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Soil-ecological conditions of the north taiga flat-mound bog, Western Siberia

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Of particular interest in the north of Western Siberia are frozen flat-mound bogs. Being formed in a transitional climatic zone, on the southern front of the permafrost zone, these frozen peatlands may turn out to be highly reactive upon thawing and deliver high amounts of solutes to the hydrological network. A detailed study of a flat-mound bog was carried out in a key area of about 3 hectares (Purovsky district, Yamalo-Nenets Autonomous Okrug). The soil-ecological conditions of the site are described, as well as the effect of spatial heterogeneity on the composition and properties of soils. Using topographic mapping and photogrammetry, it was identified that the bog surface is characterized by distinct microtopography (mounds-hollows-thermokarst subsidence with a percentage areas ratio of 49:30:21, respectively). Small-scale variations in ecohydrological settings, microtopography, and vegetation affect the distribution of nutrients, organic carbon in soils, and DOC (dissolved organic carbon) in bog waters. The main soil types are Dystric Hemic Cryic Histosols and Dystric Hemic Histosols (Gelic) found on mounds and in subsidence, respectively. If the peat thickness decreases to 40– 60 cm, then Spodic Histic Turbic Cryosols (Albic, Arenic) and Histic Turbic Cryosols (Albic, Arenic) form. In hollows and fens, Dystric Epifibric Histosols, Spodic Histic Turbic Cryosols (Arenic), and Gleyic Histic Entic Podzols (Turbic) are the most common. The proportion of soils with frozen peat is no more than 20% of the area of the key site and permafrost lies deeper, in the underlying rocks. It was found that carbon stocks within the key area vary from 31.1 to 91.3 kg/m2. The maximum values are observed in transit subsidences/hollows between mounds, where water is discharged. Concentrations of macro-microelements in bog waters vary depending on microform types. For some elements (e.g., DOC, Fe, Al, B, Si, Ti, V, Rb, Sb, Cs, REEs (rare earth elements), Pb, Th, U), they are approximately equal or 1.5–2 higher on the mounds. The export of DOC and other elements in permafrost areas is primarily controlled by the residence time of water and movement ways along the profile. In addition to this, the physicochemical properties of peat and biomass, which are also higher on mounds, influence the distribution and accumulation of nutrients.

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Keywords

Microtopography, Histosols, peatlands, bog waters, microform type, frozen flat-mound bog, Yamalo-Nenets Autonomous Okrug

Introduction

The West Siberian Plain stands out among other boreal plains with its phenomenal paludification, playing an important role in global carbon balance due to their capacity to store carbon and exchange both CO_2 and methane with the atmosphere (Liss et al. 2001; Friborg et al. 2003; Smith et al. 2004; Bohn et al. 2007; Novikov et al. 2009; Kirpotin et al. 2009; Raudina et al. 2018; Serikova et al. 2019; Karlsson et al. 2021). Due to the high level of lakes and intense paludification (in some parts up to 70–80%), a great diversity of peatland and wetland types are widely represented in the landscape structure of the plain. Much more attention is paid to a part of the bog system areas of transitional climatic zones in the north of Western Siberia (Vasil’chuk and Vasil’chuk 2016; Pokrovsky et al. 2016; Kaverin and Pastukhov 2018; Koronatova et al. 2018; Payandi-Rolland et al. 2020; Matyshak et al. 2021; Manasypov et al. 2022; Kuzmina et al. 2023). Of particular interest here are flat-mound frozen bogs (palsa) formed under permafrost conditions, which are represented by both waterlogged modern ecosystems (hollows, fens, pools) and specific cryogenic peatlands of various genesis and age. Being formed in a transitional climatic zone, on the southern front of the permafrost zone, these peatlands are highly sensitive to fluctuations in external factors (for example, temperature and precipitation). Accordingly, with climate warming, these frozen bogs will experience the most dramatic changes compared to others.

Small-scale variations in surface elevation (microtopography) often form distinct spatial patterns in these carbon-rich landscapes (Couwenberg and Joosten 2005; Belyea et al. 2015; Nijp et al. 2019; Loiko et al. 2019; Harris et al. 2020). Raised bogs patterning are particularly distinct within the vast northern West Siberian peatlands of the southern front of the permafrost zone. In addition, feedback processes are observed in these bogs between the variability of soil parameters and ecohydrological setting, microtopography, vegetation, and the underlying permafrost table topography. In this regard, moisture flows change, and, accordingly, the redistribution of heat and nutrients occurs. To this, the peculiarity of peat to change its thickness and surface shape depending on the water table position and structural characteristics (for example, vegetation cover) is added, which creates conditions for the emergence of new soil microcombinations. Various hypotheses and models describe how small-scale feedbacks among vegetation, hydrology, and soils cause spatial differences in nutrients and peat accumulation that surface patterns to develop over time (Couwenberg and Joosten 2005; Sullivan et al. 2008; Eppinga et al. 2009; Malhotra et al. 2016). Because of the significant landscape heterogeneity it is necessary to characterize the ecosystem functioning in the different microtopographic features to understand and predict the impact of climate change on greenhouse gas exchange. Therefore, this work is aimed at studying the soil cover complexity in conjunction with the local factors that determine it.

Materials and methods

A detailed study was made of a flat-mound bog in a key area of about 3 hectares (63°47′9″N, 75°38′28″E and 63°47′7″N, 75°38′33″E). The area is located within the northern macroslope of the Siberian Uvals on the interfluve of the Pyakupur and Chuchuyakha rivers in the zone of the northern taiga, Purovsky district, Yamalo-Nenets Autonomous Okrug (Fig. 1). Quaternary clays, sands, and alevrolites underlying the surface peat deposits range in thickness from several meters to 200–250 m and have fluvio-glacial and lake-glacial origin. The climate is humid semi-continental with mean annual temperature ranging from -1°C to -4.4°C. The annual precipitation is 594 mm. The study area is located on the border of discontinuous and sporadic permafrost zones, on the southern front of permafrost zone, where the changes in permafrost are the highest, and C stock in soils is also high (40–100 kg/m2).

The flat topography of the study area causes a weak surface runoff, wide surface waterlogging and an abundance of lake coverage (limnicity). The main part of the territory is occupied by frozen flat-mound bogs, a characteristic feature of which is a large area of thermokarst lakes (between 45 and 55%). The bog surface is characterized by distinct microtopography (mounds-hollows-thermokarst subsidence with a percentage areas ratio of 49:30:21, respectively), which strongly affects the soil cover structure, soil thermal and hydrological regimes and, consequently the dynamics of nutrients and carbon in these landscapes. The vegetation types covering this site are typical for the northern taiga bogs of Western Siberia. The mounds are covered by dwarf shrubs (*Ledum* ssp., *Betula nana*, *Andromeda polifolia*, *Vaccinium* ssp., *Empetrum nigrum*), lichens (*Cladonia* ssp., *Cetraria*, *Ochrolechia*) and mosses (*Dicranum* ssp., *Polytrichum* ssp., *Sphagnum angustifolium*, *S. lenense*). The wet microforms contain moss-sedge associates (grasses *Eriophorum russeolum*, *E. vaginatum*, *Carex rotundata*, *C. limosa*, *Menyanthes trifoliate*, *Comarum palustre*; mosses *S. balticum*, *S. majus*, *S. lindbergii*, *S. warnstorfii*) and dwarf shrubs (*Oxycoccus palustris*) (Ilina et al. 1985; Peregon et al. 2007, 2009). Pine-shrub-lichen forests grow in drained positions of riverine territories.

Comprehensive studies were carried out at the key site. To assess the topographical heterogeneity, a topographic mapping (Nikon Nivo 3.0 C total station, more than 1000 points captured) and photogrammetric (DJI Phantom drone) survey of the surface were carried out. To determine the soils diversity, describe the seasonally thawed layer, and estimate the content of organic carbon and elemental composition, four soil transects were described taking into account the microtopography of the site. A spatial assessment of the thickness of peat, the occurrence of permafrost was carried out.

The identification of the soil was given in accordance with the World Reference Base (IUSS WRB, 2014). 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 (6 mL bi-distilled HNO3, 0.2 mL ultrapure HF and 1 mL ultrapure H2O2) using a Mars 5 microwave digestion system (CEM, France). The major and trace element concentrations were measured by ICP–MS (Agilent 7500 ce) using a three-point calibration against a standard solution of known concentration. The carbon concentration (Corg) in dry peat samples was measured by Cu-O catalysed dry combustion at 900°C with 60.5% precision for standard substances (Thermo Flash 2000 CHNS Analyser).

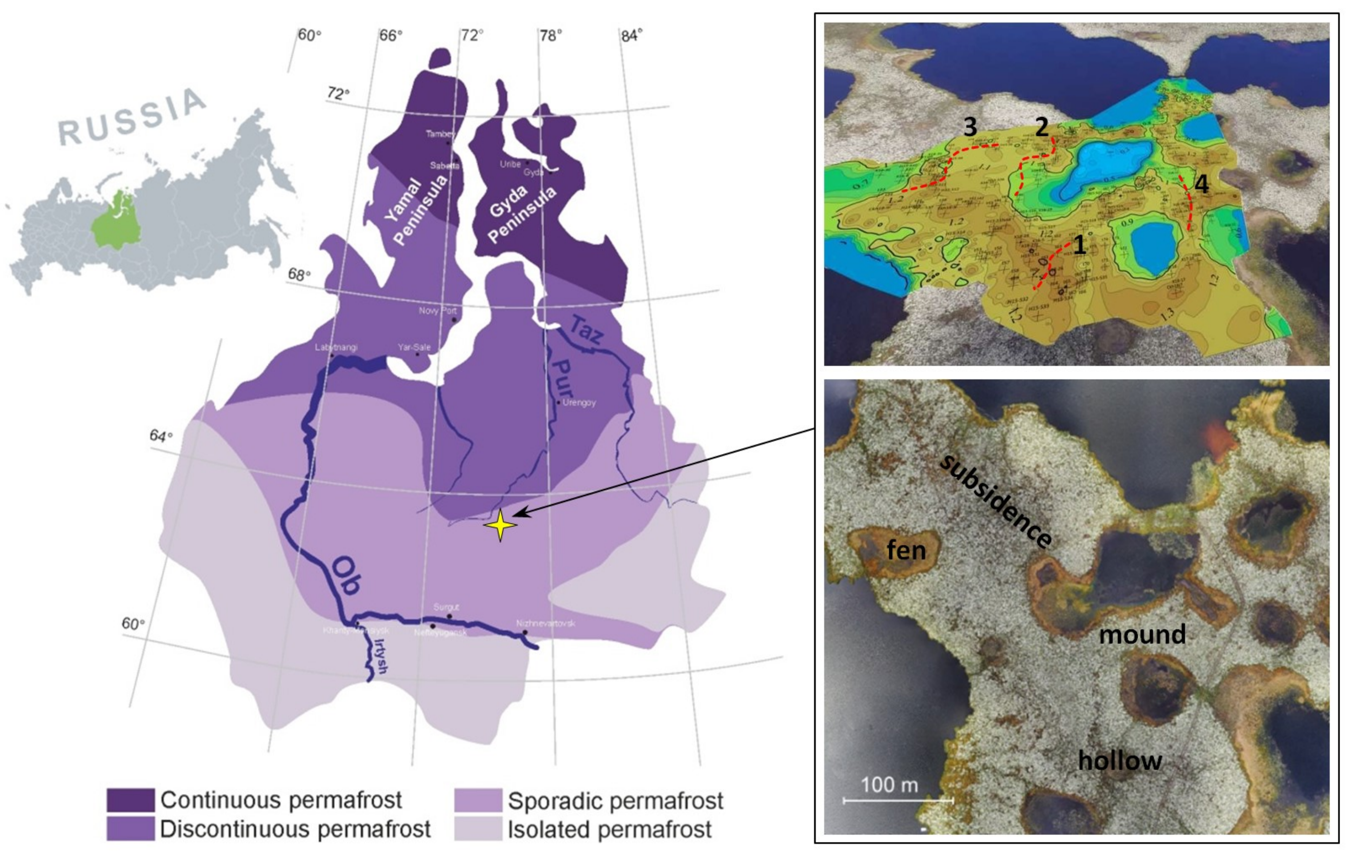

Figure 1. *Map of the study site with permafrost boundaries. The inserts represent aerial (drone-made) photos with microtopography (mound/ permafrost subsidence/ hollow/fen) and soil transects position (1–4).*

The bog waters from the soil active layer were collected in pre-cleaned PVC jars after digging. Collected waters were immediately filtered in 30 mL of pre-washed PP Nalgene® flacons through single-use Minisart filter units (0.45µm pore size, Sartorius, acetate cellulose filter). The dissolved organic carbon (DOC) was measured by a high-temperature thermic oxidation method using a Shimadzu TOC-LCPN analyzer, with an uncertainty of 2%. Major cations (Ca, Mg, Na, K), Si, and trace elements were determined with an Agilent ce 7500 ICPMS with In and Re as internal standards and 3 various external standards. At each sampling point, the pH, water temperature, specific conductivity (Cond) were measured in the field using a multiparameter instrument (WTW MULTI 3430 SET). All calculations and graphics were performed using MS Excel 2010 and standard package of STATISTICA-12.

Results and discussion

According to the topographic survey, the surface of the bog is hummocky, characterized by small differences in heights and is formed by flat, irregularly shaped hummocks or mound. The mound surface is usually no more than 0.5 m above the surface of adjacent hollows that may be defined relative to water table position. The maximum difference between mounds and hollows is no more than 80 cm. In turn, the mounds have height differences of the order of 30–40 cm between themselves. Under them, the thinnest active layer is observed, with an average thickness of 47 cm (at the end of August 2018). The mounds alternate with flat hollows, which, in the presence of erosion, acquire a trough-like shape. Peat thickness ranges from 0.1 to 1.4 m and from 0.4 to 1.1 m on the mounds and in the hollows, respectively. The thawing of mounds in summer reaches 60 cm and deeper; in turn, all studied hollows and fens are thawed. In thermokarst subsidences with a greater thickness of peat, the deepest occurrence of permafrost is observed, comparable to hollows (from 1.5 m and more). This is due to the warming effect of the flows of intrasoil moisture. The growth rate of peat in fens is higher than in hollows. In one fen, peat has grown at a rate of 0.54 mm/year over the past 700 years, while in another, the rate has reached 0.96 mm/year over the past 360 years. On mounds, the rate is several times less, and amounting, for example, to 0.15 mm/year over 1850 years and 0.28 mm/year over the last 1070 years.

During the laying of four soil transects on the main microform types, it was found that the soil cover is very contrasting. The main soil types are Dystric Hemic Cryic Histosols and Dystric Hemic Histosols (Gelic) found on mounds and in subsidence, respectively. If the peat thickness decreases to 40–60 cm, then Spodic Histic Turbic Cryosols (Albic, Arenic) and Histic Turbic Cryosols (Albic, Arenic) form. On locally elevated areas or lakeside slopes, where the peat thickness decreases to 40–60 cm, Spodic Histic Turbic Cryosols (Albic, Arenic) and Histic Turbic Cryosols (Albic, Arenic) occur. In hollows and fens, Dystric Epifibric Histosols, Spodic Histic Turbic Cryosols (Arenic), and Gleyic Histic Entic Podzols (Turbic) are most common (Fig. 2).

A feature of all soils (including those frozen on mounds) is the presence of an illuvial horizon with an accumulation of black organic matter and/or reddish Fe oxides (spodic horizon). This illuvial horizon is typically overlain by an ash-grey eluvial horizon, ranging in thickness from a couple of cm (in the form of an "e" sign) to a thickness of 1 m. In addition, in the lower parts of the profiles (especially in the Gleyic Histic Entic Podzols (Turbic), cryodeformations are quite pronounced in the form of a flexural occurrence of layers of various particle size distributions (eolian bedding). On shallow-leaved massifs of flat-mound bogs, when the seasonally thawed layer reaches mineral horizons, burial of peat horizons during cryoturbations is often noted. When the thickness of peat is within the first tens of cm, sometimes the sandy mass is squeezed out onto the surface of peat. On the whole, mechanical cryogenic disturbances in the spatial position of soil horizons (or their parts) and profiles are important factors in the formation of the morphological appearance of soils with various granulometric compositions and moisture conditions in the permafrost zone of Western Siberia (e.g. Makeev 1981; Matyshak et al. 2009, 2017). It was also noted that the proportion of soils with frozen peat in their profile is no more than 20% of the area of the key site. The permafrost lies deeper, in the underlying rock. Therefore, such flat-mound bogs can rather be attributed to thawed bogs, which are at the last stages of permafrost degradation.

In the course of the geobotanical description, it was shown that several layers are distinguished in the vegetation cover with the predominance of certain species, depending on the bog surface patterning. The ground cover is predominantly shrub-lichen (*Ledum* ssp., *Betula nana*, *Andromeda polifolia*, *Vaccinium* ssp., *Empetrum nigrum*, *Cladonia* ssp., *Cetraria*, *Ochrolechia*). Lichens usually occupy 70– 80% of the surface, which, after dying off, form peculiar black layers 1–2 cm thick in the peat deposit. Peat horizons are distinguished by great diversity and mosaic composition and structure. The upper part of the mounds consists of alternating layers of sphagnum and lichen-sphagnum peat. In the lower part of the soil profile, the botanical composition changes to lichen-shrub, tree-lichen, lichen-sphagnum, and hypnum dark peat. Peat soil horizons of hollow/fens are represented by light peat with dominance of sphagnum and cotton grass residues, including its roots (*Eriophorum russeolum*, *E. vaginatum*, *Carex rotundata*, *C. limosa*, *Menyanthes trifoliate*, *Comarum palustre*; *S. balticum*, *S. majus*, *S. lindbergii*, *S. Warnstorfii*, *Oxycoccus palustris*). Within all bog ecosystems, the lower layer of peat belongs to the mesotrophic stage of development.

Changes in soil properties are observed along the soil profile and depending on microform types. In the peat horizons of Dystric Hemic Cryic Histosols, the organic carbon content (40.3–55.2%) is slightly higher than that of Dystric Epifibric Histosols, Spodic Histic Turbic Cryosols (Arenic) (39.8–53.7%). At the same time, the illuvial horizon can contain up to 40% or more carbon in relation to the overlying peat deposit. Statistically significant differences ($p<0.05$) were identified for the soils of the two considered microform. The concentrations of Fe, Ca, and Mn are higher in the soils of the fens compared with the mounds. Conversely, the highest values of K, Na, Al, Zn are traced in the Histosols of the elevated position. In addition, there are higher concentrations of Mn, Cr, Co, which exceed those encountered in the Histosols of other boreal plains of northern Eurasia. This, in turn, is a characteristic feature of the Histosols of Western Siberia (Moskovchenko et al.

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2016; Moskovchenko and Babushkin 2015; Stepanova et al. 2015). There is a high degree of intraprofile variation in the chemical element concentrations in the studied soils. In the soils of mounds, Corg, K, Na, Ni, Cs, Cu, Cr, Mo, Zr, Al, Ti, Ba, Th, V, Ce accumulate to a greater extent in deeper profile horizons, while Pb, Zn, Sb, Mg , Mn, Cd, Ca, Co, P, Sr, Fe tend to accumulate on the surface. In hollows/fens, almost all of the elements presented, with the exception of B, U, As, Se, and some REEs (rare earth elements) have higher values in the upper part of the soil profile.

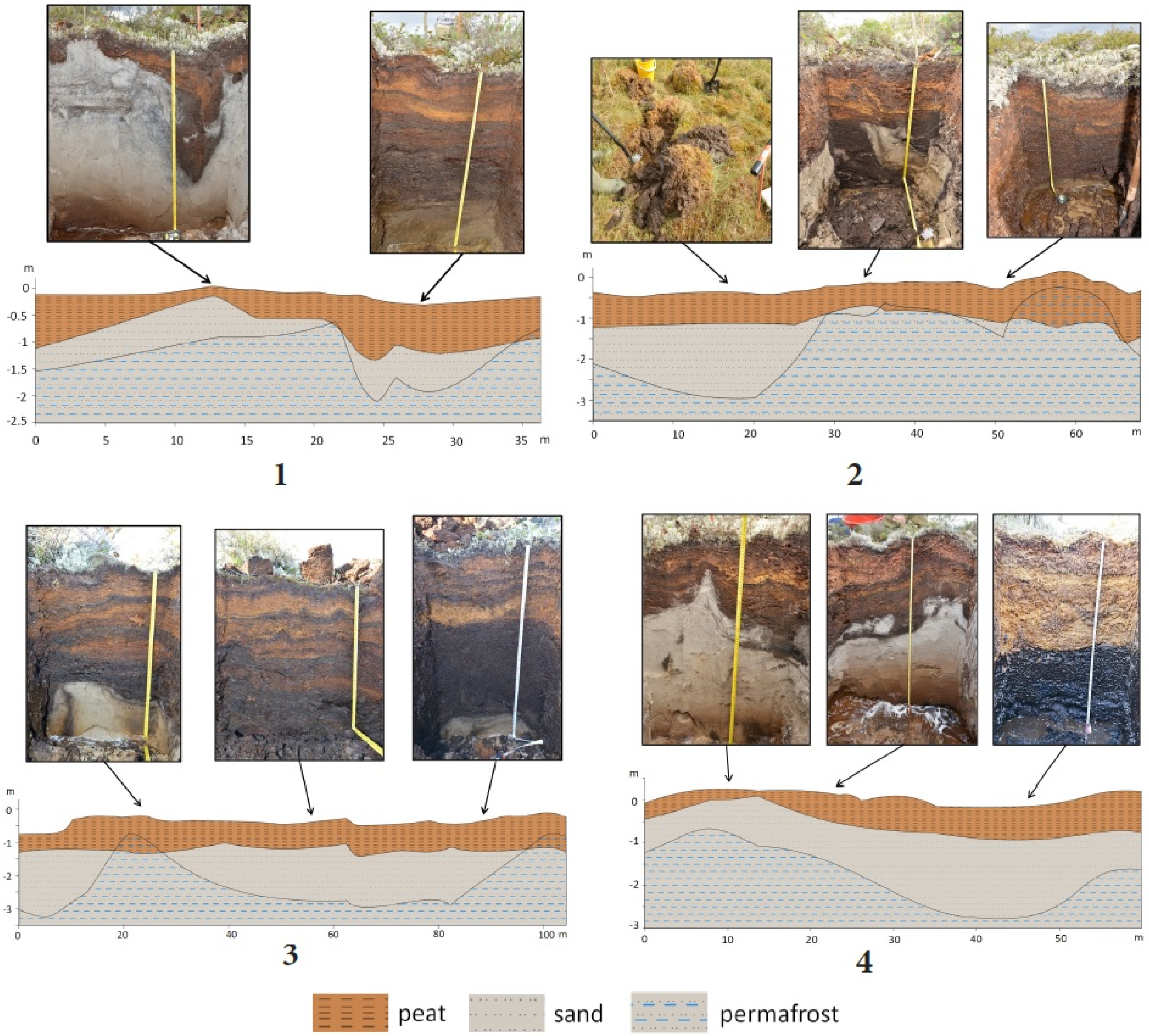

Figure 2. *Soil transects (1–4) with their positions on the landscape bog profile here (schematically) and above in Figure 1.*

It was shown that carbon stocks within the key area vary from 31.1 to 91.3 kg/ m2 (mean±SD = 61.1±21.9 kg/m2). The maximum values are observed in transit subsidences/hollows between mounds, where water is discharged. Within this microform, the thickness of peat ranges from 90–110 cm. A powerful illuvial horizon, up to 1.5 m thick, is developed in the mineral horizons. The percentage of carbon stock in the mineral horizon relative to its stock in the peat horizon was calculated. In general, for the key area, this value was 44.6±11.2 kg/m2. The average value of 45% turned out to be quite a significant value. This means that it is possible to increase the carbon reserves in the flat-mound bogs by almost 50%, relative to accounting for carbon only in peat.

Accordingly, for northern taiga bogs, which are characterized by the smallest depth of peat deposits, the carbon stock in mineral horizons can be even higher than in peat (1.2–1.5 times). This agrees with laboratory experiments on DOC release from peat and adsorption onto various mineral soils (Lim et al. 2022) showing that DOC released during peat thaw in upper soil horizons in permafrost regions can be sizably attenuated via adsorption on mineral layers. Significant contributions to the C pool in mineral layer are provided by organo-Al-Fe-rich Bh horizons. Therefore, DOC released during peat thaw in upper soil horizons in permafrost regions can be sizably attenuated via adsorption on mineral layers.

Differences in the export fluxes of DOC and other elements were noted. Namely, the composition of bog waters differs significantly from lakes and rivers that are located in a geochemically conjugated landscape. The main difference is the high concentrations of DOC, macro- and microelements. The application of the Wilcoxon-Mann Whitney test for assessing the differences between mean values of DOC and major and trace elements in dominant ecosystems demonstrated that a large number of elements depict significant differences in their concentration between different microforms. Comparison of the average values of bog water parameters for the entire sample showed that the concentrations of most elements are approximately equal or slightly higher by 1.5–2 on mounds. In accordance with the Mann-Whitney criterion, the values of Cond, DOC, Fe, Al, B, Si, Ti, V, Rb, Sb, Cs, REEs, Pb, Th, U showed a clear trend of decreasing values of bog waters ($0.63<R2<0.97$, $p<0.05$) from the mound to the fens with the watercourse. And, on the contrary, there is ($0.38<R2<0.85$, $p<0.05$) a gradual increase in pH, K, Na, Mn, Cr, Co, As, Cd, Ni, Cu, Zn, Sr in the series mound<fens/hollows<fens with the watercourse (Fig. 3). Thus, DOC concentrations on mounds are 82.9±29.7 mg/L, which is 2 times higher than in hollows (49.6±13.5 mg/L). For other elements, the difference in concentrations may differ by 2–3 times. Consequently, it may be concluded that the overall export fluxes of DOC, major cations, and trace elements from the peatland to the hydrological network is defined by the water amount that passes through the unfrozen peat column until the permafrost boundary before being evacuated to the river.

Thus, the concentrations of DOC and several elements in the catchment area of a peat bog decrease with an increase in runoff. The export of DOC and other elements in areas with permafrost is primarily controlled by the residence time of water and the movement waterways along the profile. Therefore, on mounds, there is a longer contact between peat layers and water migrating in the lateral and vertical directions, while in hollows it moves faster with subsoil and surface runoff. Accordingly, the shorter residence time of water and higher runoff, hydraulic conductivity in hollows compared to convex microforms, explains the predominance of DOC and other elements in the waters of mounds. In addition, more dense peat (more than 2 times) lies on the mounds, with less water loss, and ten times lower filtration coefficients. In addition, the sampled suprapermafrost waters of the mound occurring in the active layer, typically at the border between the thawed and frozen part of the soil profile can also be enriched in DOC, macro-nutrients and DOM-bound metals during some thawing of frozen peat. The study of dispersed peat ice and peat porewaters from the active layer within the permafrost peatland in Western Siberia showed that DOC, alkali and alkaline-earth metals (Ca, Mg, Sr, Ba, Li, Rb, Cs), some trace elements (Al, Fe, Mn, Zn, Ni, Co, V, As, Y, REE, Zr, Hf, U) were sizably (more than 3 times) enriched in peat permafrost ice compared to peat porewaters (Raudina et al. 2017; Lim et al. 2021). Plant biomass is also higher on mounds, which also leads to more carbon being leached. In addition, seasonal warming conditions in hollows/fens contribute to greater heat accumulation, which determines the deeper position of permafrost in summer. This, in turn, is an important factor determining the water-thermal conditions and, accordingly, the course of biogeochemical processes, including the dynamics of organic matter. Cryoconcentration of dissolved substances during freezing of bog water is also much more pronounced on mounds compared to hollows. All the factors noted above contribute to the difficult movement of bog waters, an increase in the residence time of dissolved substances in soils of elevated microform types.

Conclusions

The studied bog is distinguished by contrasting soil and ecological conditions. Thus, the thickness of peat on mounds ranges from 0 to 110–120 cm. Sandy horizons underlying the peat deposit can have a carbon reserve of up to 40% or more in relation to the overlying peat deposit. The upper boundary of the permafrost is also quite heterogeneous, which depends on: 1. the thickness of peat, which isolates the permafrost from atmospheric heat, and 2. the presence of migrating intrasoil moisture, which has a strong warming effect. Small-scale variations in ecohydrological set- tings, microtopography, and vegetation affect the distribution of nutrients, organic carbon in soil, and DOC in bog waters. Investigating soil catenas, it was found that the soil cover is very diverse and varies within a meter. The main soil types are Dystric Hemic Cryic Histosols and Dystric Hemic Histosols (Gelic) found on mounds and in subsidence, respectively. If the peat thickness decreases to 40–60 cm, then Spodic Histic Turbic Cryosols (Albic, Arenic) and Histic Turbic Cryosols (Albic, Arenic) form. In hollows and fens, Dystric Epifibric Histosols, Spodic Histic Turbic Cryosols (Arenic), and Gleyic Histic Entic Podzols (Turbic) are most common. A feature of all soils is the presence of an illuvial horizon with an accumulation of black organic matter and/or reddish Fe oxides (spodic horizon). It was found that the proportion of soils with frozen peat is no more than 20% of the area of the key site and permafrost lies deeper, in the underlying rocks. Therefore, such flat-mound bog can rather be attributed to thawed bogs, which are at the last stages of permafrost degradation. Changes in soil properties are observed along the soil profile and depending on microform types. It was found that carbon stocks within the key area vary from 31.1 to 91.3 kg/m2. The maximum values are observed in transit microform types between mounds, where water is discharged. The values of several bog water parameters vary depending on landscape position. Some of them (Cond, РОУ, Fe, Al, B, Si, Ti, V, Rb, Sb, Cs, REEs, Pb, Th, U) are approximately equal or 1.5–2 higher on the mounds. The concentrations of DOC and a number of elements in the catchment area of a peat bog decrease with an increase in runoff. Therefore the export of DOC and other elements in permafrost areas is primarily controlled by the residence time of water and movement ways along the profile. In addition to this, the physicochemical properties of peat (e.g. density) and biomass, which are also higher on mounds, influence the distribution and accumulation of nutrients.

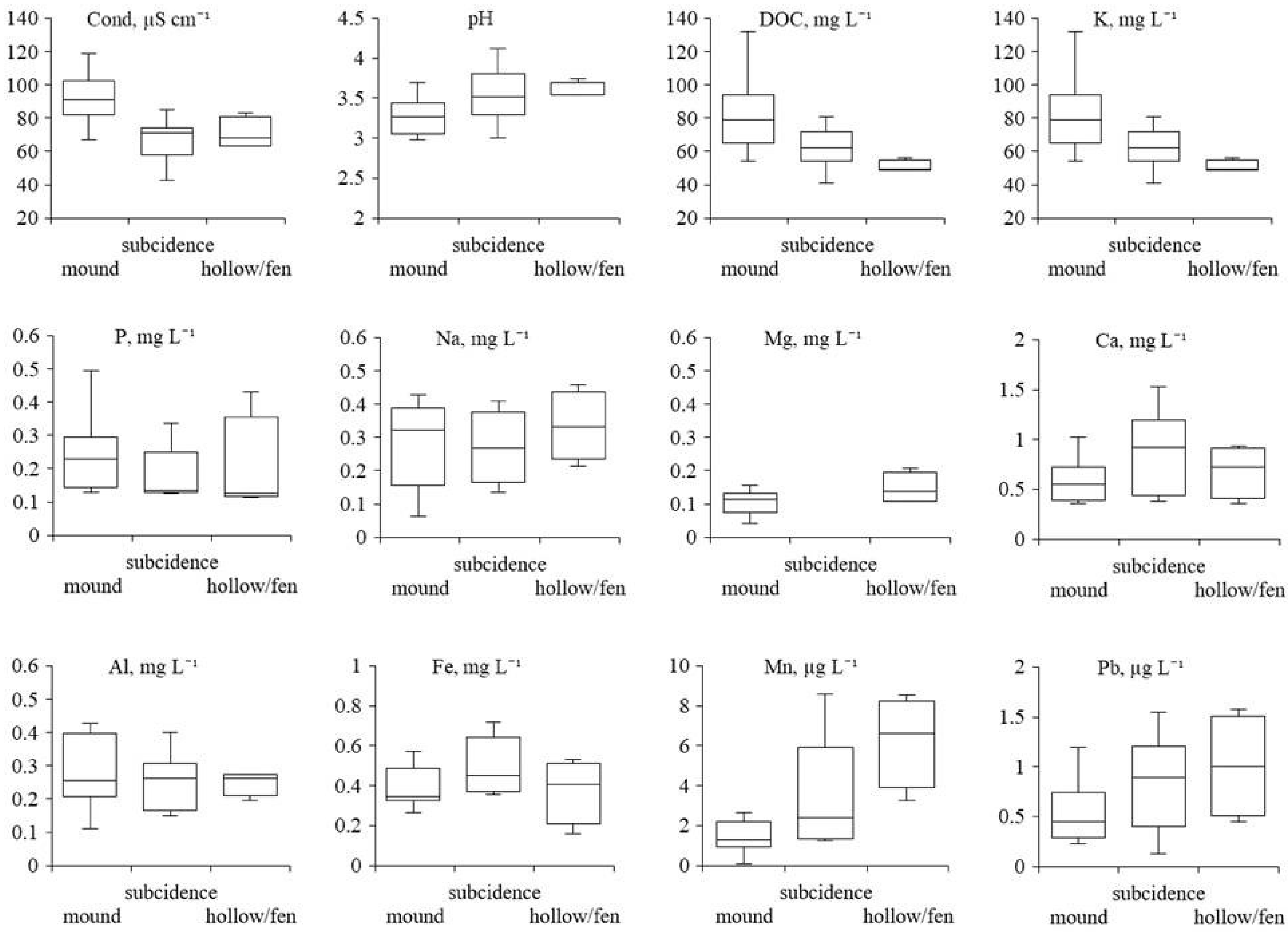

Figure 3. *Comparison of several water parameters between ecosystems of the frozen flatmound bog.*

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