Modeling of the net ecosystem exchange, gross primary production, and ecosystem respiration for peatland ecosystems of Western Siberia

E A Dyukarev¹², E D Lapshina², E A Golovatskaya¹, N V Filippova², E A Zarov², and I V Filippov²

¹Institute of Monitoring of Climatic and Ecological System of the Siberian Branch of Russian Academy of Sciences, Akademicheskii 10/3, Tomsk, Russia
²Yugra State University, Chekhov st. 16, Khanty-Mansiysk, Russia

egor@imces.ru

Abstract. Observed and simulated carbon dioxide fluxes in oligotrophic peatlands of Western Siberia are discussed. Net ecosystem exchange, gross primary production, and ecosystem respiration are measured at a ridge-hollow complex in the South Taiga zone (Bakchar bog – field station “Vasjuganie”) and Middle Taiga zone (Mukhrino bog - field station “Mukhrino”). A model of net ecosystem exchange is used to study the influence of different environmental factors and to calculate daily the growing season carbon budget for an oligotrophic bog. The model uses the air and soil temperature, the incoming photosynthetically active radiation, and the leaf area index as the explanatory factors for gross primary production, heterotrophic and autotrophic respiration. The model coefficients are calibrated using data collected by an automated soil CO₂ flux system with a clear long-term chamber. The studied ecosystems are sinks of carbon according to modelling and observation results.

1. Introduction
Peatland ecosystems play a significant role in the global carbon cycle, being sources and sinks of greenhouse gases [1,2]. In Western Siberia peatlands occupy over 30% of the area [3-5]. According to IPCC estimates [2], the methane emissions from natural mires are 61-82% of all natural sources of methane. The intensity of greenhouse gas flows is controlled by the hydrological and thermal regime of the peat deposit [6-8].

The gaseous exchange between the atmosphere and the peatlands is dominated by photosynthetic fixation of CO₂ from the atmosphere and by the soil and vegetation respiration losses of CO₂. The balance between them is known as the net ecosystem exchange (NEE) of CO₂ [9, 10]. The other major gaseous loss of C into the atmosphere is CH₄, which is produced via anoxic decay of the soil organic matter [8, 11]. The loss of C into the fluvial system occurs via export of dissolved and particulate organic carbon and dissolved gases (CO₂ and CH₄). The rise in the surface air temperature [2,12] and the lowering of the water levels cause peat drying, temperature increase and aeration, which contributes to the growth of greenhouse gas emissions [12,13]. Peatland ecosystems in different years can serve as both a source and a sink of carbon [14,15]. The variety of direct and inverse relationships existing between the components of the peatlands and the surrounding areas indicates a complex nonlinear nature of the impact of peatlands on the environment in different geographic and...
2. Materials and methods
Carbon dioxide fluxes were measured using an automatic transparent chamber and an infra-red gas analyzer at two oligotrophic peatland complexes in southern and middle taiga zones of Western Siberia on the basis of the field stations “Mukhrino” (Yugra State University, Khanty-Mansiysk) and “Vasjuganie” (Institute of Monitoring of Climatic and Ecological System SB RAS, Tomsk).

2.1. Mukhrino field station
The study of the functioning of the bog ecosystems in the middle taiga zone of Western Siberia was carried out on the basis of the international scientific field station “Mukhrino” founded in 2009 [22]. The necessary supporting infrastructure was constructed for comprehensive research of the wetland ecosystems, the meteorological equipment was installed, and monitoring observations were launched. The field station is a part of the international network INTERACT and is actively used by Russian and foreign scientists.

The uniqueness of the Mukhrino field station is explained by the availability of two progressive systems for measuring carbon and energy flows: an automatic ground-based chamber system and an eddy-covariance system. Routine measurements of CO₂ and heat fluxes were made in 2015-2016 by the eddy-covariance system, at that time consisting of an anemometer Gill R3 and a gas analyzer LI-7500. The results of the first year of measurements were published in [23], where high quality of the data was shown. The surface heat balance is closed (the ratio of the outgoing to incoming heat is 107%), which further confirms the success of the measurements. According to various characteristics of the heat balance, the Mukhrino bog approaches other similar ecosystems in northern Europe and Canada. Relatively high photosynthetic assimilation of CO₂ was discovered, which is explained by unusually wet weather in 2015.

Automated monitoring of the carbon dioxide fluxes from the peatland surface was organized in 2017-2018 with the help of an autonomous atmospheric soil measuring system (ASMS) at the Mukhrino bog. The ASMS measured and recorded the following environmental parameters: the air temperature (Ta) and humidity (RH) (at a height of 2 m and at the surface), the incoming photosynthetic active solar radiation (PAR), the carbon dioxide content, and the water vapor in the atmosphere. The complex includes a two-channel gas analyzer Li-7000 (Li-COR Biogesosciences, USA) and two transparent measuring chambers with a volume of 120 l. The chambers are in the open...
state most of the time, and for flux measurements they are closed for 5-10 minutes every one-three hours. The air sample is continuously pumped through the chamber and the gas analyzer with the help of a powerful pump. The measurements of the concentration of CO₂ and H₂O, Ta, RH, and PAR are accumulated in the ASMS and transferred to the server.

2.2. Vasjuganie field station
The measurement site is located in the south of Western Siberia (Russia) at the Bakcharskoe bog (area: 1400 km²) in the interfluves of the Ikisa and Bakchar Rivers in Bakcharsky district of Tomsk region, Russia [24]. The observation site is arranged since 1999 at a mesoooligotrophic open sedge-sphagnum fen and ridge-hollow complex [15].

An automated soil CO₂ flux system LI-8100A (Li-Cor Biogeoscience, USA) with a transparent long-term chamber LI-8100-104 was used for carbon dioxide emission measurements during field campaigns in 2014-2015. The chamber was installed on a plastic cylindrical basement deepened into the peat to 15 cm. The vegetation cover under the chamber consists of mosses and sedges only. The carbon dioxide fluxes were estimated by increase of the CO₂ concentration in the chamber during an exposition. The exposition was 5 min, but only the first two minutes were used for the total flux calculation when the CO₂ concentration changes according to linear manner. The measurements were automatically repeated every 20 minutes. Simultaneous observations of the air, the surface and peat temperatures, the incoming photosynthetically active solar radiation (PAR), the atmospheric pressure, the air water content, the water table level, and the precipitation were made.

The net primary productivity (NPP) was determined by the cutting method [2]. The above-ground biomass was measured by clipping 50x50 cm quadrates (three to five per site). Clipped plants were grouped according to their species and divided into living and dead biomass. The total dead biomass consists of litter and dead parts of mosses. The live biomass consists of the annual and perennial photosynthetic biomass (shrub leaves, green parts of herbs and mosses) and the nonphotosynthetic biomass (steam shrubs, roots of herbs and shrubs).

2.3. Mathematical modelling
To disseminate the obtained observation data to other periods of research and to calculate the annual carbon budget of the ecosystem, a model of total ecosystem exchange was proposed [21]. The measured total ecosystem exchange (NEE) was partitioned into the incoming (GPP) and expenditure (ER) components:

\[ \text{NEE} = \text{ER} - \text{GPP}. \]

The total ecosystem respiration was subdivided into heterotrophic respiration (HR) and autotrophic respiration (AR). The plant parts and microbes have different temperature sensitivities, and temporal decoupling of autotrophic and microbial processes might, therefore, enhance the model of the temperature response of respiration. Each respiration component was modeled using an exponential equation (2-3) widely used for explanation of ER variations [25-27]:

\[ \text{ER} = \text{HR} + \text{AR}; \]

\[ \text{HR} = E_H \times \exp(k_H \times T_a); \]

\[ \text{AR} = \text{LAI} \times E_A \times \exp(k_A \times T_a), \]

where \( T_a \) is the air temperature (°C), \( E_H \) and \( E_A \) are the basal levels of heterotrophic and autotrophic respiration at 0 °C, respectively, \( k_H \) and \( k_A \) are the temperature sensitivity coefficients. The air temperature was used as an explanatory factor. The autotrophic respiration started to increase proportionally to LAI with the growth of green vegetation.
A rectangular hyperbolic function was used for the light response of the GPP in the daytime [25-27]:

\[
GPP(PAR) = \frac{LAI \times \alpha \times PAR \times G_m}{(\alpha \times PAR + G_m)},
\]

where \( \alpha \) is the initial slope of the light response curve at low light (photosynthetic efficiency), \( G_m \) is the theoretical maximum rate of photosynthesis at infinite PAR (photosynthetic capacity).

In this study the NEE is negative when the GPP value exceeds the ER value and there is a net removal of carbon dioxide from the atmosphere. The NEE is positive when the ER value exceeds the GPP value and carbon dioxide is released from the ecosystem into the atmosphere. The NPP or carbon accumulated in plants during a year is positive according to [2].

3. Results and discussion

3.1. Mukhrino field station

Experiments on the calibration of the automated chamber system were performed from July 21 to July 25 in 2017 at ridge and hollow of a typical ridge-hollow complex. From July 25 to September 1, 2017 and in June 2018 the system operated in the measuring mode. The flux rates of CO\(_2\) and water were calculated using a specialized software module in the Matlab R2014b system (MathWorks, USA) using a linear model for changing the concentration in the chambers during the first two minutes of exposure.

![Figure 1. Monthly averaged diurnal variations of CO2 fluxes measured at ridge and hollow at Mukhrino field station.](image)

Analysis of the measurement results showed that, despite a significant difference in the structure of the vegetation cover, the ridge and hollow absorb carbon dioxide from the atmosphere, accumulating it in the form of organic matter of plants. The value of the total assimilation of CO\(_2\) on the ridge is much lower than in the hollow, and the average fluxes for the period under study are 112 and 18 mg CO\(_2\) m\(^{-2}\) h\(^{-1}\), respectively. The daily course of the carbon dioxide fluxes has a clear maximum in the night hours (23, 01 hours) when CO\(_2\) is released into the atmosphere and a minimum at 10-13 hours of the
day, when the CO₂ absorption by vegetation exceeds the ecosystem respiration [28]. The daily course of the fluxes obtained in the hollow in different summer months does not vary significantly (Fig. 1). On the ridge from June to August there is a slight decrease in the CO₂ absorption before noon and an increase in the emissions in the evening.

The change in the water content inside the chamber makes it possible to estimate the transpiration of moisture by the bog vegetation. It is found that the transpiration of water in June 2017 on the ridge and in the hollow increases from 2 to 12 gH₂O·m⁻²·h⁻¹ from midnight to 16:00. In July 2017, the transpiration for both observation points increases by 2-4 gH₂O·m⁻²·h⁻¹, and in August due to lowering of the air temperature the transpiration is reduced (Table 1).

Table 1. Monthly averaged carbon dioxide and water fluxes at ridge and hollow at Mukhrino field.

| Station | CO₂ flux, gC/m²·h | H₂O flux, mm·h⁻¹ |
|---------|-------------------|------------------|
| Hollow  | Ridge             |
| JUN 2017| -27.5             | 9.6              |
| JUL 2017| -19.8             | 17.0             |
| AUG 2017| -18.6             | 12.3             |
| JUN 2018| -8.2              | 6.4              |

3.2. Vasjuganie field station

The carbon dioxide flux measurements were conducted two times a month during daytime only. Intense field campaigns were on 15-17 July 2016 and 21-25 August 2016 for diurnal observation of the CO₂ fluxes. The net primary productivity (NPP) was determined by the cutting method in 2008-2011.

On average, the NPP at ridge and hollow have similar values of 295 and 270 g / m² per year (Table 2). The contribution of the underground production is 45 and 59%, and the production of sphagnum mosses is 20-37% on the ridge and hollow, respectively. On the ridges, the role of shrubs in the production is also great (32%). Measurement of the CO₂ emission has shown that, on average, the intensity of CO₂ emission is slightly higher in comparison with the hollow. The average emission intensity during the study period is 242 and 219 mgCO₂·m⁻²·h⁻¹. The results of the study have shown that, despite the differences in the composition of the vegetation, the average values of net primary production (NPP) are similar at oligotrophic mire sites.

Table 2. Net primary production (NPP, gC m⁻² yr⁻¹) and total CO₂ emission (Em, gC m⁻² yr⁻¹) in the ridge-moth complex and sedge-sphagnum fen at Vasjuganie field station.

| Year | Ridge | Hollow | Fen |
|------|-------|--------|-----|
|      | NPP   | Em     | NPP | Em     | NPP | Em     |
| 2008 | 345   | 224    | 367 | 188    | 230 | 238    |
| 2009 | 278   | 216    | 195 | 182    | 305 | 266    |
| 2010 | 267   | 194    | 233 | 164    | 261 | 254    |
| 2011 | 289   | 202    | 285 | 170    | 253 | 256    |

The model (1-4) was calibrated based on the field observations of carbon dioxide fluxes in 2008-2011. The proposed model allows calculating carbon dioxide fluxes for the studied ecosystems. The time course of the total annual values of the main components of the carbon balance is shown in Fig. 2.
The total ecosystem respiration is controlled by the air temperature and varies insignificantly during the study period. The emission fluxes of CO$_2$ at the hollow are by 30-60 gC m$^{-2}$ yr$^{-1}$ lower than at the ridge, but the total accumulation of carbon in the vegetation on the ridge is higher by 5-100 gC m$^{-2}$ yr$^{-1}$. The amount of carbon assimilation by vegetation during all years of the study is greater than the value of the total ecosystem respiration, and the accumulation of carbon is more intensive on the ridge. The hollow is a more "active" regulator and a more variable component of the carbon cycle of the bog compared to the hollow and fen. The interannual variability of the carbon balance and its components is higher on the hollow, which indicates higher sensitivity of the NEE to changes in the external parameters.

3.3. Comparison of CO$_2$ fluxes in south and middle taiga
The proposed model (1-4) allows one to simulate components of the carbon balance at peatlands using the above-described observation data. The multiply optimization procedure was performed in the MATLAB software using the fminsearch function. The minimum of the unconstrained multivariable function was found using the derivative-free method. The root-mean-square error was used as a minimizing function. There is a good agreement between the model output and the observations in the daytime, but it is not so satisfactory for the night period. The observed nighttime variations of the ecosystem respiration are much greater than the modeled ones.

|                | Vasjuganie |             | Mukhrino |             |
|----------------|------------|-------------|----------|-------------|
|                | Hollow     | Ridge       | Hollow   | Ridge       |
| GPP            | -305.2     | -373.3      | -250.5   | -207.4      |
| AR             | 18.9       | 82.9        | 25.8     | 44.8        |
| HR             | 151.6      | 118.1       | 103.1    | 76.2        |
| ER             | 170.5      | 201         | 128.9    | 121.0       |
| NEE            | -134.7     | -172.3      | -121.6   | -86.4       |
| NPP            | 286.3      | 290.4       | 224.7    | 162.6       |
Table 3 illustrates the results of modelling performed for 2017. The northern peatlands (the Mukhrino field station) have lower fluxes of carbon exchange, including both the incoming (GPP) and expenditure (ER) components. The ridge in the south taiga bog has stronger variations of carbon fluxes than the hollow, but in the middle taiga the variations of fluxes at the ridge are smoother than at the hollow.

4. Conclusions
A model of net ecosystem exchange was performed to study the influence of different environmental factors and to calculate daily the growing season carbon budget. The model uses air temperature, incoming photosynthetically active radiation, and leaf area index as the explanatory factors for gross primary production, heterotrophic and autotrophic respiration. The model coefficients were calibrated using data collected by an automated soil CO$_2$ flux system with a clear long-term chamber at an oligotrophic ridge-hollow complex and a mesotrophic open sedge-sphagnum fen on two peatlands in the south and middle taiga zones of Western Siberia. The results allow us to calculate different values of temperature sensitivity of heterotrophic and plant respiration. It indicates that the proposed model is a promising tool for better understanding of the ecosystem biogeochemical processes. The model can be applied to the simulation of intra-annual variations in CO$_2$ flux components in peatland ecosystems.

Acknowledgments
This study was carried out with support of a grant for the creation of leading scientific schools under the guidance of leading scientists in the priority areas of scientific research at Yugra State University on "Research and Simulation of the Response of Wetland Ecosystems in Western Siberia to Modern Climate Change and Anthropogenic Impact". The field works at the Vasjuganie field station were funded by the RFBR under project 16-45-700562. The field works at the Mukhrino field station were funded by the RFBR and the Government of the Khanty-Mansi Autonomous Region under project no. 18-44-860017.

References
[1] Rydin H and Jeglum J 2015 The Biology of Peatlands (Oxford. Univ. Press) p 400
[2] Ciais P, Sabine C, Bala G et al. 2013 Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA) p 1535
[3] Sheng Y, Smith L C, MacDonald G M et al. 2004 Glob. Biogeochem. Cycles 18 GB3004
[4] Terentieva I E, Glagolev M V, Lapshina E D et al. 2016 Biogeosciences 13 4615-4626
[5] Dyukarev E A, Pologova N N, Dyukarev A G and Golovatskaya E A 2011 Environ. Res. Lett. 6(3) 035203
[6] Glagolev M V, Ilyasov D V, Terentyeva I E et al. 2017 Atmospheric and Ocean Optics 30(4) 301-309
[7] Naumov A V 2009 Soil respiration (Novosibirsk, Izd SO RAN) p 208
[8] Veretennikova E and Dyukarev E A 2017 Russian Meteorol. and Hydrol. 42(5) 319–26 doi:10.3103/S1068373917050077
[9] Bubier J L, Crill P M, Mosedale A, Frolking S and Linder E 2003 Glob. Biogeochem. Cycles. 17(2) 1066
[10] Golovatskaya E A and Dyukarev E A 2012 Eurasian Soil Sci. J. 45(6) 588–97 doi:10.1134/S106422931206004X
[11] Saunois M, Bousquet P, Poulter B et al. 2016 Earth Syst. Sci. Data 8 697–751
[12] Baird A, Belyea L, Comas X, Reeve A and Slater L 2013 Carbon Cycling in Northern Peatlands (Geophysical Monograph Series, AGU) p 297
[13] The second assessment report of Roshydromet on climate change and their consequences on the...
territory of the Russian Federation 2014 (Federal service for Hydrometeorology and environmental monitoring) p 605

[14] Parazoo N C, Koven C D, Lawrence D M et al. 2017 The Cryosphere, 189

[15] Golovatskaya E A, Dyukarev E A, Ippolitov I I and Kabanov M V 2008 Rep. of the Russian Acad. of Sci. 418(1) 187–90

[16] Ratcliffe J L, Creevy A, Andersen R et al 2017 The Science of the Total Environment 607-608 816-828

[17] Peatlands of West Siberia. Their composition and hydrological regime 1976 (Leningrad, Hydrometeoizdat) p 615

[18] Vomperskiy S E 1994 The role of peatlands in carbon cycling. Biogeocenotic features of peatlands and their rational exploitation (Moscow, Nauka) 5-37

[19] Kabanov M V 2015 Geography and Natural Sciences 3 207-113

[20] Falge E, Baldocchi D, Olson R et al. 2001 Agric. For. Meteorol. 107 43–69

[21] Dyukarev E A 2017 Agric. For. Meteorol. 239 236–48 doi:10.1016/j.agrformet.2017.03.011

[22] Lapshina E D, Alexeychik P, Dengel S et al. 2015 Report series in aerosol science 236-240

[23] Alekseychik P, Mammarella I, Karpov D et al. 2017 Atmos. Chem. Phys. 17 9333-9345

[24] Dyukarev E A, Golovatskaya E A, Duchkov A D and Kazantsev S A 2009 Russian Geol. and Geoph. 50(6) 579–86

[25] Mäkelä A, Hari P, Berninger F et al. 2004 Tree Physiol. 24(4) 369–76

[26] Laine A, Riutta T, Juutinen S, et al. 2009 Ecol. Modell. 220 2646–55 doi:10.1016/j.ecolmodel.2009.06.047

[27] Kandel T P, Elsgaard L, Larke P E 2013 Bioenergy 5(5) 548–61 doi:10.1111/gcbb.1202

[28] Golovatskaya E A and Dyukarev E A 2011 Russian Meteorol. and Hydrol. 36(6)