Properties and major element concentrations in peat profiles of the polygonal frozen bog in Western Siberia

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Abstract. The properties and elemental composition of the Histosols of polygonal frozen bog in Western Siberia are characterized. The study of peat soils allowed an evaluation of the effect of micro-landscape on main properties and major element concentrations. According to acid-base characteristics and the ash content, the studied soils can be qualified as oligotrophic. The soil profile shows a tendency to increase the TOC in the lower horizons, and especially, in the peat soils of the polygons. The highest average TOC, Ca, Mg, K, P, Fe, and Na concentrations in the peat profile are observed in the soils of polygons (1.2-2.2 times). A large number of phytomass and plant productivity contribute to the enrichment of soils with carbon and some elements on the polygons. In addition, the difference between the soils of polygons and hollows in terms of the thermal conditions and peat hydrophysical characteristics is reflected in their elemental composition and properties.

Introduction

Peatlands are widely represented almost throughout the tundra and taiga zones of Western Siberia, and at the same time, a clear zonality is traced in their distribution [1, 2]. Thus, in the tundra zone, frozen polygonal bogs prevail in the area, the relief of which is formed by a system of frost cracks with the formation of polygonal wedge ice. There is a significant spatial heterogeneity characterized by various land cover types, namely peat plateaus or polygons, frost cracks and hollows. Accordingly, the conditions of soil formation determine the complexity of the soil cover of polygonal peatlands, in the contours of which peaty, as a rule, frozen soils of polygons and depressions are common, which differ in the structure of the peat deposit, temperature conditions, peat accumulation rates, and elemental composition. Due to the accumulation of a significant amount of soil organic matter [3-7], these soils become key components in the global carbon cycle and play a decisive role in the formation of the elemental composition of water bodies draining peatlands [8]. It is believed that the destabilization of frozen peat, an increase of the active layer thickness represent a major environmental threat but also constitutes a very important factor of nutrients (including metal micronutrients) and toxicants release to the hydrological network and their subsequent transport to the Arctic Ocean [9-10]. The degree of a major and trace elements release will be strongly dependent on the elemental composition of the soil peat profile. In this regard, the goal of this
work is to identify the main properties and patterns of the chemical elements content and distribution in the peat cores, related to specific microenvironments of the frozen polygonal bogs in Western Siberia.

**Materials and methods**

The study area is located in the north of the West Siberian Plain in the Tazovsky District of the Yamalo-Nenets Autonomous Okrug and belongs to the southern tundra subzone and the continuous permafrost zone. The key site is situated on a frozen polygonal bog (67°22ʹN, 78°41ʹE), 9 km south of the Tazovsky village. Key physico-geographical and landscape characteristics of the studied site are described in Table 1. The peat was actively forming since the beginning of the Holocene until freezing of bogs in sub-Boreal period (9-4.5 thousand y.a.). After that, the rate of peat formation in bog areas has decreased [11-14]. The main mineral substrates underlying frozen peat layers in Tazovsky is alluvial sands with alevrolites [15]. The climate ranges from moderately humid and cold in summer to cold and snow-deficient in winter. Mean annual temperature is $-9.1\, ^\circ \text{C}$ and the annual precipitation is 360 mm [16].

**Table 1. Physico-geographical and landscape of the studied site characteristics.**

| Micro-landscape | Peat thickness, m | ALT, cm | Vegetation Types and Dominant Plant Species | Soil [17] |
|----------------|------------------|--------|-------------------------------------------|----------|
| polygons       | 2.0-4.0          | 41     | Dwarf shrub-green mosses-lichen            |          |
|                |                  |        | *Betula nana*, *Ledum palustre*,           | Hemic Epicryic Histosols (Hyperorganic) |
|                |                  |        | *Vaccinium vitis-idaea*, *V. uliginosum*,  |          |
|                |                  |        | *Arctous alpine*, *Rubus chamaemorus*,     |          |
|                |                  |        | *Empetrum nigrum*, *Cladonia stellaris*,   |          |
|                |                  |        | *Alectoria ochroleuca*, *Cetraria nivalis*,|          |
|                |                  |        | *Sphagnum balticum*, *S. fuscum*,          |          |
|                |                  |        | *Drepanocladus ssp.*, *Polytrichum ssp.*   |          |
| hollows        | 0.2-1.5          | 65     | Sedge-Sphagnum                             | Epifibric Endohemic Cryic Histosols |
|                |                  |        | *Carex chordorrhiza*, *C. rotundata*,      |          |
|                |                  |        | *C. limosa*, *Eriophorum polystachyon*,    |          |
|                |                  |        | *Menyanthes trifoliata*, *Comarum palustre*,|          |
|                |                  |        | *Sphagnum balticum*, *S. jensenii*, *S. majus*,|          |
|                |                  |        | *S. lindbergii*                           |          |

A typical feature of the studied bog is the presence of positive and negative forms of relief (micro-landscapes). The positive form includes polygons and the negative form comprises hollows and frost cracks (Figure 1). Vegetation is essentially oligotrophic which indicates ombrotrophic conditions. On polygons, the upper 50 cm of peat deposits consist mainly of residues of dwarf shrubs, hypnum mosses, grasses, lichens, sphagnum mosses (*Sphagnum fuscum*, *S. majus*) and, less commonly, wood. In the hollows, the upper 50 cm of peat deposits consist mainly of sphagnum mosses, cotton grass, sedges, and less commonly, grasses.
Figure 1. Micro-landscape of the studied polygonal bog. The inserts represent aerial (drone-made) photos of main sites with the position of polygons (P), hollows (H), and frost cracks (FC).

The soil sampling was performed in August at the end of the active season. A peat corer with Ti blades and a holder was used to extract the soil samples from the surface to the permafrost ice. The identification of soils on the key site was given in accordance with the World Reference Base [17]. All peat cores were sampled from thawed or frozen soils that belonged to the Histosols group (soils having a peat thickness >60 cm) (Table 1). For the measurement of the element concentrations, the peat soil samples were first processed in a clean room (class A 10,000) and then were digested in Teflon (Savilex®) reactors using a Mars 5 microwave digestion system (CEM, France). The major element concentrations were measured by ICP-MS (Agilent 7500 CE) using a three-point calibration against a standard solution of known concentration. Nitrogen and carbon concentrations in dry peat samples were measured by Cu-O catalyzed dry combustion at 900 °C with 60.5% precision for standard substances (Thermo Flash 2000 CN Analyzer). Standard laboratory analyses were also performed to determine the ash content (GOST 11306-83), exchangeable bases (GOST 27821-88), and base saturation. The pH values were measured by data recorders WTW Multi 3320 (Germany) with sensors pH-Electrode SenTix® 41.

The data were analyzed using STATISTICA version 8 software (StatSoft Inc., Tulsa, OK, USA). All graphics and figures were created using MS Excel 2010, and the GS Grapher 11 package.

Results and discussion
Histosols are the main soil type within the studied polygons and hollows of the polygonal bog. Dystric Hemic Epicryic Histosols (Hyperorganic) and Dystric Murshic Hemic Epicryic Histosols (Hyperorganic) are common on the polygons, which have an average active layer thickness is 41 cm and peat thickness varying from two to four meters (Figure 2a). Dystric Fibric Cryic Histosols and Histic Reductaquic Cryosols (Clayic) are common in the hollows (Figure 2b). The average thickness of the active layer in the latter reaches 65 cm, and the peat deposit ranges from 0.2 to 1.5 m. Accordingly, the peat thickness is lower in the hollows, than on the polygons, and the ALT is greater within the hollows.
All the considered peat soils are characterized by the acid reaction (pH 3.0-3.9). The pH values of the peat slightly increase down the profile remaining in the range of strongly acid and acid reaction (Figure 3a). However, in comparison with the peat soils of the polygons, the soils of the hollows are characterized by the somewhat higher pH values. Accordingly, the Histosols and especially those occupying elevated micro-landscape are unsaturated with bases (<30%). The total exchange bases in peat soils in the active layer are low and the maximum accumulation of exchangeable bases (39.8 meq/100 g of soil) is seen in the contact zone between the active soil layer and the underlying permafrost (Figure 3b). The ash content of peat soils varies on the polygons from 4.02 to 7.9% and in the hollows in the range of 2.6-5.19% (Figure 3c). This slight difference in values between the Histosols of the polygons and hollows may be related to the mineralization intensity and the botanical composition of peat. The dwarf shrubs predominate on the polygons where decompose more intensely than sphagnum mosses absolutely dominant in the hollows [18]. Thus, the Histosols of the polygons and the hollows according to their acid-base characteristics and the ash content can be qualified as oligotrophic.

The average content of the total organic carbon (TOC) in the peat soils profile of the studied bog micro-landscape range from 46.9% to 43.5% for the polygons and the hollows, respectively (Figure 3d). These values vary within the vertical profile and significantly (p<0.05) depend on the chosen ecosystem. The soil profile shows a tendency to increase the TOC in the lower horizons, and especially, in the Dystric Hemic Epicryic Histosols of the polygons. In general, the polygons have a greater phytomass supply than hollows especially at the expense of root systems of the dwarf shrubs. Therefore, the larger phytomass supply [19] contributes to the carbon enrichment of soils on the polygons. The plant productivity is also higher on the polygons than in the hollows [19], however, the peat accumulation rate on the polygons is lower. This is due to more active peat decomposition, including the role of lichens [20], which slow down peat accumulation and are absent in the hollows.

With respect to the C/N ratio, the organic matter of all soils is impoverished of nitrogen (Figure 3e). The predominantly sphagnum composition of the peat with the low ash content and low nitrogen content...
explains the higher C/N values. However, in the lower horizons, this ratio narrows somewhat, and especially in the peat soils of polygons due to the relatively greater degree of decomposition.

Figure 3. Physicochemical properties of the studied peat soils of different micro-landscapes.

The highest average Ca, Mg, K, P, Fe, and Na concentrations in the peat profile are observed in the soils of polygons (1.2-2.2 times) characterized by an eluvial landscape position (Figure 4). Elevated element concentrations in the peat soils of the polygons compared to the hollows can be associated with the differences in their thermal regime and peat hydrophysical properties [21]. The general tendency of the element distributions in the soils of the polygons is a decrease in concentrations (except for Fe) to the lower supra-permafrost part of the profile with the presence of maxima in the upper and middle parts of the profile, especially for K, P, and Na. In the soils of the hollows, the elements considered are unevenly distributed and tend to accumulate in the lower horizons as shown in Figure 4. The values of K, P, and Na over the peat profile of micro-landscapes are correlated ($r^2=0.68-0.83$), and the concentration of Ca and
Mg are highly correlated ($r^2 \geq 0.9$) in the peat profile of the polygons. Apparently, the trend of decrease in the K, P, and Na concentrations on the polygons reflects high mobility due to their leachability from the biological peat matrix [22] and the plant/mycorrhizae uptake from the peat [23]. The role of atmospheric deposition of Na on the moss layer, transferred to the upper part of the peat profile, and removed subsequently through the washing by surface flow, should also be considered. In contrast, the removal of K and P is mostly through the plant uptake, given its high affinity to the vegetation. The similarity in the accumulation of the Ca and Mg within the peat column profile indicates their stability and simultaneous supply to the peat deposits.

![Diagram of Ca, Mg, K, Na, P, and Fe concentrations in the peat profile](figure4)

**Figure 4.** Ca, Mg, K, Na, P, and Fe concentrations in the studied peat soils of different micro-landscapes.
Conclusion

The study of peat soils collected on the polygonal frozen bog in the western Siberia Lowland allowed determining the properties and major element concentrations in soils, depending on the micro-landscape. The soils of various contrasting micro-landscape vary in botanical composition, peat thickness and seasonal thaw layer depth. All Histosols are characterized as acidic, base-unsaturated, with a high content of organic carbon and low ash content. The average concentrations of the total organic carbon and major elements are higher in the soils of polygons. These parameters change with different rates in the depths of the soil profile. The presence of the maxima in element concentrations is usually observed in the upper and middle parts of the peat profile, primarily represented by green and live Sphagnum. In addition, the difference between the soils of polygons and hollows in terms of the thermal conditions and peat hydrophysical characteristics is reflected in their elemental composition and properties.

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