Evolution of ecosystems in the southern Yenisei Siberia in the Holocene

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Abstract. Ecosystems of different ranks are represented by components (climate, topography, soil, vegetation, wildlife, people). Over the course of evolution ecosystem components are interconnected with each other complexly. The study of any of them provides information about the evolution of the natural environment and material for identifying features of natural zoning, including regionality. Soil is a key component of the terrestrial ecosystem and many critical processes occur in the soil. The content of humus, its group and fractional composition allow us to draw conclusions about the genesis of paleosols. In the modern warming period – Holocene – there was a fluctuation of ecosystems on the territory of the southern Yenisei Siberia in the range: forest-tundra – forest (taiga) – steppe (forest-steppe).

1. Introduction
Understanding the evolution of ecosystems is necessary for realizing the current state of the natural environment and predicting its changes in the future. Soil is a key component of the terrestrial ecosystem. There is a parallel between the features in soil formation and the development of ecological communities [1].

The vast territory of Siberia is less studied than the European part of Eurasia. Identification of the main stages in ecosystem evolution in the territory of the Yenisei Siberia is the result of paleoecological (dendrochronological) [2], paleopedological [3], [4], [5] and other studies of the paleo-environment.

The Holocene is the modern warming (interglacial period) with a duration of 10-12 thousand years. The main factor influencing the evolution of ecosystems in Eurasia is climate. There are several Holocene climatic periods: pre-boreal (PB1; PB2); boreal (BO1; BO2); Atlantic (AT1; AT2), sub-boreal (SB), sub-Atlantic (SA), and modern (SOV). Humanity measured its way of life depending on climatic factors changing.

2. Methods and Results
The research was carried out on geological sections of Holocene deposits with paleosols horizons. They are located in the southern Yenisei Siberia in the forest-steppe natural zone. They are part of the database «Evolution of the natural environment of the Holocene in Siberia» [5].

The main research method is paleoecological monitoring, which studies the ecosystems of the Earth's geological past. Paleosols, as components of paleoecosystems, are studied by the paleopedological
A comprehensive method for studying organic matter includes the humus characteristic (the content of humus, its group and fractional composition) as the most informative indicators for the diagnosis of the paleosols type [6]. The total content of humus was determined by the method of I. V. Tyurin, modified by V. V. Ponomaryeva and T. A. Plotnikova [7]. Correlation relationships between indicators were evaluated using correlation, factor, and regression analysis [8, 9].

The carbon content in the humus horizons of paleosols is a diagnostic feature that allows diagnosing the soil profile analytically (table 1, 2, 3, 4). Humus horizons of paleosols (Ah) are distinguished by the amount of humus carbon in sections: “Nyasha 2” (table 1); “Ust-Karaulnaya 3” (table 2); “Local history museum 2” (table 3); “Tatychev island 3” (table 4).

| Horizons of the paleosols | C, % to the soil | Chumic acids, amount | Cfulvic acids, amount | Chumic acids + Cfulvic acids | Chumic acids: Cfulvic acids |
|---------------------------|-----------------|----------------------|-----------------------|-----------------------------|-----------------------------|
| Ah1                       | 1.52            | 40.1                 | 31.6                  | 71.7                        | 1.3                         |
| Ah 2                      | 2.20            | 42.5                 | 25.1                  | 67.6                        | 1.7                         |
| Ah 3                      | 0.86            | 20.9                 | 27.8                  | 48.7                        | 0.5                         |
| Ah 4                      | 1.28            | 44.6                 | 27.1                  | 71.7                        | 1.6                         |

| Horizons of the paleosols | C, % to the soil | Chumic acids, amount | Cfulvic acids, amount | Chumic acids + Cfulvic acids | Chumic acids: Cfulvic acids |
|---------------------------|-----------------|----------------------|-----------------------|-----------------------------|-----------------------------|
| Ah1                       | 1.17            | 52.2                 | 23.8                  | 76.0                        | 2.2                         |
| Ah 2                      | 1.95            | 57.8                 | 23.2                  | 81.0                        | 2.5                         |
| Ah 3                      | 0.40            | 27.0                 | 37.8                  | 64.8                        | 0.7                         |
| ABh 4                     | 0.41            | 5.0                  | 45.0                  | 50.0                        | 0.1                         |

| Horizons of the paleosols | C, % to the soil | Chumic acids, amount | Cfulvic acids, amount | Chumic acids + Cfulvic acids | Chumic acids: Cfulvic acids |
|---------------------------|-----------------|----------------------|-----------------------|-----------------------------|-----------------------------|
| Ah 1                      | 1.12            | 43.2                 | 23.4                  | 66.6                        | 1.8                         |
| Bh1                       | 0.46            | 25.0                 | 33.6                  | 58.6                        | 0.7                         |
| Ah 2                      | 1.31            | 23.3                 | 16.1                  | 48.4                        | 1.4                         |
| Ah 3                      | 0.62            | 11.3                 | 41.8                  | 53.1                        | 0.3                         |

| Horizons of the paleosols | C, % to the soil | Chumic acids, amount | Cfulvic acids, amount | Chumic acids + Cfulvic acids | Chumic acids: Cfulvic acids |
|---------------------------|-----------------|----------------------|-----------------------|-----------------------------|-----------------------------|
| Ah 1                      | 1.22            | 34.9                 | 21.8                  | 56.7                        | 1.6                         |
| Ah 2                      | 1.02            | 37.2                 | 22.8                  | 60.0                        | 1.6                         |
| Ah 3                      | 0.94            | 32.0                 | 41.1                  | 73.1                        | 0.8                         |
| BCh3                      | 0.57            | 19.9                 | 43.6                  | 63.5                        | 0.4                         |

This value increases from the Ah paleosols horizons of forest genesis to the Ah paleosols horizons of steppe genesis.
Humus group composition for humus horizons of sections: «Nyasha 2» (A1, A2, A4); «Ust-Karaulnaya 3» (Ah1, Ah2); «Local history museum 2» (Ah3); «Tatyshhev island 3» (Ah1, Ah4) showed their belonging to the soils of steppe genesis. Humus is characterized by a high degree of humification and belongs to the fulvate-humate type. Humic acids dominate over fulvic acids. The ratio of Сhumic acids: Сfulvic acids is greater than 1.

Humus group composition for humus horizons of sections: «Nyasha 2» (Ah3); «Ust-Karaulnaya 3» (Ah3); «Local history museum 2» (Ah1, Ah2); «Tatyshhev island 3» (Ah3) showed their belonging to the soils of forest genesis. Humus is characterized by a low degree of humification. Humus of humus horizons Ah3 belongs to the humate-fulvate type. The ratio of Сhumic acids: Сfulvic acids is less than 1.

The first paleosol (Ah1) developed in the steppe conditions in a dry and warm climate as chernozems. The second paleosol (Ah2) is similar to the first one in terms of the humus distribution and its group composition. The morphological appearance of the second paleosol suggests the formation under forest-steppe vegetation in the conditions of pronounced wind activity. The third paleosol (Ah3) has the characteristics of the forest zone soil. It was formed in moderately warm and humid conditions under forest vegetation by the type of gray forest soil. The fourth paleosol (Ah 4) belongs to the sod forest with signs of meadow soil formation. This is manifested in the presence of glandular and ferruginous-manganese neoplasms. It was formed in cold climatic conditions with increased ground moisture.

The evolution of ecosystems in the study area shows the change of forest and steppe ecosystems within the climatic periods: boreal (BO2) - modern (SOV) (table 5).

| Age, thousands of years. | Climate period, index | Soils                               | Humus, % | Chumin acids: Cfulvic acids | Vegetation                                      | Indicator of dryness |
|------------------------|-----------------------|-------------------------------------|----------|----------------------------|------------------------------------------------|----------------------|
| 0.0-0.1                | SOV                   | Chernozezms, dark gray forest       | 9.0      | 1.2                        | Pine-birch forest-steppe                        | 2.0                  |
| 0.1-3.0                | SA                    | Chernozezms, dark gray, turf forest | 2.0      | 1.1                        | Pine-birch forest-steppe with cedar and fir     | 1.8                  |
| 3.0-4.5                | SB                    | Forest turf, grey forest            | 0.8      | 0.9                        | Deciduous-birch-pine forests with spruce and cedar | 1.7                  |
| 4.5-6.0                | AT2                   | Chernozezms                         | 2.2      | 1.7                        | Mixed grass steppes                             | 2.0                  |
| 6.0-8.0                | AT1                   | Grey forest                         | 0.9      | 0.8                        | Birch-larch forests                             | 1.9                  |
| 8.0-8.7                | BO2                   | Turf forest                         | 1.3      | 1.6                        | Birch and pine forests                          | 1.9                  |
|                        |                       | Gray forest, podzolic               | 0.7      | 0.8                        | Pine and birch forests with cedar and fir        | 1.8                  |

Changes in forest (taiga) and steppe (forest-steppe) ecosystems are associated with climate changes in the Holocene and are determined by temperature and precipitation indicators. Correlation of diagnostic features in humus horizons of paleosols and climatic indicators shows the dynamics in soil and plant communities. The ratio of changes in climate indicators and humus (group composition)
indicates climate change in different periods of the Holocene. Soil and plant characteristics determine the range of climate fluctuations specifically for each territory. The natural warming associated with the cycle of increasing temperature and dryness in the last decade is significant.

The evolution of ecosystems in the southern Yenisei Siberia had specific features in different climatic periods of the Holocene.

Pre-boreal (PB) period of the Holocene. The landscape of cold steppes was typical for periglacial alluvium. Then micromorphological study of deposits in this period allows identifying signs of taiga soil formation. There was a landscape of the northern and middle taiga.

The boreal (BO) period of the Holocene. There was a landscape of aspen-birch subtaiga. The deposits are represented by two paleosols: one paleosol formed in steppe conditions; the other paleosol (Ah3) in forest (taiga) conditions. In this paleosol inclusions from coals of woody vegetation and bone remains of forest animals (elk, roe deer, bear) were found. In the section Local history museum («Tatyshev island 3») this paleosol correlates with the humus horizon (Ah3) of the third paleosol on the Tatyshev island («Tatyshev island 3»). This paleosol is also of forest origin, but has passed the meadow stage of development.

The Atlantic (AT) period of the Holocene is divided into two halves. In the southern Yenisei Siberia in the first half of the period (AT1) there was a birch forest-steppe with the soil cover of dark gray forest, sod-podzolic, and sod-gley soils. Climate conditions were defined as moderately warm and humid. In the areas adjacent to the city of Krasnoyarsk forest communities existed and soils of forest genesis were formed. On the Tatyshev island («Tatyshev island 3») features of heat and moisture led to the formation of steppe paleosol. In the second half of the Atlantic period (AT2) forest-steppe and steppe landscapes with the soil cover of chernozems, dark gray forest, sod-forest and brown-earth soils were characteristic.

Subboreal (SB) period of the Holocene. There was a tendency to cool the climate. The bioclimatic conditions corresponded to the subtaiga - forest-steppe landscape. With the onset of some cold weather, the vegetation acquired a taiga appearance. The soil cover was represented by a combination of zonal and azonal soils. In the deposits structure of geological sections from the Tatyshev island («Tatyshev island 3») the formation of paleosol occurred under conditions of forest genesis. The genetic horizons of this paleosol contain inclusions of charcoal and bones of forest animals. The structure of the geological sections from «Nyasha 2» also has paleosol of forest genesis. Humus-accumulative horizons of the paleosol are interrupted by aeolian deposits. They were formed when wind activity increased in the territory. A layer of aeolian sandy loam with signs of humus can reach the thickness of more than two meters. There was a taiga appearance of vegetation and the main forest-forming species were larch, pine, birch, spruce, and cedar.

Sub-Atlantic Holocene period (SA). It is characterized by the formation of modern natural complexes. Under the natural complex of the forest-steppe dark gray forest, sod-forest, brown-earth soils were formed, in the steppe areas – chernozems.

Modern Holocene period (SOV). It is characterized by a combination of forest (pine and pine-birch forests) and steppe ecosystems. There was a tendency to increase the air temperature and decrease the annual precipitation. The concentric arrangement of fragments in steppe, forest-steppe and subtaiga ecosystems is typical. In the northern and middle (typical) parts of the territory small-leaved, mixed and coniferous forests grow in combination with steppe and meadow formations. The southern part of the territory is represented mainly by steppe formations and plowed.

Climate was the main factor influencing the evolution of ecosystems in the southern Yenisei Siberia during the time period under study. There are shifts in the boundaries of steppe and forest communities depending on global climate changes. This is expressed in the fluctuation of ecosystems in time and space. Paleosols can be called «benchmark» in the state of ecosystems. In each climatic period of the Holocene the continuity in soil formation processes led to the formation of zonal types in soil cover. Local changes in latitudinal zoning depended on fires, near ground water level, and other factors. In modern times climate change contributes to increasing in air temperature and decreasing in annual precipitation.
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