Assessment of the carbon balance of treed bogs under climate change with observation and modelling data

E A Dyukarev1,2, Yu V Martynova1 and E A Golovatskaya1

1 Institute of Monitoring of Climatic and Ecological System of the Siberian Branch
Russian Academy of Sciences, 10/3 Akademicheskiy ave., Tomsk, 634055, Russia
2 Yugra State University, 16 Chekhov st., Khanty-Mansiysk, 628012, Russia

E-mail: egor@imces.ru

Abstract. Carbon dioxide fluxes in treed bogs in the South Taiga Zone of Western Siberia are estimated by using field data and a mathematical model calibrated against observation data. Forecasts of carbon balance under climate change are made by using the mathematical model.

1. Introduction

Peatland ecosystems play a significant role in the global carbon cycle, being sources and sinks of greenhouse gases (GHGs) [1, 2]. Despite covering a relatively small part of the Earth surface (about 3%), peatlands store a large amount of organic matter ranging between 500 and 700 billion tons of C [3, 4]. In Western Siberia peatlands occupy over 30% of the area [5-7]. According to IPCC estimates [1], the contribution of natural mires into the total natural methane emissions ranged between 61 and 82%. The intensity of GHG fluxes is controlled by different factors including the hydrological and thermal regime of the peat deposit [8-15].

The gaseous exchange between the atmosphere and peatlands is governed by photosynthetic fixation of CO₂ from the atmosphere and by soil and vegetation respiration losses of CO₂. The balance between them is known as the net ecosystem exchange (NEE) of CO₂ [10, 16, 17]. The rise in surface air temperature [18] and the lowering of water levels causes peat drying, increase of temperature and aeration, which contributes to the intensity of greenhouse gas emissions [19, 20]. Peatland ecosystems in different years can also serve as both a source and a sink of carbon [21, 22]. The variety of direct and inverse relationships existing between the components of peatlands and the surrounding areas indicates a complex nonlinear impact of the peatlands on the environment in different geographic, climatic, and geomorphological conditions [23-26]. Quantitative estimation of the rate of carbon exchange between peatlands and the atmosphere, as well as the revealing of environmental factors affecting carbon exchange, is an important scientific issue [5, 27].

The main purpose of this study is to assess CO₂ exchange fluxes in treed bogs in the South Taiga Zone in Western Siberia and to forecast carbon balance disturbances under climate change using a mathematical model.

2. Observation sites

Field studies of net primary production (NPP) and CO₂ emissions were carried out in the eastern part of the Ob-Irtysh interfluve, within the eastern margin of the Vasyugan Plateau in the Bakchar bog in 2008-2011 [21]. Oligotrophic peatland ecosystems with a narrow set of forming species have a
dominant position in the study area. Pine-shrub-sphagnum bogs (ryams) is the most widespread type of bogs in the south taiga subzone. They are confined to margins or well-drained slopes of bogs with surface slopes of 0.001 - 0.006 degrees. Pine-shrub-sphagnum bogs are also found in the most convex central parts of the peatlands. Observation points were organized in the tall ryam, low ryam, and drained low ryam.

The tall ryam is located at the margin of the Bakchar bog massif. The microrelief is presented by moss hummocks up to 50 cm high, occupying about 50% of the surface. The vegetation of tall ryam belongs to the pine-shrub-sedge-sphagnum association. The tree layer consists of pine (Pinus silvestris L.) with single trees of Pinus sibirica Mayr. and Betula pubescens Ehrh. The average height of the tree stand is 18 m, and the average diameter of the stems is about 20 cm. The projective cover of the tree cover is 90%. The shrub layer is well developed, the shrubs reach a height of 50 cm, and the projective cover is 90%. The dominants are Ledum palustre L., Chamaedaphne calyculata L., Vaccinium vitis-idea L., and cranberries (Oxycoccus microcarpus). Carex globularis L., Eriophorum vaginatum L., and Rubus chamaemorus L. are found in the grass cover. The dominants in the moss cover (96%) are sphagnum mosses (Sphagnum angustifolium). A small amount of green moss is found on the tree trunks, and lichens are present on the trunks of trees and shrubs. The peat deposit of the tall ryam is 1 m.

The tall ryam towards the center of the bog turns by the low ryam. The low ryam microrelief is wavy due to a large number of large moss hummocks about 30 cm high and up to 3 m in diameter. The low ryam vegetation belongs to the pine-shrub-sphagnum association with low pine trees. The oppressed tree layer is presented by Pinus silvestris f. Litwinowii. The average height of the trees is 2-3 m, and the average diameter of the stems is 3 cm. The shrub layer is developed abundantly on hummocks, and the total projective cover is 60-70%. The grass cover is composed of Ledum palustre L., Chamaedaphne calyculata L., Andromeda polifolia L., and Vaccinium uliginosum L. On the tops of the hummocks there grow small-fruited cranberries (Oxycoccus microcarpus Turcz.). The grass protective cover is less than 5%, and it is presented by Eriophorum vaginatum L., Rubus chamaemorus L., and Drosera rotundifolia L. Sphagnum fuscum Klinggr. dominates in the moss cover. The peat thickness in the low ryam is 2 - 3 m.

To reveal the effect of peatland drainage on the carbon balance of oligotrophic bogs, studies were performed at the drained low ryam at Vasyuganskoje peatland on the watershed plateau between the Bakchar and Iksa Rivers. The distance between the draining channels is 150 m, and the design drainage rate is 0.6 m. The phytocenosis of the drained area is also represented by pine-shrub-sphagnum vegetation and is characterized as a low ryam. The tree layer is formed by pine trees up to 2-3 m high, with a trunk diameter of 2-5 cm; the projective cover is 40%. In the surface cover there are abundant wild rosemary, cassandra, and blueberries (80%). Cotton grass is involved in the grass layer (5%). Sphagnum fuscum Klinggr. prevails in the moss cover. There are lichen stains occupying up to 20% of the surface. The thickness of the peat deposit is 2.5 m. The water content at the site is low, and the level of bog waters is 0.2 m and below.

3. Mathematical modelling
To obtain continuous data records, to extrapolate them to other periods when experimental data are missing, and to calculate the annual carbon budget of the ecosystem, a model of total ecosystem carbon exchange was proposed [28, 29]. The measured total NEE was partitioned into the incoming (GPP) and expenditure (ER) components [30-33]:

\[ NEE = ER - GPP; \]  \hspace{1cm} (1)

\[ ER = HR + AR; \]  \hspace{1cm} (2)
GPP is defined as the total amount of carbon fixed in the process of photosynthesis by plants in an ecosystem, while NEE refers to GPP minus ER. ER is the sum of plant respiration, or autotrophic respiration (AR) and heterotrophic respiration (HR).

It is well-known that the photosynthetic response under low light intensities is characterized by a linear response, and photosynthetic saturation is observed at high light intensities [34]. A rectangular hyperbolic function (3) is used for the light response of the NEE in the daytime [30, 31]:

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

where \(\alpha\) is the initial slope of the light response curve at low light (photosynthetic efficiency) (mg \(\mu\)mol\(^{-1}\)), and \(Gm\) is the theoretical maximum rate of photosynthesis at infinite PAR (photosynthetic capacity) (mg m\(^{-2}\) h\(^{-1}\)). Carbon dioxide fluxes are given in mg of CO\(_2\) per m\(^2\) per hour. The PAR is measured in \(\mu\)mol m\(^{-2}\) s\(^{-1}\). Possible GPP limitation at high air temperatures was not accounted for.

The respiration was modelled using an exponential equation (4) widely used for explanation of the ER variation [32, 33]:

\[
HR = E_0 \times \exp(k_T \times T_a);
\]

\[
AR = LAI \times k_A \times HR,
\]

where \(T_a\) is the air temperature (°C), \(E_0\) is the reference heterotrophic respiration (mg m\(^{-2}\) h\(^{-1}\)) at \(T_a = 0^\circ\)C; \(k_T\) is a coefficient describing the respiration temperature response (K\(^{-1}\)); \(k_A\) is the ratio of autotrophic respiration to heterotrophic one at LAI = 1.

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 the carbon dioxide is released from the ecosystem into the atmosphere.

A simple model was proposed for the seasonal changes in green phytomass (or LAI). The LAI is following variations in the mean decadual air temperature (Tm). At the beginning of the growing season (at the transition of Tm through 5 °C) the index is LAI = 0.5. The same LAI value is enforced at the end of the growing season. In the first half of the growing season (until reaching a maximum of Tm), the LAI increases:

\[
LAI_{k+1} = LAI_k + L_1 \times (T_m - 5), \text{ if } T_m > 5,
\]

After the seasonal maximum temperature Tm, the green vegetation dies off, and the LAI decreases exponentially:

\[
LAI_{k+1} = LAI_k - L_2 \times \exp(1 - T_m), \text{ if } T_m > 5,
\]

where \(L_1\) and \(L_2\) are the parameters for growth and dying off of vegetation, and \(k\) is the number of the time step. To account for the slower growth of vegetation at high air temperatures, \(L_1\) is reduced by 25% for Tm above 15 °C.

The model has been calibrated using all available data set on field NPP data in 1999-2011. The temperature sensitivity coefficient of the heterotrophic respiration was calculated from measurements of CO\(_2\) emission fluxes from the bog surface [35]. It was found that for high and low ryam the temperature sensitivity of respiration is the same and \(k_T = 0.045\) g m\(^{-2}\) K\(^{-1}\). For a drained ryam the temperature sensitivity of respiration is approximately twice as high and \(k_T = 0.109\) g m\(^{-2}\) K\(^{-1}\). The accumulated phytomass in vegetation in the model is taken into account through the increase in the LAI during the season. The multi-objective optimization procedure was performed in the Matlab software using the fmin search function. The minimum of the unconstrained multivariable function
was found using a derivative-free optimization method [36]. The root-mean-square error was used as a minimizing function.

4. Simulation results
The proposed model allows calculating carbon dioxide fluxes for the ecosystems being studied on the hourly time scale. The results of carbon flux estimations for each ecosystem were summarized annually for the period from May 1 to September 30.

The gross carbon accumulation by vegetation (GPP) in the model is completely controlled by the amount of incoming photosynthetically active radiation and biomass reserves accumulated during the growing season (via the LAI). Therefore, the interannual fluctuations of the GPP at different sites are almost synchronous ($r > 0.76$). However, the GPP value differs significantly between the sites. The greatest accumulation of carbon by vegetation is observed in the tall ryam, and the smallest one is in the drained ryam.

The total ecosystem respiration (ER) varies depending on the weather conditions and takes the maximum values in 2012 for all bogs, when the average summer temperature exceeded the multi-year average by 2 °C. Also abnormally large emission fluxes associated with an increase in the air temperature were observed in 2016. On average, over the study period, the ecosystem respiration decreases in the row high ryam – low ryam - drained ryam. The expected increase in the emission fluxes during the drainage of the peat deposit is not observed in the model estimates. Some increase in the heterotrophic respiration due to an increase in the capacity of the aerated layer is fully compensated by a decrease in the dark respiration of plants.

![Figure 1](image.png)

**Figure 1.** Carbon balance of pine-shrub-sphagnum bogs of the Bakchar peatland and its components (mean ± STD) for 1999 -2017.

The net ecosystem exchange, which is considered as an estimate of the carbon balance (Fig. 1.), has the lowest values for the drained ryam (134 g m$^{-2}$). For the undisturbed high and low ryam ecosystems, the NEE values turned out to be close (197 and 223 g m$^{-2}$). The net primary production, whose observations were used to calibrate the model, decreases from 323 g m$^{-2}$ for the high ryam to 306 g m$^{-2}$ for the low ryam, and then to 214 g m$^{-2}$ for the drained ryam.

Thus, forest reclamation after peatland drainage in the long term leads to a decrease in both the input and expenditure components of the carbon balance, but the total annual carbon absorption in the drained ecosystems decreases by 20-224 g m$^{-2}$ (or 16-70%) depending on the weather conditions. However, this decline does not shift the ecosystem from a sink of atmospheric carbon to its source.
5. Long-term changes
The forecast of changes in the carbon balance was made using the model described above. As control parameters of the model (air temperature and incoming photosynthetically active radiation), the results of calculations using the PLASIM model [36] for 1901-2100 were used, with an increase in the carbon dioxide concentration according to the RCP 8.5 scenario [37] (http://climate.uvic.ca/EMICAR5). The PASIM model consists of a series of modules of varying complexity: atmospheric, oceanic, soil ones, modules for sea ice and land surface. Being a model of intermediate complexity, the PASIM allows modeling for a sufficiently long period in a reasonable estimated time and, at the same time, makes it possible to estimate the magnitude and overall dynamics of the studied processes.

According to the RCP 8.5 scenario, the average global concentration of CO\textsubscript{2} increases from 296 to 936 ppm, and according to the model estimates, the surface air temperature also increases (Figure 2). Thus, the average annual temperature averaged over the first and last 20 years of the study period increases from -0.4 to 5.0 °C, and the average temperature of the growing season (May-September), from 9.7 to 15.8 °C. The average PAR during the growing season for two centuries does not undergo significant directional changes, increasing from 278 to 330 μmol m\textsuperscript{-2} s\textsuperscript{-1} (Figure 2). However, in the twenty-first century the interannual variability of the PAR increases.

![Figure 2](image)

**Figure 2.** Changes of meteorological parameters in XX-XXI centuries according to model estimations in scenario RCP 8.5. 1 - average annual air temperature, 2 - average air temperature in May-September, 3 - scenario of growth of average CO\textsubscript{2} concentration, 4 - average annual PAR, 5 - average PAR for May-September (black lines: 10-year running average).

Model (1-7) allows one to extrapolate data on carbon fluxes both in the past (from 1901) and into the future (until 2100). The model parameters were determined by the results of field studies of the net primary production of bog vegetation. Since the end of the 21st century, according to the model calculations the duration of the period with air temperatures above 5 °C increases. Figure 4 shows the changes in the net annual carbon fluxes in the 20th – 21st centuries. Since the model does not support the transformation of the vegetation cover, changes in the hydrological regime, the existing estimates of the fluxes are simply extrapolated to the future in accordance with the predicted changes in the temperature and the carbon fluxes in different ecosystems are synchronous. The linear correlation coefficient of annual carbon fluxes in various ecosystems is 0.99 - 0.92. The exception is the correlation coefficient between the NEE in the drained and the native ryams (r = 0.58 and 0.64). Like the air temperature, the carbon fluxes over the 20th century change slightly, and the main changes in the magnitudes of the fluxes are predicted during the 21st century (Figure 3).
Figure 3. Forecast of annual carbon fluxes (GPP, ER, NEE, NPP) in XX and XXI centuries (points - model, lines - 10-year running average).

The model incorporates the exponential sensitivity of the ecosystem respiration to the temperature, and the ER value increases in accordance with the increase in the air temperature over two centuries. In the low and tall ryams, the annual value of ER increases by 75 and 71% (Table 1). The coefficient of respiration sensitivity to temperature for the drained ryam is approximately 2 times higher, which leads to a significant increase in the ER by 182%.

Table 1. Forecast estimates of carbon fluxes (g m^-2) in pine-shrub-sphagnum bogs during the first 20 years of XX century and the last 20 years of XXI century, \( \Delta \) is the difference between fluxes (%).

|                  | GPP  | NPP  | ER   | NEE  |
|------------------|------|------|------|------|
| **Tall ryam**    |      |      |      |      |
| 1901-1920        | -305 | -220 | 183  | -122 |
| 2081-2100        | -523 | -339 | 313  | -210 |
| \( \Delta \)     | 71%  | 54%  | 71%  | 73%  |
| **Low ryam**     |      |      |      |      |
| 1901-1920        | -277 | -208 | 134  | -143 |
| 2081-2100        | -478 | -328 | 235  | -243 |
| \( \Delta \)     | 73%  | 58%  | 75%  | 70%  |
| **Drained low ryam** |      |      |      |      |
| 1901-1920        | -198 | -154 | 88   | -110 |
| 2081-2100        | -349 | -192 | 248  | -101 |
| \( \Delta \)     | 76%  | 25%  | 182% | -8%  |

The gross carbon accumulation by plants (GPP) also increases in all ecosystems. The GPP growth is partly due to minor increases in the PAR and, to a greater extent, due to an increase in the maximum
values of biomass storages accumulated during the growing season. However, it is most likely that with significant warming there will be a violation of the hydrological regime of the wetlands and a change in the vegetation type. Thus, according to the present model estimates in all studied ecosystems the GPP growth is projected at 71 - 76%.

6. Conclusions
The net primary production of the above-studied treed bogs increases over two centuries under climatic changes. However, the NPP growth in a drained treed bog is projected to be approximately two times less (a NPP growth of 25% over the study period) than in the native high and low treed bogs (the NPP rises by 54 and 58%). Although in the above scenario of warming and increasing carbon dioxide concentration, both the expenditure (ecosystem respiration) and input (gross primary production) parts of carbon balance are predicted to grow, the net ecosystem exchange (carbon accumulation in the ecosystem) also increases in the native treed bogs. The increase in the NEE for a high treed bog is 73% and for a low treed bog 70%. However, in a drained treed bog with warming the ecosystem respiration increases faster than the gross primary production, which results in a certain (of 8%) decrease in the NEE. Nevertheless, even with a significant warming scenario it was predicted that even a drained treed bog will continue to act as an absorber of atmospheric carbon. Some additional forecast estimates have shown that a drained treed bog will transit to a net carbon source in an atmosphere with additional two degrees of warming, according to the RCP 8.5 scenario.

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