophic shrub-grass-sphagnum type and mesotrophic grass-moss type. More information on the characteristics of peatland vegetation was presented in [14, 19].

The data of EC measurements from 1st of April to 31st of August 2013 are presented in this article. The system was installed in 3 m height in the peatland and included an ultrasonic anemometer (CSAT 3D, Campbell Scientific Inc., USA) and an open-path CO_2 and H_2O gas analyser (Li-7500A, Li-Cor Inc., USA). An ultrasonic anemometer (Wind Master, Gill Instruments Ltd, USA) and an open-path CO_2 and H_2O gas analyser (EC-150, Campbell Scientific Inc., USA) was installed in 30 m height in the spruce forest.

The pulsations recorded by the instruments do not characterize the only point in which the measuring instruments are located, but a certain area around this point, which is called a footprint and can be calculated using models. The size of this area is determined by the speed and direction of the wind, as well as the height of the instruments and the average height of the vegetation. Thus, the EC estimates the gases and heat fluxes, spatially averaged to the scale of the ecosystem. The analysis of the footprint showed that in the spruce forest 76% of the data points and 90% of the total volume of air flow, which was used by the system to calculate the flow of CO_2 (F_{CO2}) and H_2O (ET), was formed at the distance of less than 200 m from the eddy tower, in 90% of all cases the maximum air flow came from a distance of less than 100 m. The wind directions during the summer were mainly S-W or S.

The raw data were logged at 20 Hz and calculated in the LoggerNet software (Campbell Scientific Inc., USA) and the EddyPro software (Li-Cor Inc., USA) in accordance with the generally accepted method of statistical processing of data [20]. At the next step data points of EC fluxes over 30 min intervals, which were obtained during unstable operation of gas analyser, low turbulence and unstable environment were removed.

At the next step the quality of the selected data was evaluated according to the ratio of Monin-Obukhov surface-layer scaling parameter (z/L) and footprint ($d_{fetch70}$) to friction velocity (u*) at the moment of measurement. The critical value of u* was 0.2 m/s for the spruce forest and 0.1 m/s for the peatland. Often, these were night-time measurements when the turbulence of the atmospheric boundary layer is low. At the final stage the data was checked visually, and poor data that had not previously been detected were removed from the dataset. In total, 5286 data points of 30-minute measurements for the forest and 7344 data points for the peatland were used in statistical analysis.

The calculated flux of carbon dioxide F_{CO2} is equivalent to the net exchange of CO_2 (NEE), which represents the sum of two different processes: gross-photosynthesis (P_{gross}) and ecosystem respiration (R_{eco}) [21]:

$$NEE = P_{gross} + R_{eco}. \quad (1)$$

In this study, the NEE will have a positive sign if R_{eco} exceeds P_{gross}, and negative if P_{gross} exceeds R_{eco}. NEE with "–" sign indicates an uptake of CO_2 by the ecosystem from the atmosphere and with the "+" sign indicates upward fluxes e.g. emission from the ecosystems to the atmosphere.

Additional parameters (relative humidity and temperature of air and soil, radiation) were recorded at automatic weather stations on both sites.

The net radiation at the atmospheric boundary surface can be expressed by the equation [22]:

$$R_n = H + LE + G, \quad (2)$$

where R_n – net radiation, H – turbulent sensible heat flux, LE – turbulent latent heat flux, G – ground heat flux. During the investigation period this quality target was achieved in 84%.

It is assumed that R_n and G with the sign "+" correspond to the direction of heat fluxes from the atmosphere to the earth's surface, and H and LE with the sign "+" – from the surface to the atmosphere .

Total evapotranspiration (ET) is calculated in accordance with the equation:

$$ET = LE / \lambda, \quad (3)$$

where λ is the heat of vaporization at 20 °C equal 2.45 MJ/kg.

The total flow of CO_2 and water vapor over a time was calculated as an integral with a 30-minute measurement step. The gaps were filled using average values calculated for a given time of a 15 days period.

Results and discussion

Weather conditions during the measurements. In 2013, the cold weather persisted until mid-March. The average daily temperatures above zero were recorded after 13th April. In the forest snow was gone by the beginning of May, and on the peatland by 20th April. The weather in April and May was warm, in June the average daily air temperature exceeded the long-term average (1965–2012 years) by 3.4 °C (Table 1).

Warm weather was observed in July and August, but a short-term drop in air temperature to 13 °C was measured at the end of July. The duration of the growing season (when the average daily air temperature exceeded 5 °C) was 146 days. The precipitation during the investigation period was about 160 mm, or 30% of the annual amount in 2013.

Heat fluxes at the atmospheric boundary surface. The structure of the vegetation effects the absorbing solar radiation and heat energy, and its transformation into turbulent fluxes.

Table 1

Average monthly air temperature and precipitation in 2013*

Month	Temperature, °C		Precipitation, mm/month	
	average	deviation**	in total	deviation**
April	2.2	1.0	15.3	−16.6
May	8.9	0.8	38.6	−2.1
June	17.4	3.4	34.9	−3.4
July	19.5	2.4	31.3	−41.2
August	16.2	2.5	40.2	−19.1

*Note: * – according to Rosgidromet for Syktyvkar station (http://rp5); ** – deviation from the long-term average for the period 1961–1990.*

Higher roughness of vegetation in forests decrease the wind speed and increase the turbulent heat exchange between the atmosphere and spruce stand [22]. As a result, the average daily air temperature over the forest in May-August was higher than over the peatland, the difference reached 5 °C on some days (Fig. 1).

At the same time, the temperature of the soil in spruce forest was lower than in the peatland, as a result of the shielding effect of tree crowns, which hamper the solar radiation to penetrate of under the canopy.

The albedo was lower in the forest (0.07–0.12), because the crown of spruce trees is characterized by a lower reflectivity than the other plants (Fig. 2). This is associated with a higher net radiation (R_n) of spruce forest (Fig. 3) and, consequently, higher energy exchange, compared to a peatland ecosystem.

The change from negative to positive net radiation in the forest and on the peatland was registered at the end of March, when the snow cover still remained. During the growing season the maximum of the net radiation was in late June – early July, and R_n was twice higher in the forest compared to the peatland. There was a short-term decline in the net radiation in both ecosystems in late July, which could be due to a short-term decrease of temperature.

During the growing season spruce forest was characterized by higher values of turbulence heat exchange *(H)* than the peatland (Fig. 3). Daily values of *H* in the forest ecosystem reached 225 W/m², while at the peatland they did not

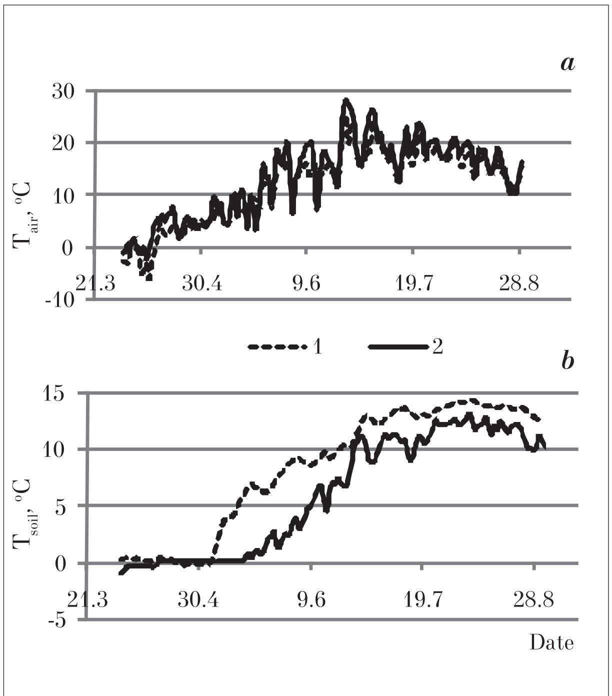

Fig. 1. Seasonal variation of average daily temperature at the atmospheric boundary surface (*a*) and the soil temperature at a depth of 20 cm (*b*): 1 – peatland, 2 – spruce forest

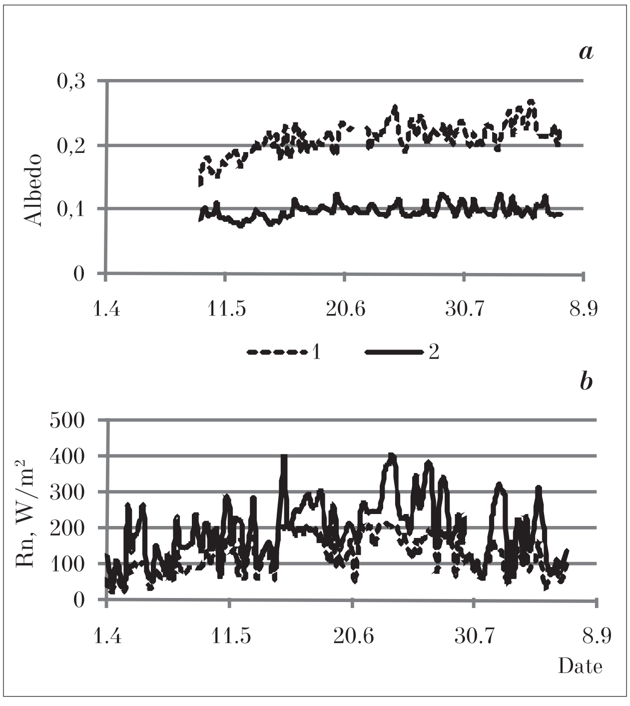

Fig. 2. Seasonal course of the average daily albedo (*a*) and the net radiation (*b*) at the boundary surface of atmosphere: 1 – peatland, 2 – spruce forest

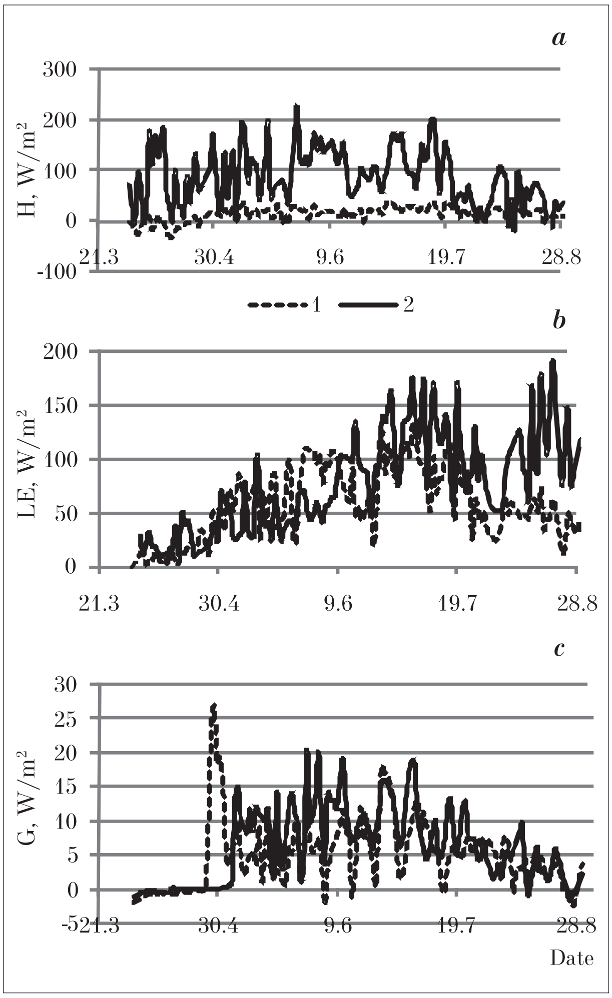

Fig. 3. Seasonal variation of the average daily turbulent heat flux (*a*), latent heat flux (*b*) and ground heat flux (*c*) in peatland (1) and spruce forest (2)

exceed 40 W/m^2. Turbulent heat exchange in July was about 60% of the net radiation in the spruce forest, and 20% in the peatland. Thus, the latent heat flux exchange (*LE*) at the peatland rised to 70%. There was a short-term decline in *LE* and *H* due to a decrease in R_n. In the summer the heat exchange in the soil (*G*) of the forest and peatland was less than 10% of R_n. At the peatland site there we could observe some exceptions (in April) where it reached 25%.

Thus, the studied ecosystems show differences in the net radiation and its components. As the summer evaporation was not limited by the availability of soil moisture at the peatland ecosystem, *LE* exceeded *H* significantly, in contrast to the spruce forest (Fig. 4). At the peatland average daily values of the ratio *H/LE* (*Bowen* ratio) was 0.2–0.4 in July. In the spruce forest, *Bowen* ratio had its maximum in spring, during the summer it gradually decreased, reaching 0.4–0.5 in July. According to the available results of EC measurements from other forest ecosystems, *Bowen* ratio can vary from 0.42 to 1.21 in summer, depending on the weather conditions [23]. For the northern peatlands of the European Russia in the summer, the ratio *H/LE* was 0.33–0.63 [28], and in Siberia – 0.3 [7].

Net ecosystem exchange CO_2. Net ecosystem exchange CO_2 (*NEE*) is a result of two processes – photosynthesis and respiration. We measured differences in diurnal and seasonal course of *NEE* in the spruce forest and peatland ecosystems. In spring 2013 the conversion of the spruce forest from the source to the CO_2 sink was observed at the beginning of April, and at the peatland in May (Fig. 5). Autumn conversion of ecosystems from uptake to CO_2 emission was registered in late August. The rate the CO_2 fluxes increased in the first part of the season. The maximum *NEE* was measured in July in the spruce forest and at the peatland –0.6 mgCO_2/(m^2 • s) and –0.1 mgCO_2/(m^2 • s), respectively. However, these ecosystems did not differ in duration of carbon dioxide uptake during the daytime. Cumulative average daily *NEE* in April–August varied in the spruce forest in the range –0.2 to –16.6 gCO_2/(m^2 • d) (or –0.06 to –5.0 gC/(m^2 • d) (Table 2). Other studies reported different *NEE* values for the snow free season e.g. the average daily *NEE* value in the European southern taiga spruce forest was –1.82 gC/(m^2 • d) [15], in spruce forests of Siberia –8 gC/(m^2 • d) [25], and in North America – –5 to –6 gC/(m^2 • d) [26].

NEE at the peatland varied from 0.78 to –1.94 gCO_2/(m^2 • d) at the beginning of the measurements and increased to –9.29 gCO_2/(m^2 • d) at July – the time of most favorable temperature and light conditions for photosynthesis (Table 2). The mean diurnal CO_2 exchange decreased gradually in August. Thus, during the observation period the peatland ecosystem functioned as a sink of

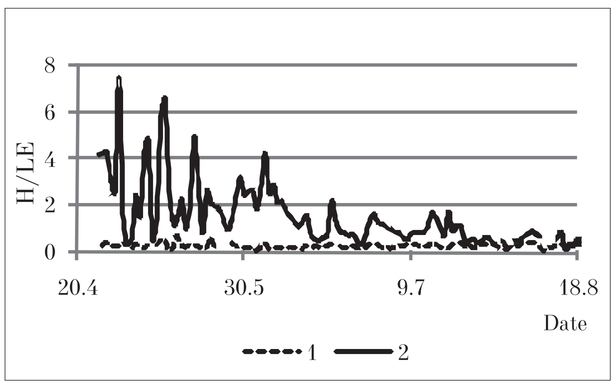

Fig. 4. The seasonal course of *Bowen* ratio at the boundary surface of atmosphere: 1 – peatland, 2 – spruce forest

Table 2

Cumulative value of *NEE* ($gCO_2/(m^2 \cdot d)$) and evapotranspiration (mmH_2O/d) in peatland and spruce forest ecosystems in April–August 2013

Month	Peatland		Spruce forest	
	NEE	*ET*	*NEE*	*ET*
April	0.782	0.250	–0.198	0.376
May	1.239	2.156	–10.077	1.049
June	–1.941	3.093	–10.302	1.798
July	–9.294	0.237	–16.684	3.056
August	–2.289	1.684	–2.884	2.239

atmospheric carbon. Our continuous eddy covariance flux observations were also compared to data from studies of peatlands in Canada [27] and Russia [28].

Thus, the studied spruce forest and the meso-oligotrophic peatland differed in the rate of daily *NEE*, which affected the balance of *NEE* during the warm period of the year. The cumulative sum of *NEE* in April–August 2013 was –1.089 gCO_2/m^2 in the spruce forest or –327 gC/m^2, which is comparable with the data obtained in the research of boreal spruce forest in Siberia (–270 gC/m^2; [25]) and in North America (–174 gC/m^2; [26]), and green moss spruce forest in the southern taiga in European Russia (–300 $gC/(m^2 \cdot year)$; [15]).In general, the average value of *NEE* in forest at the age of 200 years and older can reach –240 g $C/(m^2 \cdot year)$ [29] .

NEE of the peatland from 1st April to 31st August 2013 was –468 g of CO_2/m^2 (or –140 gC/m^2), which is comparable to the results obtained for Greenland boreal bogs (–310 – –372 gCO_2/m^2 [30]). The data was higher than observed at the mesotrophic swamp in the north of Finland (–186 – –217 gCO_2/m^2 [26]) and oligotrophic bogs of western Siberia (–132.44 – –133.32 gCO_2/m^2 [28]). *NEE* at peatlands of different regions can vary from 22 $gC/(m^2 \cdot year)$ to 144 $gC/(m^2 \cdot year)$ [31].

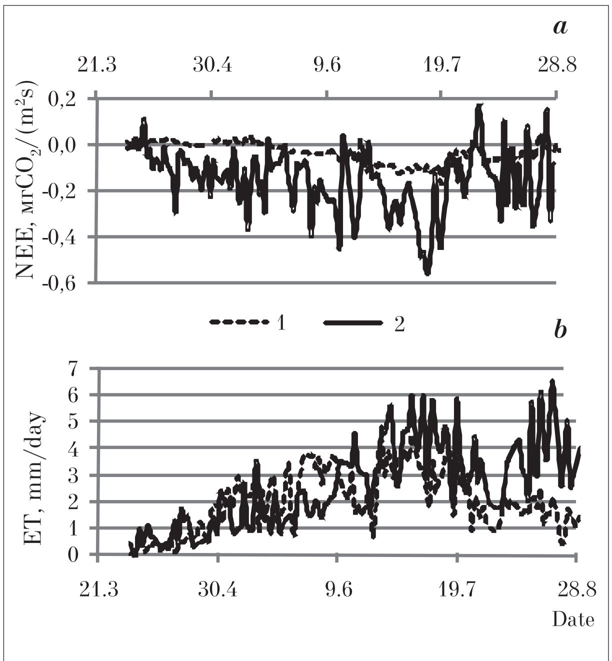

Fig. 5. The seasonal dynamic of the average daily net exchange CO_2 (*a*) and evapotranspiration (*b*) at the boundary surface of atmosphere. 1 – peatland, 2 – spruce forest

Evapotranspiration. The total evaporation or evapotranspiration (*ET*) of a terrestrial ecosystem is the result of two processes – physical evaporation of water from surfaces and transpiration of plants. In dark coniferous forests in the European North, transpiration reaches 80% of the total evaporation [27]. According to EC measurements evapotranspiration in ecosystems is mainly controlled by the stomatal conductance, which is strongly dependent on the moisture content of the atmosphere [32]. Evapotranspiration is characterized by interannual variability, e.g. in the coniferous forests of North America it varied between 230 mm and 305 mm [10] and was mostly independent on the amount of precipitation.

The spruce forest and the mesooligotrophic peatland differed in the availability of soil moisture. The volumetric water content of the upper soil in the spruce forest (0–20 cm) was 0.4 m^3/m^3 in April-May and gradually decreased at the end of July to 0.1 m^3/m^3. The water level at the peatland was 2 cm below the surface in May, dropped to –21 cm in July, its minimum of 27 cm was measured in late August.

In our study in May and June, the time of high ground water level, the average monthly value of evapotranspiration (*ET*) at the peatland was in 1.5–2 times higher compared to spruce forest (Fig. 5, Table 2).Water vapor fluxes markedly decreased in July, when the level of ground water did not exceed 20 cm, and in August, it was close to the values obtained for spruce. Maximum daily values of evapotranspiration (3 mm/d) in the peatland were observed in June, and in spruce forest in July. It was shown that the absolute values of *ET* for different mire types can vary within the range of 2–15 mm/day. This variation is determined by local climate and wetland characteristics rather than by location [6].

The evapotranspiration of the investigation period differed slightly between the peatland and spruce forest and was 300 mm and 324 mm, respectively. Other studies showed the interannual variation of evapotranspiration, e. g. at the peatland of Canada it was 348–458 mm and in spruce forest – 238–325 mm [10], at pine forests in Finland 218–361 mm [26]. Chebakova et al. [7] reported 235 mm for an oligotrophic peatland in Siberia and Kurbatova et al. [24] 320 mm for the ombrotrophic peatland in European Russia. In the annual cycle, the total evaporation in boreal ecosystems is not a constant value and in some years it can significantly exceed the precipitation [33]. In a dry summer, evaporation is higher than in wet years.

The strong correlation between *NEE* and *ET* was observed in the spruce forest and peatland ecosystems (R^2 = 0.7–0.9). This confirms existing hypotheses about stomatal regulation of photosynthesis and water vapor exchange between the atmosphere and the ecosystem [9, 10]. This explains also that the water use efficiency in terrestrial ecosystems is relatively constant in different years [10]. The average daily values of net CO_2 exchange in spruce forests are closely correlated with the net radiation (R^2 = 0.63) and turbulent heat exchange (R^2 = 0.57). For the meso-oligotrophic peatland, heat transfer factors turned out to be less significant (R^2 = 0.38–0.45). The leaf area index and *pH* of the water are more appropriate predictors of carbon exchange of northern peatlands [31]. Obviously, the strength of correlation between *NEE* and climatic factors during the snow free period is determined by the weather conditions, so it can vary from year to year.

Conclusion

Our EC measurements showed that ecosystem CO_2, heat and water vapor exchange differ in the boreal spruce forest and in the mesooligotrophic peatland. In the peatland ecosystem, which is characterized by excessive moisture and no water resource limitation, 70% of the net radiation was spent on evapotranspiration. Evapotranspiration in the spruce forest was much lower, and turbulent heat exchange reached 60% of the net radiation. The studied spruce forest and mesooligotrophic peatland functioned as carbon sink during the vegetation period. Net ecosystem exchange of CO_2 from 1st April to 31st August was −327 gC/m² in the spruce forest and −40 gC/m² in the peatland, and the total evapotranspiration was 324 mm and 300 mm, respectively. A close correlation was established between NEE and ET in daily dynamics (R^2 = 0.7–0.9). The average daily values of net exchange CO_2 in spruce forests are closely correlated with the net radiation (R^2 = 0.63) and turbulent heat exchange (R^2 = 0.57). For the meso-oligotrophic peatland, heat transfer factors turned out to be less significant (R^2 = 0.38–0.45). The obtained data can be used to predict carbon exchange processes and water vapor fluxes in terrestrial ecosystems due to expected climate changes in the region.

The studies were supported by the UNDP/GEF project "Strengthening Protected Area System of the Komi Republic to Conserve Virgin Forest Biodiversity in the Pechora Headwaters Region" No. 00059042, project of the Ural Branch of the Russian Academy of Sciences "Vertical fluxes of carbon-containing greenhouse gases in the boreal forest and peatland ecosystems at present climate" No. 18-4-4-17. The authors thank Mikhail Miglovets for assistance in the collection of field data, and Sergei Shvetsov and Sergey Kuzin for technical assistance.

References

1. Pan Y., Birdsey R., Fang J., Houghton R., Kauppi P., Kurz W., Phillips O., Shvidenko A., Lewis S., Canadell J., Ciais Ph., Jackson R., Pacala S., McCuire A.D., Piao Sh., Rautiainen A., Sitch S., Hayes D. A large and persistent carbon sink in the world's forests // Science. 2011. V. 333. P. 998–993. doi: 10.1126/science.1201609

2. Gorham E. Northern peatlands: role in the carbon cycle and probable responses to climatic warming // Ecol. Appl. 1991. V. 1. P. 182–195.

3. Yu Z.C. Northern peatland carbon stocks and dynamics: a review // Biogeosciences. 2012. V. 9. P. 4071–4083. doi: 10.5194/bg-9-4071-2012

4. Tarnocai C., Canadell J.G., Schuur E.A.G., Kuhry P., Mazhitova G., Zimov S. Soil organic carbon pools in the northern circumpolar permafrost region // Global Biogeochemical Cycles. 2009. V. 23. P. gb2023. doi: 10.1029/2008GB003327

5. Gauthier S., Bernier P., Kuuluvainen T., Shvidenko A.Z., Schepaschenko D.G. Boreal forest health and global change // Science. 2015. V. 349. P. 819–822. doi: 10.1126/science.aaa9092

6. Lafleur P.M. Connecting atmosphere and wetland: energy and water vapour exchange // Geography Compass. 2008. V. 2 (4). P. 1027–1057. doi: 10.1111/j.1749-8198.2007.00132.x

7. Chebakova N.M., Vygodskaya N.N., Arnet A., Belelli-Markezini L., Kolle O., Kurbatova Yu.A., Parfyonova E.I., Valentini R., Vaganov E.A., Shul'ce E.-D. Energy and mass exchange and productivity the main ecosystems in Siberia 1. Structure of heat balance during vegetation // Izvestiya RAN. Seriya Biologicheskaya. 2013. No. 6. P. 727–737 (in Russian). doi: 10.7868/S0002332914010044

8. Amiro B.D., Barr A.G., Black T.A., Iwashita H., Kljun N., McCaughey J.H., Morgenstern K., Murayama S., Nesic Z., Orchansky A.L., Saigusa N. Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada // Agricultural and Forest Meteorology. 2006. V. 136. P. 237–251. doi: 10.1016./j.agroformet.2004.11.012

9. McCaughey J.H., Pejam M.R., Arain M.A., Cameron D.A. Carbon dioxide and energy fluxes from a boreal mixedwood forest ecosystem in Ontario, Canada // Agricultural and Forest Meteorology. 2006. V. 140. P. 79–96. doi: 10.1016/j. agroformmet.2006.08.010

10. Brummer Ch., T. Black A., Jassal R., Grant N., Spittlehouse D., Chen B., Nesic Z., Amiro B., Arain M.A., Barr A., Bourque Ch., Coursolle C., Dunn A., Flanagan L.B., Humphreys E., Lafleur P., Margolis H., McCoughey J.H., Wofsy S. How climate and vegetation type influence evapotranspiration and water use efficiency in Canadian forest, peatland and grassland ecosystems // Agricultural and Forest Meteorology. 2012. V. 153. P. 14–30. doi: 10.1016/j.agroformet.2011.04.008

11. Forests of Komi Republic. Syktyvkar: DiK, 1999. 332 p. (in Russian).

12. The second assessment report of Roshydromet on climate change and its consequences on the territory of the Russian Federation. Moskva: Roshydromet, 2014. 58 p. (in Russian).

13. Chebakova N.M., Vygodskaya N.N., Arnet A., Bellely-Markesini L., Kurbatova Yu.A., Parfenova E.I., Valentini R., Verkhovets S.V., Vaganov E.A., Schulze E.-D. Energy and mass transfer and productivity of the main ecosystems in Siberia (according to the results of measurements by the method of turbulent pulsations). 2. Carbon exchange and productivity // Izvestiya RAN. Seriya biologicheskaya. 2014. No. 1. P. 65–75 (in Russian). doi: 10.7868/S000233291306009

14. Schneider J., Kutzbach L., Wilmking M. Carbon dioxide exchange fluxes of a boreal peatland over a complete growing season, Komi Republic, NW Russia // Biogeochemistry. 2011. doi: 10.107/s10533-011-9684-x

15. Zamolodchikov D.G., Gitarsky M.L., Shilkin A.V., Marunich A.S., Karelin D.V., Blinov V.G., Ivaschenko A.I. Monitoring of cycles of carbon dioxide and water vapor at the "Log Taiga" polygon (Valdai National Park) // Fundamentalnaya i prikladnaya klimatologiya. 2017. V. 1. P. 54–68 (in Russian). doi: 10.21513/2410-8758-2017-1-54-68

16. Baldocchi D.D., Hincks B.B., Meyers T.P. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods // Ecology. 1988. V. 69. No. 5. P. 1331–1340 (in Russian).

17. Bioproduction in forest ecosystems of the North. Sankt-Peterburg: Nauka, 2011. 278 p. (in Russian).

18. Indigenous spruce forests of the North: biodiversity, structure, functions. Sankt-Petersburg: Nauka, 2006. 337 p. (in Russian).

19. Miglovets M.N., Zagirova S.V., Mikhailov O.A. Methane emission in plant communities of the middle taiga meso-oligotrophic bog // Theoretical and Applied Ecology. 2014. No. 1. P. 93–98 (in Russian). doi: 10.25750/1995-4301-2014-1-092-098

20. Vickers D., Mahrt L. Quality control and flux sampling problems for tower and aircraft data // Journal of atmospheric and oceanic technology. 1997. V. 14. P. 512–526.

21. Greco S., Baldocchi D.D. Seasonal variations of CO_2 and water vapor exchange rates over a temperate deciduous forest // Global Change Biology. 1996. V. 2. P. 183–197.

22. Pavlov A.V. Energy exchange in the landscape sphere of the Earth. Novosibirsk: Nauka, 1984. 254 p. (in Russian).

23. Launianen S. Seasonal and inter-annual variability of energy exchange above a boreal Scots pine forest // Biogeosciences. 2010. V. 7. P. 3921–3940. doi: 10.5194/bg-7-3921-2010

24. Kurbatova J., Atneth A., Vygotskaya N., Kolle O., Varlagin A., Milyukova I., Tchebakova N., Schulze E.-D., Lloid J. Comparative ecosystem-atmospere exchange of energy and mass in a European Russian and a central Siberian bog 1. Intersesonal and interannual variability of energy and latent heat fluxes during the snowfree period // Tellus B: Chemical and Physical Meteorology. 2002. No. 54B. P. 497–513 (in Russian). doi: 10.3402/tellusb.v54i5.16683

25. Röser C., Montagnani L., Schulze E.-D., Mollicone D., Kolle O., Meroni M., Papale D., Marchesini L.B., Federici S., Valentini R. Net CO_2 exchange rates in three different succession stages of "dark taiga" of central Siberia // Tellus. 2002. No. 54B. P. 642–654.

26. Hollinger D.Y., Aber J., Dail E., Davidson E.A., Goltz S.M., Hughes H., Leclerc M.Y., Lee J.T., Richardson A.D., Rodrigues C., Scott N.A., Achuatavarier D., Walsh J. Spatial and temporal variability in forest-atmosphere CO_2 exchange // Global Change Biology. 2004. V. 10. P. 1689–1706. doi: 10.1111/j.1365-2486.2004.00847.x

27. Lafleur P.M., Roulet N.T., Bubier J.L., Frolking S., Moore T.R. Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog // Global biogeochemical Cycles. 2003. No. 17 (2). doi: 10.1029/2002GB001983

28. Arneth A., Kurbatova J., Kolle O., Shibistova O.B., Lloyd J., Vygodskaya N.N., Schulze E.-D. Comparative ecosystem-atmosphere exchange of energy and mass in a European Russian and a central Siberian peatland II. Interseasonal and interannual variability of CO_2 fluxes // Tellus. 2002. No. 54B. P. 514–530. doi: 10.1034/j.1600-0889.2002.01349.x

29. Luyssaert S., Schulze E.-D., Börner A., Knohl A., Hessenmöller D., Law B., Ciais P., Grace J. Old-growth forests as global carbon sinks // Nature. 2008. V. 455. P. 213–215. doi: 10.1038/nature07276

30. Nordstroem C., Soegaard H., Christensen T.R., Friborg T., Hansen B.U. Seasonal carbon dioxide balance and respiration of a high-arctic fen ecosystem in NE-Greenland // Theoretical and Applied Climatology. 2001. V. 70. P. 149–166.

31. Lund M., Bjerke J.W., Drake B.G., Engelsen O., Hansen G.H., Parmentier F.J.W., Powell T.L., Silvennoinen H., Sottocornola M., Tømmervik H., Weldon S., Rasse D.P. Low impact of dry conditions on the CO_2 exchange of a Northern-Norwegian blanket peatland // Environment Research Letters. 2015. No. 10. doi: 10.1088/1748-9326/10/2/025004

32. Kasurinen V., Alfredsen K., Kolari P., Mammarella I., Alekseychik P., Rinne J., Vesala T., Bernier P., Boike J., Langer M., Bellelli Marshesini L., Huisstened K.V., Dolman H., Sachs T., Ohta T., Varlagin A., Rocha A., Arain A., Oechel W., Lund M., Grelle A., Lindroth A., Black A., Aurela M., Laurila T., Lohila A., Berninger F. Latent heat exchange in the boreal and arctic biomes // Global Change Biology. 2014. V. 20. P. 3439–3456. doi: 10.1111/gcb12640

33. Barr A., Black T., Hogg E., Griffits T., Morgenstern K., Kljun N., Theede A., Nesic Z. Climatic controls on the carbon water balances of a boreal aspen forests, 1994–2003 // Global Change Biology. 2007. V. 13. P. 561–576. doi: 10.1111/j.1365-2486.2006.01220.x