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Paludification on Vasyugan Mire

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Abstract—Results of long-term estimates of carbon stock and current carbon sequestration in pine–shrub–sphagnum BGC in Vasyugan Mire (VM) are discussed. In different climatic conditions (different years), NPP varies from 206 to 337 g $\mathrm{Cm^{-2}}$ $\mathrm{year^{-1}}$. An increase in carbon-emission intensity was detected in drier vegetation periods. Most of the carbon losses are the emission of carbon dioxide (average is 61.3 g $\mathrm{Cm^{-2}}$ $\mathrm{years^{-1}}$, or 23.5% NPP). It is possible to ascertain the progression of peat formation. The removal of the carbon by bog waters was calculated using a mathematical model. It was estimated as 3.0% NPP with a mean value of the removal of 7.9 g $\mathrm{Cm^{-2}}$ $\mathrm{years^{-1}}$. Based on the model of bogs vertical growth, the modern rate of carbon accumulation was estimated in the range from 10.3 g $\mathrm{Cm^{-2}}$ $\mathrm{years^{-1}}$ in polygonal bogs to 51.7 g $\mathrm{Cm^{-2}}$ $\mathrm{years^{-1}}$ in grassy bogs.

Keywords: Vasyugan Mire, ecosystems, long-term deposit, carbon balance, rate of carbon accumulation, bog waters, model of vertical growth

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INTRODUCTION

In the conditions of carbon increase in an atmosphere, biogeocenoses, which are able to absorb more CO_2 from atmosphere and return the least amount possible, are the most valuable. Such biogeocenoses are bogs. World estimations of deposited carbon by bogs vary from 329 to 528 Gt (Lappalainen, 1996 and others). It is known that, in regards to the steady content of C_{org} in the soil per square unit, ecosystems of Russia form following order: bogs, grasslands, and forests (Zavarzin, 1994). Growing bogs are unique ecological systems absorbing CO_2 from the atmosphere for a long period, and this issue is subject to numerous studies (Inisheva et al., 2015; Naumov et al., 2009, Cory et al., 2013, Lappalainen, 1996).

The growth of peat is divided into "long-term medium" and "short-term average growth." The first includes peat growth during the entire period of the bog existence (a thousand years and more) and the second includes peat growth during a time interval of several decades or centuries. The main question of interest for researchers is the question of which process prevails at the present time: carbon deposition or its excretion in the form of greenhouse gases. To resolve this problem, it is necessary to address in more detail the incoming and outgoing flows of carbon in peat bog ecosystems.

This report aims to analyze the rate of carbon deposition in the Holocene and determine modern rates of carbon accumulation on Vasyugan Mire (VM).

MATERIALS AND METHODS

Vasyugan Mire is the largest bog in the world. It embraces the Ob–Irtysh watershed between 55°40′–58°60′ N and 75°30′–83°30′ E with a west–east extension of 573 km and north–south ca. 320 km. Detailed information on VM was published separately (Inisheva et al., 2003). The VM area is 5 269 437 ha, 36.9% of which belong to the territory under study and 63.1% to forecasted resources. VM contains 18.7 billion t of peat, which composes 16% of peat storage of total Siberian region. Calculations revealed that the content of deposited carbon in VM is 5.1 billion t, or 12% of deposited carbon in peat deposits of Siberian region. The lowland deposit type prevails (56.4%), while the upper deposit composes 25.9% and other storages belong to transitional and mixed types. The BGC diversity on VM is fairly large. We will concentrate on some generalized types: pine–shrub–sphagnum (*ryams* of various kinds), ridge–hollow and ridge–hollow–lake, sedge–mire, bogs, and others.

Peat growth during the entire period of Holocene on VM was determined by results of absolute dating of the lower and upper boundaries of the layers of peat deposits of appropriate thickness.

To determine the modern rate of carbon accumulation in bog ecosystems, two main methods were used: (1) balancing of carbon in the ecosystem and (2) using the Clymo model of peat accumulation process in Turchinovich modification based on historical data on the functioning of bog ecosystem (Clymo, 1996, Kobak et al., 1998).

Balance studies of carbon on VM included an analysis of carbon income and emissions on 3 BGC pine–shrub–sphagnum formations in the southern taiga subzone of Western Siberia and on the landscape profile of the catchment area. Aboveground production was determined by the cutting method and underground production by monoliths method. Net primary production was calculated as the sum of aboveground and underground productions (Titlyanova et al., 1988). The gas regime was studied by the “peepers” method (Eilrich, 2000). As samplers we used chambers with a size of 30 × 40 mm and volume of 30 mL. Distilled water-filled chambers were connected and put down throughout the depth of the peat deposit. A month later, water-filled chambers were extracted from the peat soil and water samples were taken in vacutainers with subsequent analysis on a Crystal-2000.1 gas chromatograph. The chamber method was used for measurements of the CO_2 and CH_4 emission. The gas composition was analyzed on a Crystal-5000.1 chromatograph.

As an object to study the flow of carbon surface runoff, we selected the catchment within the territory under study. To determine the removal from particular catchment areas, it is necessary to have observation points of the water flow and concentration of chemical elements, which is practically impossible on bog catchments. Therefore, to determine the removal of carbon with bog waters, a mathematical model of the carbon runoff from the surface of the catchment basin and their movement in the channel network was developed. Water-soluble carbon, humic, and fulvic acids were determined in bog waters (*Tekhnicheskii analiz torfa*, 1992).

RESULTS AND DISCUSSION

The extensive development of bogs on the West Siberian Plain started at the beginning of the Atlantic Period and is characterized by optimal climatic conditions for the process of peat formation. The formation of VM was noted also in the Atlantic Period, and 500 years ago VM consisted of 19 individual bogs. Now, due to the proliferation of these sites, a single massive has formed where 25% of the occupied territory has an age of no more than 500 years, with the lower age limit being 9000 years (Inisheva et al., 2003).

Let us discuss the growth of peat on VM for the entire Holocene Period. Based on our studies and published sources, we can conclude that the rate of peat accumulation on VM in the Early Holocene was 0.5 mm/year, in the Middle Holocene 0.4–0.7 mm/year, and in Late Holocene 0.88 mm/year (Vasil’ev, 2000; Liss et al., 2001). The peak of carbon accumulation was 70 g Cm^{-2} $year^{-1}$ at the gain of 1.79 mm/year in the Boreal Period (9000–8000 years B.P.). In the conditions of gradual climate warming on the territory of VM, the value of this gain was very sensitive to a series of cold growth in the Subatlantic Period (2000–1700 years B.P., 1500–1400 years B.P., and 700–600 years B.P.), growing in some peat bogs up to 1.5–2 mm/year.

How are things going with the process of bogging on VM at present? Let us discuss the results of determining the modern carbon accumulation rate on VM using the balance method on the example of pine–shrub–sphagnum BGC in different years by meteorological conditions, representative in the multiyear row. Years of studies were chosen by the Selyaninov hydrothermal coefficient (HTC), representing the ratio of the precipitation sum for the period with temperatures above 10°C to evaporation expressed by the sum of temperatures for the same period, reduced by 10 times.

In the studied peat bogs, NPP varies from 206 to 337 g Cm^{-2} $year^{-1}$ (Table 1). Extreme NPP values belong to the year with a HTC 0.51 (in a dry year). In regards to the mean values, maximum NPP is characteristic for an average heat–moisture year (HTC 1.02). Estimation of the total carbon flux during the growing season is of particular interest. Mean values of the CO_2 and CH_4 emission rate over the three years of study were 69, 72, and 47.7 g Cm^{-2} $year^{-1}$. Extremely large emissions noted in the year with HTC 1.02–111 g Cm^{-2} $year^{-1}$. Mean values of emissions allowed us to trace the same pattern. Most of the carbon losses are conditioned by the carbon dioxide emission (mean value was 61.3 g Cm^{-2} $year^{-1}$, or 23.5% NPP). The proportion of methane is much smaller, 1.6 g Cm^{-2} $year^{-1}$, or 0.6% NPP. In sum, the share of removal is 24.1% NPP. Let us analyze the removal of carbon with runoff. The removal with runoff varies by individual bogs considerably due to the nature of bogs themselves, according to fluctuations in the volume of runoff. It may vary within broad limits. We developed a mathematical model of the removal of substances from the surface of the catchment area. We have also taken into consideration the following: the removal of chemical elements (in our case, carbon compounds) in the period of spring flood and rainfall floods occurs mainly with surface runoff water, which varies not only in time but in catchment square; spatial heterogeneity of the conditions of runoff formation is taken into account by splitting the catchment square according to the characters of landscape. In the calculations of solute movement, the following assumptions were introduced:

(1) the problem is solved in one-dimensional formulation. The concentration of compounds under

Table 1. Elements of carbon balance in the pine–shrub–sphagnum BGC, g Cm^{-2} $year^{-1}$

Years by hydrothermal coefficient	Income	Emission of CO_2 and CH_4	Deposition
0.51	206–337 264.6 ± 38.43	61–80 69.0 ± 6.96	140–276 195.6 ± 50.40
1.02	277–301 290.3 ± 7.06	45–111 72.0 ± 24.46	166–248 218.3 ± 32.14
1.34	214–245 227.0 ± 11.37	31–79 47.7 ± 19.2	166–189 179.3 ± 8.44
Mean	260.6 ± 15.69	62.9 ± 8.94	197.7 ± 16.24

Note: Numerator shows extreme values and denominator shows mean values; ±6.96 is the confidence interval.

consideration is taken averaged by the live flow cross section or effective square of cross-sectional square of the slope for the slope runoff; i.e., it is changing only in length and time;

(2) it is believed that solutes are spread due to water movement and together with its particles; they do not have their own facilities of movement (molecular diffusion etc.);

(3) the process of water self-purification in a first approximation is not taken into account. This is possible if the intensity of decomposition of substances is small (e.g., at low temperature of water) or the water passes an estimated plot during a relatively short interval of time.

One peculiarity of the model is that it is being implemented in relation to the expenditure of the ingredient under consideration, i.e., the mass of a substance carrying through a given cross section of flow per unit of time. Transition to the concentrations of impurity is processed on necessity. A detailed description of the model was published earlier (Inisheva et al., 2003). Calculations of the carbon runoff in the form of humic acids from the surface catchment of the Klyuch River were done as an example of the model application. The results (Fig. 1) indicated the satisfactory convergence of the calculated and actually observed hydrographs of the expenditure of humic acids in the closing section of the Klyuch River and, therefore, possibility of applying this approach to the modeling of solute removal from bogs.

As a result of model calculations for the spring and summer period, the removal of total carbon in different compounds from the catchment area reached 7.9 g Cm^{-2} $year^{-1}$. Thus, the loss of carbon from bog waters was 3.0% NPP. It is important to note that the removal of carbon with bog waters occurs in the form of humic substances, while the highest share belongs to the carbon of fulvic acids, the content of which reaches in some periods 98% of the total removal of carbon by the bog runoff (6.9 g Cm^{-2} $year^{-1}$ or 6790 kg Ckm^{-2} $year^{-1}$, Fig. 2).

Based on the results obtained for growing periods differing in weather conditions, we can conclude that the carbon accumulation in peat deposits prevails (197.7 g Cm^{-2} $year^{-1}$), as well as, accordingly, the progressive peat-forming process on VM in the modern period. The greatest deposition and the emission of CO_2 and CH_4 were noted in the year with optimal conditions of heat and moisture provision (HTC 1.02). At the same time, it is important to note that the balance studies concerned only the pine–shrub–sphagnum BGC and, in this case, we can note only the fairly high rate of the peat-formation process. Upon the creation of possibilities for simultaneous balance research in all representatives of BGC of the VM, it will be possible to obtain a fuller idea about the development of the process of peat formation throughout a unique bog ecosystem, including VM.

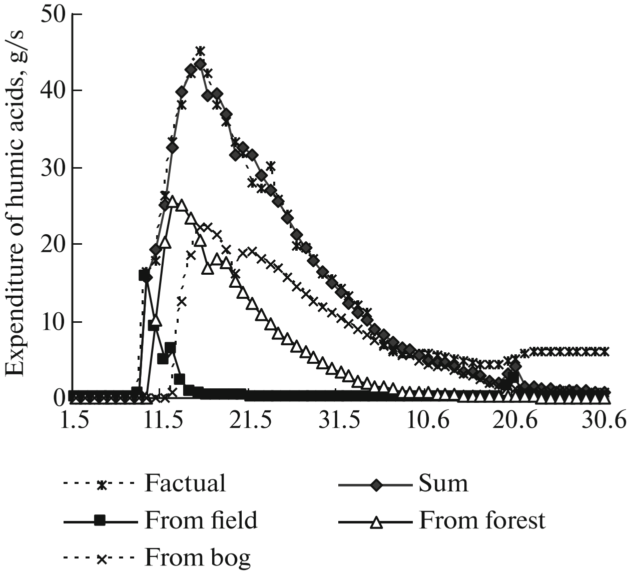

Fig. 1. Factual and calculated hydrographs of the runoff of humic substances.

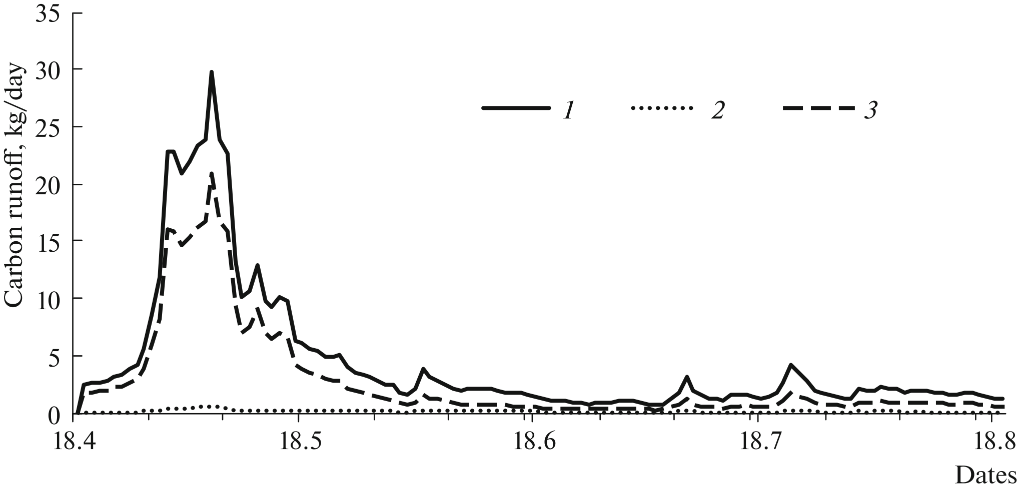

Fig. 2. Carbon runoff with bog waters, calculation by the model. (*1*) Wsc, Water-soluble carbon; (*2*) HA, humic acids; and (*3*) FA, fulvic acids.

However, in recent years there has been a clear trend of increased transgression of bogs in forests, for example, in northwestern Russia. The linear growth of bogs and their advance to the surrounding watershed areas in this territory at present is 30–50 cm/year, and the vertical growth of the peat is on average 3 mm/year (Kuzmin, 1993). Variations of vertical growth values are in the range of 0.4–0.6 mm/year (e.g., for peats from the wood and wood–herb groups) to 10–12 mm/year (oligotrophic sphagnum BGC).

Therefore, back to the question of the modern bogging rate, we should note that the total carbon accumulation by bogs in Russia currently stands at 37.6 million t/year, based on their area (Novikov and Usova, 2000) and data on their types (Botch et al., 1995, Kobak et al., 1998). According to our estimates, ridge–hollow bogs covering more than 40% of the area of modern bogs make the maximum contribution, 46.8% in this accumulation.

For determining the modern accumulation rate of carbon in bog ecosystems of VM, we can use the model of accumulation processes of peat and carbon based on historical information on the functioning of a bog ecosystem together with data on the density of peat profile, its age, etc. (Clymo, 1984, 1996). According to this model, a bog can be represented in the form of two layers: the upper active layer and the lower inert layer, where all processes are much slower. The process of organic matter accumulation in the active layer can be represented as follows:

$$d\mathrm{Ma}/dt = \mathrm{Pa} - \mathrm{AaMa} - \mathrm{Pc}, \quad (1)$$

where Ma = PaHa is the mass of organic substance on a square unit in the active layer, Pa is yearly income of live organic substance onto the bog surface, Ha is the depth of the active layer, and Pc is the flow of organic substance coming from the active layer into the lower inert layer every year. The share of the substance entering the active layer, determined by the Ma/Pa ratio, depends on many factors: the productivity of bog plants, climatic conditions, etc. This ratio has different values for different types of bogs.

The rate of destruction of organic substance in the active layer depends on many factors. According to many specialists (Turchinovich et al., 2000, Clymo, 1996 and others), it is proportional to the mass of organic substance remaining after decomposition in the active layer, whereas the decomposition coefficient Aa is usually considered a constant value for a given bog and vegetation type.

The inert layer of the bogs undergoes similar processes, but the intensity of organic matter decomposition under anaerobic conditions is less by one to two orders of magnitude. The accumulation of organic matter can be represented as

$$d\mathrm{Mc}/dt = \mathrm{Pc} - \mathrm{AcMc}, \quad (2)$$

where Mc is the mass of the peat organic substance on the unit of square accumulated to moment of time t, Ac is a parameter that is usually considered a constant value for a long interval of time during which environmental conditions may be considered unchanged, and Pc is an analogue of yearly production for the active layer.

The accumulation of organic substance in the upper layer of a bog ecosystem occurs until the occurrence of a constant thickness of the active layer, which persists during a long time at the absence of significant changes in the environment. In this period of the development of a bog ecosystem, the flow of organic matter in the inert layer can be neglected. The formation of the active layer takes from several decades to hundreds of years in different types of bogs. According to our estimates, the fastest formation of stationary

Table 2. Peat increase in some bog types in modern epoch

Bog type	Phytomass productivity, kg/m^2 per year, ADS	Peat density in the active layer, kg/m^3, ADS	Thickness of the active layer, m	Decomposition constant, Aa, g/m^2 per year	Flow of organic substance into the active layer, kg/(m^2 per year), Pc, ADS	Linear increase of the peat, mm/year
Aapa	0.14–0.54	65–90	0.1–0.3	0.02–0.06	0.058	0.46–0.53
Ridge–hollow upper bogs	0.43–0.52	30–50	0.38–0.44* 0.42–0.49c	0.01–0.05	0.070	0.88–0.93
Upper wooded bogs	0.21–0.63	30–50	0.47–0.58c	0.01–0.04	0.063–0.079	0.79–0.84
Lowland (forest) bogs	0.78	140	0.85	0.06	0.02	0.10–0.20
Lowand grass–forest bogs	0.72	100–110	0.49	0.01	0.10	0.70–0.90

*Data from field studies; c, calculated data; and ADS, absolutely dry organic substance.

active layer occurs in the aapa bogs and hummock–hollow complexes, where the time of its formation is 50–60 years. The longest term for this process is in fens: 400–600 years. If the thicknesses of the active layer and the density of organic matter in it, as well as the net productivity of plant communities for this bog type, are known, we can estimate values of the decomposition constant Aa.

In the stationary condition since the formation of the stationary active layer (Ta), the influx of organic matter in this layer is compensated by its losses from the active layer and the by the runoff from the lower inert layer. This allows us to express the equation (1) as $d\text{Ma}/dt = 0$ and estimate the value of organic matter flow from the active layer into the inert level (Rs).

The Rs value characterizes the mean long-term rate of peat accumulation in the initial stage of bog development, when the formation of peat deposit has just begun and the rate of loss of organic matter in the active layer is negligible. In the initial period of bog formation, the rate of peat accumulation is determined by the intensity of net productivity of bog ecosystems in that period of time and by processes occurring in the active layer, whose parameters such as the rate of various processes in it are different from those existing now.

In the calculations in Table 2 we used our experimental values of net productivity, thickness of the active layer, and density of the absolutely dry matter in the active layer, as well as those from publications (Bazilevich, 1993; Bazilevich and Titlyanova, 2008; *Bolota Zapadnoi Sibiri*, 1976; Boch, 1994). The Aa parameter values listed in the table for the studied bog types were estimated by us using the bog vertical-growth model.

The modern rate of carbon accumulation (with average carbon content in absolutely dry substance 51.7%) ranges from 10.3 g Cm^{-2} year^{-1} in polygonal bogs to 51.7 g Cm^{-2} year^{-1} in lowland grass marshes. Since the calculation is made without account of organic matter losses in peat deposits, we believe that they are somewhat overstated.

CONCLUSIONS

In the Boreal period (9000–8000 years ago), in the conditions of gradual climate warming on the territory of VM, the peak of carbon accumulation was determined as 70 g Cm^{-2} year^{-1}, with a maximum value of the gain of 1.79 mm/year.

Studies on the balance of pine–shrub–sphagnum BGC showed that, in different climatic conditions, the years of NPP vary from 206 to 337 g Cm^{-2} year^{-1}. An increase in the deposition and the intensity of carbon emissions in the growing periods optimal by moisture and heat provision were noted. Most of the carbon losses are caused by carbon dioxide emission: the mean is 61.3 g Cm^{-2} year^{-1}, or 23.5% NPP.

The removal of carbon by bog waters, determined by calculation using the model of removal of chemicals, is 3.0% NPP, with the mean value of removal being 7.9 g Cm^{-2} year^{-1}, and occurs in the form of humic substances, while the highest share belongs to the carbon of fulvic acids, 6.9 g Cm^{-2} year^{-1}, or 6790 kg Ckm^{-2} year^{-1}.

In general, we can conclude that in VM the accumulation of carbon in peat deposits and, correspondingly, peat formation in the modern period are progressed, and the activity of its flow is high enough.

Based on the model of bog vertical growth, we also calculated the modern accumulation rate of carbon, which varies from 10.3 g Cm^{-2} year^{-1} in polygonal bogs to 51.7 g Cm^{-2} year^{-1} in lowland grassy bogs, which is 1.4–6.8 times less in comparison with the results in the Boreal period of Holocene.

Currently, many countries are developing programs aimed at protecting bog ecosystems, first and foremost, for the conservation of species biodiversity on the planet. There is even the restoration of previously drained peat bogs (e.g., in Scotland) or the retransformation of territories used for agricultural crops into bogs (e.g., rice fields in Japan). It is supposed that, as a result of such events, the net accumulation of carbon dioxide from the atmosphere can increase.

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