Dynamics of mire ecosystems of Siberia in the Holocene and paludification process at the present stage

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Abstract. The paper considers the Holocene paludification process in West Siberian Plain; peat increase for the entire Holocene according to radiocarbon dating of peat deposits. The comparison of results by peat accumulation activity with the climate of Western Siberia in the Holocene is carried out, and the forecast of the natural evolution of mires is given. To determine the contemporary accumulation rate and linear peat increment, we used the model of peat and carbon accumulation process, and the field studies of carbon balance parameters of oligotrophic bog catena as an example. The modern rates of carbon accumulation and the linear peat increment of some types of mires were determined. The field studies of carbon balance parameters on the example of oligotrophic bog catena showed, in years with different climatic conditions, the NPP values varied from 206 to 337 g C m⁻² year⁻¹. Most of the carbon losses are the carbon dioxide emission (an average is 61.3 g C m⁻² year⁻¹, or 23.5 % NPP). The carbon flux, determined by the model of the removal chemicals, is 3.0% NPP with a mean value 7.9 g C m⁻² year⁻¹. The calculations of the carbon balance indicate the progression of the paludification process in the studied area.

1. Introduction
The role of continental biota in the concentration fluctuations of atmospheric CO₂ (Cco₂) is still not completely clear, but most experts believe that biomass and soils served as a net flow of the atmospheric CO₂. Eighteen thousand years ago, the pool of organic carbon was 625 billion tons (Gt), at present, it is 2100 Gt of C [1]. The increase in the soil carbon pool is undoubtedly associated with the development of bogs and the accumulation of peat in them. By contemporary estimates, the global reserves of carbon accumulated in mires (over an area of 6.41 mil. km²) range from 329 to 528 Gt [2]. In Russia, the total area of peaty and swampy lands is 3.691 mil. km², or 21% of the country's territory, and the carbon content in them is 100.93 Gt [3]. It should be noted that we have a more complete understanding of the rates of peat and carbon accumulation and the paludification rate in the Early Holocene (in different time spans) than of the mire formation process over the last 100 years. Therefore, the goal was to analyze the rate of the paludification process in different time spans of the Holocene and nowadays using the central part of Western Siberia as a sample.

2. Results and Discussion
By the studies, it has been established that the onset and development of mire formation in the West Siberian Plain refers only to the Holocene. According to scientists [4,5,6,7], its age-related limit is between 10–12 thou years. The oldest sediments in Western Siberia have been estimated at 9900 ± 100 14C yr BP.

The spatio-temporal correlation of stratigraphic, palynological and radiometric data allowed O.L. Liss [8] to reconstruct gradually the development of mire ecosystems in the central part of Western Siberia during the Holocene, which was reflected in a series of map schemes (figure 1). Trends: 1 - transformation of less hygrophilic complexes into more hygrophilic ones, 2 - intensive oligotrophy process of sedge-hypnum type eutrophic complexes, 3 – moderate oligotrophy process of grass type eutrophic complexes and their transformation into complexes.

Figure 1. The location of marshes in the central part of Western Siberia: a) in the Boreal period (9500 - 8000 14C yr BP), b) in the Atlantic period (8000 - 4500 14C yr BP), c) in the Sub-Boreal period (4500 - 250014C yr BP), d) in the Sub-Atlantic period (2500 14C yr BP - the present time).

In the late glacial period, in conditions of a rather severe climate, a considerable part of the territory of Western Siberia was presented with treeless spaces with periglacial steppes and tundra. As for that time span, only a few foci of swamping have been known. The beginning of the continuous accumulation of bog and lake-bog sediments in Western Siberia is associated with the Boreal period (9500-8000 14C yr BP) (figure 1a). In the greater territory of the taiga zone, the development of mires
occurred under the conditions of poorly dissected relief, excessive atmospheric moisture, and low salinity groundwater running close to the earth surface. The combination of such natural conditions determined the predominance of the oligotrophic stage in the development of mires. On average, the peat accumulation rate did not exceed 5%.

The cooling period that occurred at the Boreal-Atlantic turn affected the decrease in the rate of vertical peat accumulation. In the second half of the Atlantic period (8000–4500 14C yr BP), climatic conditions were changed by warming and increased humidity. Gradually, the waterlogging centers interflowed and turned into extensive mire ecosystems. The average rate of peat accumulation on the territory increased to 15–20% (figure 1 b). In the most part of the contemporary taiga zone, the mire complexes of the eutrophic grassy-moss and woody-grass-moss types transformed into mesotrophic and oligotrophic ones. In the Atlantic period, flat mires came into existence, represented mainly by sphagnum, grass-sphagnum and pine-shrub-sphagnum type complexes, and, to a lesser extent, by string bog type complexes.

In the Subboreal period, the mire formation process covered watershed plains, high and low terraces, and river flood plains. The peat formation increment ranged from 30 to 40% (figure 1 c). In the northern part of the taiga zone, the mire complexes of the lake and string bog type were widespread, with the prevalence of string mires in the middle part of the zone. The mire complexes of the mesotrophic and eutrophic woody-grass-moss type covered significant areas in the southern part of the zone. The appearance of the first foci of swamping in the forest-steppe zone is also associated with the Subboreal period. A high degree of the soil salinity had led to the beginning of paludification since the eutrophic stage exclusively. The vast depressive areas, filled with slightly mineralized waters, became the places of formation of concave eutrophic grass mires (water meadows) with inclusions of oligotrophic pine-shrub-sphagnum islands (ryams). In small flat depressive areas, there appeared hillock bogs. In some of them, small sphagnum quagmires emerged; and the conditions for the transition of bogs from the eutrophic developmental stage to the meso- and oligotrophic stages were created.

The Subatlantic period (2500 14C yr BP up to the present) is the most heterogeneous in terms of changes in climatic parameters (figure 1 d). In the taiga zone, the further development of oligotrophic type bogs was directed towards increasing their watering. In the southern taiga zone and forest-steppe, the development of mires occurred along with the strengthening of mesotrophic processes and further oligotrophic stage due to the expansion of the areas occupied by ryams. During the second half of the Holocene, the average peat accumulation rate in this zone increased from 17% to 25%.

Thus, the transformations that mire ecosystems had undergone during the Holocene in Western Siberia represented unified persistent process aimed at strengthening the homeostatic mechanism, which ensured the conservation of mires as a special type of holocoenotic cover of the Earth.

Let us consider the peat increment over the entire Holocene period by the results of absolute dating of the lower and upper layers of peat deposits and by the data of a palynological analysis. For this purpose, more than 65 reference peat sections from various natural zones of Western Siberia were selected with the involvement of studies by other authors [9]. The maximum linear peat accumulation rate in the Holocene was established for mire ecosystems of sub-taiga (1.1 mm / year), due to significant biological productivity (figure 2). In the southern taiga, intense peat accumulation was caused by favorable climatic parameters and the relatively high biological productivity of biogeocenosis. In the southern taiga, the exception was the low linear peat accumulation rate (0.3–0.36 mm / year) in buried Holocene peatlands in river valleys. In the middle taiga, the linear peat increment rate was 0.57 mm / year, in the north - 0.37 mm / year, in the forest-tundra - 0.35 mm / year, in the tundra - 0.31 mm / year (figure 2).
In the forest-steppe zone, the process of peat accumulation was also slowed down up to 0.73 mm / year, and more intensively, it occurred only in ryams – 1.64 mm / year. The maximum values of the vertical increase in peat deposits (from 0.53 mm / year to 0.83 mm / year, with an average of 0.77 mm / year) were established for the Boreal period, which confirms the opinion of N.A. Khotinskii [10] concerning the thermal boreal maximum in the Holocene, which is characteristic for Western Siberia. In the Atlantic period, there was a minor decrease in peat increment. The process happened to be more pronounced in the northern taiga zone than in the middle one. The minimum increase in peat deposits (0.27–0.34 mm / year) was noted for the Subboreal period, when the climate was relatively dry and cold. In the Subatlantic period, the average peat accumulation rate increased slightly (up to 0.53 mm / year), but did not reach the value established for the Boreal period. The higher peat accumulation rates characteristic for the Subatlantic period can be explained by the fact that the upper layer of peat deposits was less dense. In the northern taiga, forest-tundra and tundra on frozen mounds, the process of peat accumulation completely ceased.

In the last 500 years, the process of paludification has generally slowed down, since the ancient depressive areas turned out to be filled with peat. However, the manifestation of zoning in the transgression of mires to the forests surrounding them has been preserved. As noted by S.V. Vasiliev [11] in the modern time period, minimal peat accumulation is observed in the north and maximum of it is in the south.

Two processes were applied to determine the current peat accumulation rate and linear peat increment of some types of mires. The first was the model of peat and carbon accumulation process by R.S. Clymo [12] in Turchinovich’s modification [13]. The next was the calculation of the carbon balance in the ecosystem based on the determination of the primary productivity of bog plants (NPP), measurements of gas flows (the CO₂ and CH₄ emissions from the soil surface), and of the carbon flux by mire waters.
In our calculations by the model, we used the values of net productivity, the acrotelm thickness, and the density of absolutely dry matter in acrotelm. The values of the parameter Aa given in Table 1 for the studied types of mires were estimated by us with the vertical increment model. According to the performed calculations [14], the contemporary rate of the linear peat increment ranges from 0.10 to 1.10 mm/year (table 1). The maximum contribution (46.8%) to this accumulation is associated with string bogs, which occupy more than 40% of the area of modern bogs [15].

**Table 1.** Flow of organic matter from acrotelm to catotelm and maximum possible peat increment in some types of bogs of Russia for the contemporary epoch.

| Type of bogs          | Phytomass productivity, kg/m²/year (ADM) | Peat density in acrotelm, kg/m³ (ADM) | Thickness of acrotelm, m | Decomposition constant, Aa, per year | Flow of organic matter to catotelm, kg/m²/year (ADM)= Pc | Peat linear increment, mm/year |
|-----------------------|------------------------------------------|---------------------------------------|--------------------------|--------------------------------------|-------------------------------------------------------|-------------------------------|
| Aapa                  | 0.14–0.54                                | 65–90                                 | 0.1–0.3                  | 0.02–0.06                            | 0.058                                                 | 0.46–0.53                     |
| String bog            | 0.43–0.52                                | 30–50                                 | 0.38–0.44*              | 0.42–0.49                            | 0.01–0.05                                             | 0.070                         | 0.88–0.93                     |
| High forested bog     | 0.21–0.63                                | 30–50                                 | 0.47–0.58               | 0.01–0.04                            | 0.063–0.079                                           | 1.00–1.10                     |
| Fen (forest)          | 0.78                                     | 140                                   | 0.85                     | 0.06                                 | 0.02                                                 | 0.10–0.20                     |
| Grass-forest fen      | 0.72                                     | 100 – 110                             | 0.49                     | 0.01                                 | 0.10                                                 | 0.70–0.90                     |

*aNotes. ADM – absolutely dry organic matter; c – calculated data, * – data of field observations, Pc – annual flow of organic matter from the active layer to the lower layer of the peat deposit, Aa – decomposition constant, OM – organic matter.*

In comparing the linear increase in the high-moor peat mires of Western Siberia and of the European part of Russia, we can find that the paludification process in Western Siberia in extreme values was 1.2–1.3 times higher.

Let us consider the results of determining the contemporary rate of carbon accumulation in high-moor peat mires by the balance method on the example of pine-shrub-sphagnum biogeocenosis (BGC) in years with different meteorological conditions, representative in a long-term series. The research years were selected by the hydrothermal coefficient of Selyaninov (HTC), presented as the ratio of precipitation for a period with temperatures above 10°C to evaporation expressed with the sum of temperatures for the same period, reduced by 10 times. Aboveground production was determined by the cutting method, underground ones – by the monolith method. Net primary production was calculated as the sum of aboveground and underground productions [16]. The gas regime was studied by the “peepers” method [17]. As samplers, the chambers with the size of 30 mm x 40 mm and volume of 30 ml were used. The chambers filled with distilled water were connected and descended throughout the depth of the peat deposit. A month later, the water-filled chambers were extracted from the peat soil, water samples were taken into vacutainers with subsequent analysis on a Crystal-2000.1 gas chromatograph. The chamber method was used to measure CO₂ and CH₄ emissions. The gas composition was analyzed on a Crystal-5000.1 gas chromatograph.

In the studied high-moor peat mires, the NPP values vary from 206 to 337 g Cm⁻² year⁻¹ (table 2). The highest NPP values are observed in a year with HTC 0.8 (a dry year). By average indices, the maximum NPP values are characteristic for a year with moderate heat and moisture (with HTC 1.3).
The estimation of the total carbon flux during the vegetative period is of particular interest. Mean values of CO\(_2\) and CH\(_4\) emission rate for three years of the study were 69, 72, 47.7 g Cm\(^{-2}\) year\(^{-1}\). Extremely high emissions with value 111 g Cm\(^{-2}\) year\(^{-1}\) are observed in a year with optimal conditions of heat and moisture supply (with HTC 1.3). By the mean emission values, the same pattern can be traced. Most of the carbon losses are caused by carbon dioxide emission (61.3 g Cm\(^{-2}\) year\(^{-1}\), or 23.5% of NPP, on average). The proportion of methane is much smaller, 1.6 g Cm\(^{-2}\) year\(^{-1}\) or 0.6% NPP. In total, the share of removal is 24.1% NPP.

| Years by hydrothermal coefficient | Income | Emission of CO\(_2\) and CH\(_4\) | Deposition |
|----------------------------------|--------|-------------------------------|------------|
| 0.8                              | 206-337| 61-80                         | 140-276    |
|                                  | 264.6 ± 38.43 | 69.0 ± 6.96 | 195.6 ± 50.40 |
| 1.3                              | 277-301| 45-111                        | 166-248    |
|                                  | 290.3 ± 7.06 | 72.0 ± 24.46 | 218.3 ± 32.14 |
| 1.8                              | 214-245| 31-79                         | 166-189    |
|                                  | 227.0 ± 11.37 | 47.7 ± 19.20 | 179.3 ± 8.44 |
| Mean                             | 260.6 ± 15.69 | 62.9 ± 8.94 | 197.7 ± 16.24 |

\(b\)Notes: Numerator shows extreme values and denominator shows mean values; ±6.96 is the confidence interval.

Let us consider the carbon removal with the runoff. This paper about the carbon loss from wetlands can be of special significance. It should be noted that the removal of dissolved organic matter with the runoff by individual mires varies greatly due to many factors. Therefore, by different authors, these numerals vary from less than 1 to more than 20 g Cm\(^{-2}\) year\(^{-1}\) [18]. The removal with runoff varies by individual mires significantly because of their characteristics, dependence on the runoff volume fluctuations, and can vary quantitatively within broad limits. We developed a mathematical model of the carbon removal from a catchment area. Within the studied territory, the watershed was selected to investigate the carbon removal with the surface runoff from the swamped catchment area. A mathematical model of the carbon removal from the surface of the catchment area and its movement through the bed network was also developed to determine the carbon removal by the mire waters. The peculiarity of the model is that it is implemented relative to the consumption of the ingredient in question, i.e. the mass of the substance transported through a given cross section of the flow per unit of time. If necessary, the transition to impurity concentrations is carried out. A detailed description of the model is given [19].

As a result of calculations by the model for a spring-summer period, the removal of total carbon in various compounds from the catchment area reached the value of 7.9 g Cm\(^{-2}\)year\(^{-1}\). Thus, the loss of carbon with mire waters amounted 3.0% NPP.

The studies on the balance of pine-shrub-sphagnum BES showed that in years with different climatic conditions, the NPP values range from 206 to 337 g Cm\(^{-2}\)year\(^{-1}\). There is an increase in deposition and intensity of carbon emission in vegetation periods optimal in terms of moisture and heat supply. Most of the carbon losses are due to carbon dioxide emission (on average, 61.3 g Cm\(^{-2}\)year\(^{-1}\), or 23.5% of NPP).

In general, it is stated that carbon deposition in a peat deposit prevails in the taiga zone of Western Siberia and, accordingly, the peat formation process is progressing in the present time period, and its activity is quite high.
3. Conclusion
Thus, the transformations undergone by mire ecosystems as a whole during the Holocene in the taiga zone of Western Siberia are considered to be a unified persistent process aimed at strengthening the homeostatic mechanism, which ensures the preservation of mires as the special type of the Earth holocoenotic cover.

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