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PALEOCRYOGENESIS AND SOIL FORMATION

SOILS OF PEAT SPOTS OF FROZEN PEATLANDS IN THE NORTH OF WESTERN SIBERIA

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The unique soils of frozen peatlands have been studied in the northern taiga of Western Siberia. These soils form on peculiar peat spots, from which the vegetation is completely absent for decades. Morphological characteristics, chemical properties of the soil of peat spots, as well as their functioning have been studied in comparison with the typical soils of frozen peatlands developing under the vegetation. The peat profile of the soils of peat spots is thicker and more transformed. The peat of studied soils is more decomposed and more acidic. The content of total carbon is significantly higher in the soils of peat spots (50.3 ± 2.1 % for peat spots and 45.7 ± 4.5 % for typical soils), as well as the total nitrogen content (2.4 ± 0.4 and 1.5 ± 0.5 %, respectively). Essential differences in the functioning were revealed. So, the average annual ground temperatures and extremes are higher in the soils of peat spots. It was revealed that on sites with bare surface the emission of carbon dioxide is on average 2 times less than on the sites under vegetation. The content of microbial biomass carbon is lower, too (250.1 ± 94.6 and 729.0 ± 71.9 μg/g, respectively).

Frozen peatlands, cryogenesis, cryoturbation, peat, peat soils, CO_2 emission, soil functioning

INTRODUCTION

Frozen peatlands are a characteristic landscape of the north of Western Siberia. The issues related to the genesis of these formations, the time of their emergence and their modern condition have been widely discussed in literature [*Pyavchenko, 1955; Shpolyanskaya and Evseyev, 1972; Romanovsky, 1993; Vasil'chuk et al., 2008*]. Several types of frozen peatlands (palsas) are identified, among which flat-topped frozen peat mounds and peat mounds, differing by the height and shape of the mounds, are the most characteristic types. Frozen peatlands (both types) are common in the zone of forest tundra and are less common in the taiga and tundra zones [*Kats, 1971*]. However, it is not always possible to differentiate the flat-topped peat mound zone from the zone of peat mounds due to the presence of transition forms and crossing of their habitats. Therefore, certain researchers [*Boch and Mazing, 1979*], as well as the authors of this study, consider flat-topped mounds and peat mounds to be one zone of genetically related palsa.

Soil formation on frozen peatlands proceeds with active impact of cryogenesis. In the northern taiga of Western Siberia, the soil cover of these landscapes is represented by a complex of Lithic Histoturbels and Typic Hemistels under sphagnum and lichen vegetation with peat thickness less than 60 cm [*Vasilevskaya et al., 1986*]. Some researchers [*Vasilevskaya et al., 1986; Seppälä, 2003; Marushchak, 2011*] note certain variations in the development of the soil cover of frozen peatland, which are different from typical areas by long-term absence of the vegetation cover on their surface. To indicate such frozen peatlands, V.D. Vasilevskaya suggests the term "peatlands undergoing degradation" [*Vasilevskaya et al., 1986*]. In foreign literature, such areas with bare spots of land are usually indicated as "peat circles" or "hot spots" [*Seppälä, 2003; Marushchak, 2011*].

By the present time, the soils of the peat spots have been investigated very little. There are very few studies devoted to the investigation of the properties, genesis and functioning of the spot soils: these are the above mentioned works by the Finnish scientists M. Seppälä and M. Marushchak, as well as the studies by D.A. Kaverin and A.V. Pastukhov [*2013*]. It is possible to come across peat spots mentioned in the publications by V.D. Vasilevskaya, V.Ya. Khrenov [*Vasilevskaya et al., 1986; Khrenov, 2011*]. The goal of this work is to carry out a detailed study of the morphological and chemical characteristics of soils developing on peat spots, as well as their functioning.

OBJECTS AND METHODS

The investigation area is situated in the north of Western Siberia (Nadym district, Tyumen region, Yamal-Nenetsky autonomous territory) within the northern boundary of the extent of northern taiga territories of the III[rd] lacustrine-alluvial plain of the Nadym River, in the Heygiyakha–Levaya Khetta interfluve (65°18′ N, 72°52′ E) (Fig. 1). This territory is developing under conditions of the discontinuous permafrost zone. In this regard, a combination of two contrasting landscapes is characteristic of this area of investigations. The first type of the landscape is represented by automorphous forest territories, where there is no permafrost. Forest ecosystems contain thin larch, birch-and pine forests, with fruticose-lichen undergrowth. The second type is polyhydromorphous and hydromorphous landscapes, where permafrost thickness varies in the range of 0.5–2.0 m. These landscapes are represented by oligotrophic bogs, not vast for their area, and widespread frozen peatlands, forming vast peat mounds varying from tens to several hundreds of square meters. On frozen peatlands, fruticose-ledum-lichen communities and fruticose-ledum-sphagnum communities are developed, bogs are characterized by sedge-sphagnum and fruticose-sedge-moss plant communities [*Moskalenko, 1999*]. Mother rocks are mostly sandy and clay sandy with lenses of light and medium-weight loam.

The object of the study was the soils of peat spots developing on the areas of frozen peatlands, the vegetative cover of which was completely absent for continuous periods (dozens of years).

From 2011 to 2013, more than 40 soil profile cuts were studied on the area of over 10 km^2 under peat spots and under the vegetation cover. The peat horizons were described in accordance with the von Post method [*Von Post and Granlund, 1926*]. The field identification of the degree of peat decomposition according to this method correlates well with the results of laboratory studies. The decomposition degree determined in the field studies is indicated as “H”, which has values ranging from 1 to 10 (corresponding to decomposition of peat from 5–10 to 60 %, respectively) [*Stanek and Silc, 1977*]. Thus, peat with the decomposition degree 1–3 is normally considered as low decomposed, the decomposition degree of 4–6 is considered as medium, and the decomposition degree of 7–10 is characteristic of highly decomposed peat.

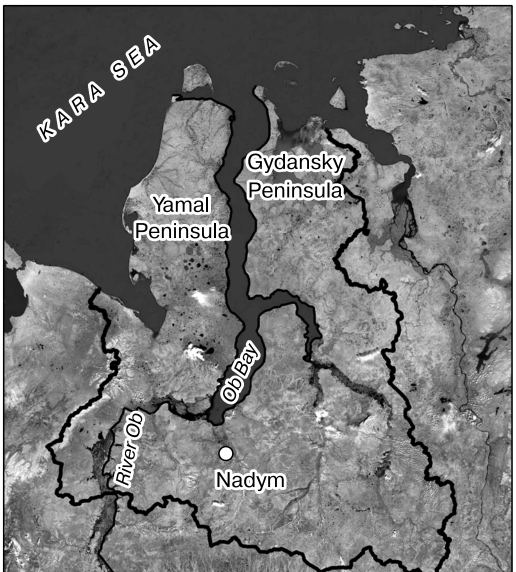

Fig. 1. Nadym on the satellite image, Landsat-7 ETM+, survey date 06.07.2002.

To study the functioning of soils at the stationary sites consisting of a peat spot and a control area under vegetation, temperature sensors *I-button* were embedded at the depths of 0, 10, 20, 40, 60 cm to carry out annual monitoring of the soil temperature at the rate of 4 times a day. Emission of carbon dioxide from the soil surface was measured in August three times a day at the same time with fivefold repetition during 10 days by the closed chamber method [*Smagin, 2005*]. CO_2 concentrations were measured by using membrane probes (sealed on the upper end of the tubes with a CO_2 permeable membrane on the bottom end) placed at the depths of 10, 40 and 60 cm [*Smagin, 2005*]. Gas concentration was determined using a portable gas analyzer RMT DX6210.

In the laboratory conditions, the basal respiration (BR) and the substrate-induced respiration (SIR) of soils were investigated [*Anderson and Domsch, 1978; Ananyeva et al., 2008*]. Basal, or heterotrophic, respiration reflects activity of the soil microbiotas under natural conditions. It is determined by the rate of CO_2 emission by soil during 24 hours of its incubation at 22 °C, is expressed in μg C-CO_2/(g of dry soil·hr) and is calculated according to the formula

$$\text{BR}\ [\mu\text{g C-CO}_2/(\text{g of soil}\cdot\text{hr})] =$$

$$= ((\%\ \text{CO}_2\ \text{sample} - \%\ \text{CO}_2\ \text{air})\cdot V\ \text{flask [mL]} \times$$

$$\times\ 12\ [\text{g/mol}]\cdot 1000)/(22.4\ [\mu\text{mol}/\mu\text{L}]\times$$

$$\times 100\ \text{soil [g]}\cdot\Delta t\ [\text{hr}]).$$

Substrate-induced respiration was measured to determine the amount of carbon in the microbial biomass. The method of determining the SIR is based on the fact that the initial rate of CO_2 production by microbes in response to introduction of easily accessible energy substrate to soil is proportional to their mass [*Anderson and Domsch, 1978*]. As easily accessible substrate, glucose was used. After glucose was introduced into the soil, the soil was incubated for 3 hours at the temperature of 22 °C, the SIR was expressed in μg C-CO_2/(g of soil·hr) and was calculated by the same formula as for the BR. The value obtained was recalculated for carbon of the microbial biomass (C_{mic}) by equation [*Ananyeva et al., 2008*]

C_{mic} [μg/g of soil] = (μL CO_2/(g soil·hr))·40.04 + 0.37.

Microbiological activity was measured for the peat soils with natural moisture content. Before the measurements, the material of the soil samples was shredded with scissors, put through a sieve with mesh diameter of 2 mm and was pre-incubated at the temperature of 4 °C during a week. All the incubation experiments were held in pressure-tight flasks 135 ml in volume.

The percentage of ash content in the peats (%), of hygroscopic moisture (%) and the pH_{H_2O} (considering the peat/solution ratio as being 1/25) were determined in accordance with the manual by *E.V. Arinushkina* [*1970*]. The percentage of total carbon (TOC) and nitrogen (TON) was determined by using an elemental C, N, H, S analyzer Vario ElIII by Elementar. The dissolved organic carbon and nitrogen (DOC and DON) were extracted with 0.05 M K_2SO_4 and were identified at an automated analyzer TOC-VCPN (Shimadzu) [*Makarov, 2013*].

The names of soils and soil horizons were given in accordance with the classification of the Russian soils [*Soil Survey Staff…, 2014*]. The data obtained were processed with the software program Statistica 6.0. The results are shown as mean arithmetic means ± standard deviation.

RESULTS AND DISCUSSION

The soil cover of frozen peatlands in the territory under study is represented by a complex of Lithic Histoturbels and Typic Hemistels. In the immediate proximity of the peat spots, there are Typic Hemistels. These soils have peat profile 0.5–1.0 m thickness lying under the moss tirr. The profile of this type of soils is characterized by the change of the peat type within the limits of the profile: the top part of the profile is oligotrophic peat, and the bottom part is the eutrophic type. The profile of this type of soils has the following structure (August 2013): **Oi-Oe-Oa** (Fig. 2).

Oi (6–12 cm). Yellow-brown medium-decomposed (H5) oligotrophic peat horizon under sphagnum tirr (0–5 cm), with moss, sometimes with lichen, loose, unstructured, easily detached from the underlying horizon, moist, and full of plant roots. The transition is clear, the borderline is wavy.

Oe (13–20 cm). Brown medium-decomposed (H6) eutrophic peat horizon, of sedge botanic composition; stratified, loose, moist, with many plant roots. The transition is noticeable, the borderline is wavy.

Oa1 (21–45 cm). Dark-brown strongly decomposed (H7) eutrophic peat horizon, of sedge and birch botanic composition; stratified, solid, moist, with a moderate number of plant roots. The transition is gradual, the borderline is wavy.

Oa2 (46–50 cm). Dark-brown strongly decomposed (H7) eutrophic peat horizon, of birch botanic composition; stratified, solid, birch remnants as twigs and pieces of bark (up to 3 cm) are well diagnosed, moist, with few plant roots. It transits into solid frozen peat horizon of similar composition, with ice content of about 30 %.

On average, the thawing depth of oligotrophic peat soil is 45–50 cm.

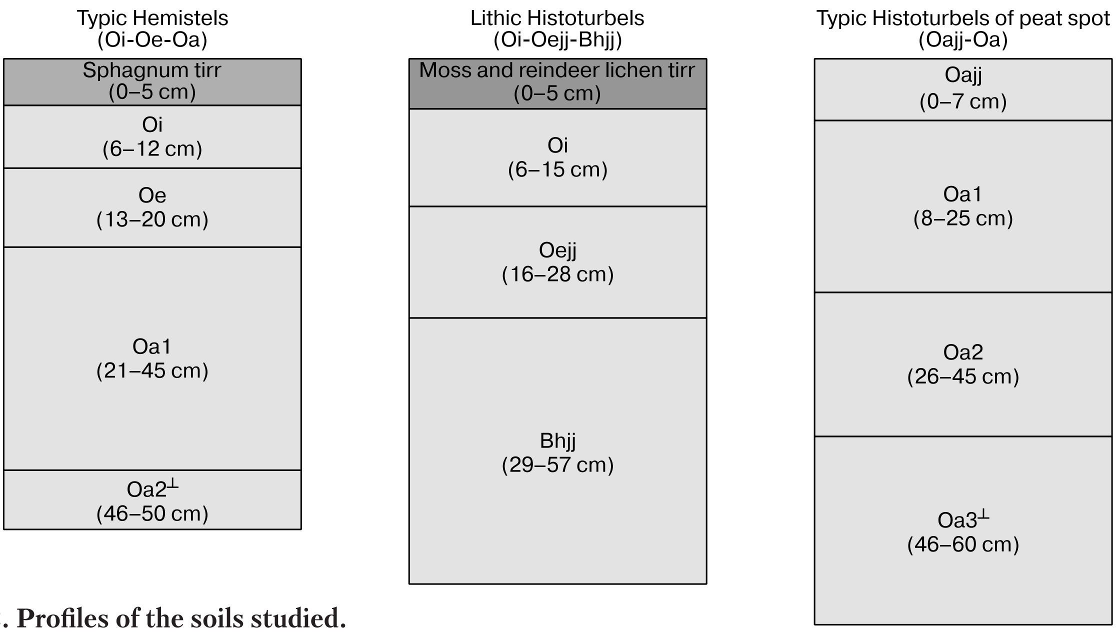

Fig. 2. Profiles of the soils studied.

The name of the horizon is followed by its depth in the soil (in brackets). Names of soil horizons and profiles are given in accordance with [*Soil Survey Staff…, 2014*].

Lithic Histoturbels, also adjacent to the peat spots, are characterized by low thickness of the peat (less than 0.5 m) and the presence of organic-mineral cryoturbated horizon. They represent two or three poorly- or medium-decomposed peat horizons of the olygotrophic type aged about 1500–3000 thousand years [*Matyshak, 2009*], lying under moss or reindeer lichen tirr (from 5 to 15 cm). As opposed to olygotrophic soils, mineral horizons are involved into soil formation; they are of sandy composition, as a rule. For the permafrost peaty soil profile, the following structure of soil is characteristic (August 2013): **Oi-Oejj-Bhjj** (Fig. 2):

Oi (6–15 cm). Brown poorly decomposed (H3) oligotrophic peat of moss composition; the peat is loose and moist, there are many plant roots. The transition is noticeable, the borderline is of a pocket type.

Oejj (16–28 cm). Dark-brown medium-decomposed (H6) peat, the botanic composition of the peat is difficult to diagnose; its structure is not expressed, it is loose, moist, with admixture of sand, there are many plant roots. The transition is sharp; the borderline is of a pocket type.

Bhjj (29–57 cm). Non-uniformly colored sand clay, permeated with humus substances, against the grey-brown background, there are dark- and light-brown spots, lenses, and interlayers; unstructured, loose, with few plant roots (single roots). The horizon is strongly cryoturbated. It transits into a dense frozen grey clay sandy horizon, with ice content of about 10–20 %.

The average thawing depth is 55–60 cm.

The soils of peat spots. This study is focused on the specific variant of the soil cover of frozen peatlands – the peat spot soils (PSS), differing from any of the above described background soils (BS). In the territory under study, peat spots are a characteristic component of the landscape. As a rule, they occur in small groups on the tops and upper slopes of the frozen peatlands. As mentioned previously, peat spots are easy to diagnose against the general landscape background by complete absence of the vegetation cover. They have an oval shape, their areas vary from 1 to 25 m^2, and there are flat-topped mounds (the mounds are 2–5 cm high) on the surface. The botanic composition of the peat of PSS could not be identified in the field conditions. The age of the peat is dated from 2570 ± 60 thousand years (SOAN-9291) at the depth of 10 cm to 5790 ± 80 thousand years (SOAN-9287) at the depth of 50 cm. We qualified PSS as Typic Histoturbels. Their profile has the following structure (August 2013): **Oajj-Oa** (Fig. 2).

Oajj (0–7 cm). Brown, strongly decomposed (H9); loose, silty, the top 1–2 cm are dried, with no plant roots. The peat has poorly expressed lumpy structure, which crumbles to a homogeneous mass of an indefinite botanic composition under weak mechanical pressure; somewhat moist. The transition is gradual, the borderline is wavy.

Oa1 (8–25 cm). Dark-brown, strongly decomposed (H8); solid, stratified, moist, plant roots are nearly absent, there are many vertical crevasses up to 2 cm wide, filled with homogeneous strongly decomposed dark-brown peat. The transition is gradual, the borderline is wavy.

Oa2 (26–45 cm). Dark-brown, strongly decomposed (H7) peat contains birch remnants (pieces of bark, twigs 1–10 cm); strongly stratified, solid, without plant roots; there are many vertical crevasses up to 1 cm wide, filled with homogeneous strongly decomposed dark brown peat. The transition is gradual, the borderline is wavy.

Oa3 (46–60 cm). Brown, medium-decomposed (H6), contains even more birch remnants, compared to the above lying horizon; stratified, solid, moist, without plant roots. It transits into a solid, frozen peat horizon of similar composition, with the ice content of about 30 %.

As a rule, the total thickness of the organogenic profile exceeds 60 cm. The thawing depth is higher than in the surrounding BP of frozen peatlands and is 60–65 cm, ensuring formation of local depressions in the top layer of permafrost under the peat spots.

Thus, the PSS profile essentially differs from the soil profile under vegetation for the variety and types of the peat horizons. Whereas the processes of peat formation prevail in BP, in PSS formation of peat prevails, primarily due to physical processes (drying–wetting, freezing–thawing). To this testifies the silty dried top PSS horizon with weakly expressed lumpy structure, signs of cryoturbations on the surface, formed as a result of emergence of the so-called “needle ice” [*Tarakanov and Bykasov, 1985*], as well as a significant number of vertical crevasses in the PSS profile due to frost cracking.

Characteristics of soils of peat spots. It has been established that the volume mass of peat in PSS is on average higher than in BS (0.20 ± 0.04 and 0.11 ± 0.07 g/cm^3, respectively). In PSS the degree of peat decomposition (H) is much higher (5.7 ± 1.3 BS and 7.8 ± 1.1 PSS), due to the age and genesis of the soil of the peat spots. In PSS, the degree of decomposition varies across the profile little and decreases downward, which is related to involvement of newly thawing peat horizons into the soil formation (Fig. 3). Characteristic of BS is the low degree of decomposition of the peat of upper horizons, caused by the oligotrophic nature of the modern peat deposits, which overlay the strongly decomposed lower part of the peat profile.

It has been found that on average PSS is more acidic than BS (pH_{H_2O} 3.8 ± 0.4 и 4.0 ± 0.2, respectively), the percentage of total carbon (50.3 ± 2.2 и 45.7 ± 4.6 %, respectively) and nitrogen (2.4 ± 0.4 and 1.5 ± 0.5 %, respectively) is higher in them. In ad-

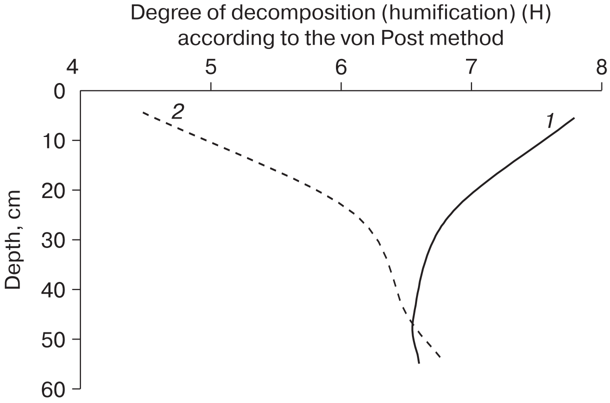

Fig. 3. The degree of peat decomposition of peat spots (*1*) and background soils of frozen peatlands (*2*) according to the von Post scale.

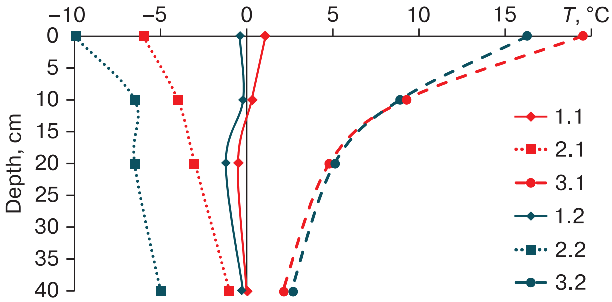

Fig. 4. Mean annual, minimal and maximum temperatures of the soil profiles of peat spots and background soils.

The temperature of the peat spot soil profile: 1.1 – mean annual temperature; 2.1 – minimum temperature; 3.1 – maximum temperature.
The temperature of the background soil profile: 1.2 – mean annual temperature; 2.2 – minimum temperature; 3.2 – maximum temperature.

dition, in PSS the percentage of DOC (672.6 ± 279.0 and 491.2 ± 181.2 μg/g, respectively) and DON (131.0 ± 63.6 and 89.3 ± 60.3 μg/g, respectively) is higher, too.

The temperature regime of the peat spot soils. The authors have ascertained that the mean annual temperature in the PSS profile at the depth of 10 cm is higher than in the BS profile (+0.3 °C of the peat spot soils and –0.3 °C for BS), and is generally positive (Fig. 4).

Comparing the temperature extremes of the soils studied, in PSS the minimum temperatures in the winter period are much higher (by 4–5 °C) across the profile, which seems to be due to the impact of the snow cover, which falls earlier in the micro depressions of the peat spots, stabilizing their temperature regime. In summer, due to the absence of the heat insulating vegetative cover, the maximum surface temperature is also higher in PSS and is comparable to the air temperature.

Thus, the PSS, and especially their top horizons, function in another temperature regime and are on average characterized by higher temperatures, primarily due to the winter period. In the spring period, after snow thaw, activation of the formation of needle ice may take place on the wetter surface of the peat spots; this ice forms flat-topped peat mounds and contributes to active transformation of peat horizons due to cryoturbation.

Biological activity of peat spot soils. Basal breathing is an important parameter which reflects the natural biological activity of soils. BR has been established to be lower in PSS (1.8 ± 0.6 μg C-CO_2/(g soil·hr)), as opposed to BS (3.8 ± 0.4 μg C-CO_2/(g soil·hr)) (Fig. 5).

The carbon of microbial biomass is the most mobile fraction of the organic matter of soil, capable of reacting fast to changes in the condition of the soil

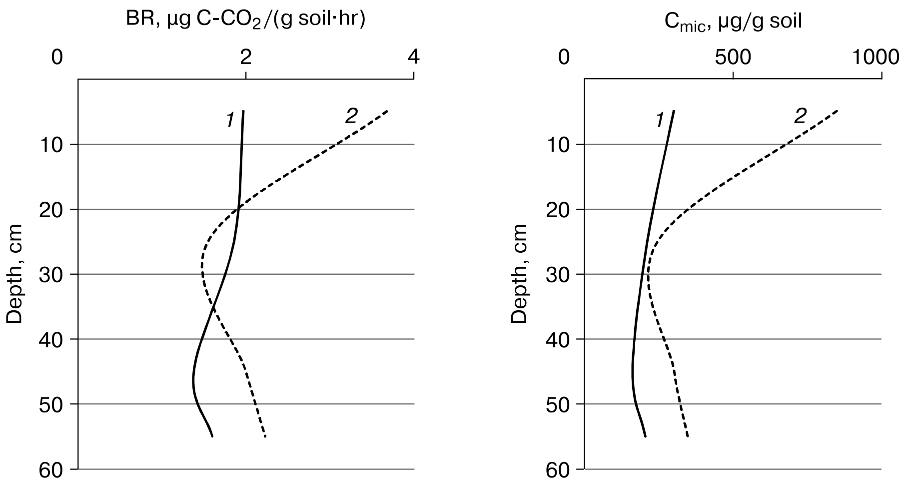

Fig. 5. The parameters of basal respiration (BR) and of carbon of microbial biomass (C_{mic}) in the profile of peat sport soils (*1*) and background soils (*2*).

and correlating with microbial activity [*Umer and Van'kova, 2011*]. The content of microbial biomass in PSS has been established to be lower than in BS (250.1 ± 94.6 и 729.0 ± 71.9 μg/g soil, respectively). By the PSS profile, the values of BR and C_{mic} are distributed relatively uniformly. BS are characterized by high values of BR and C_{mic} for top horizons lying immediately under the vegetation cover. In the lower part of the profile, all the soils demonstrate certain increase in the content of C_{mic} and the BR values above the permafrost table.

Production of carbon dioxide by the soils of frozen peatlands also well demonstrates the differences in the functioning of the landscapes under study. On average, CO_2 emission by northern taiga soils of Western Siberia is low to constitute about 120 mg $CO_2/(m^2 \cdot hr)$ [*Goncharova et al., 2014*]. We revealed that CO_2 emission from the surface of the peat spots is much lower and on average reaches 71.2 mg $CO_2/(m^2 \cdot hr)$. Concentration of CO_2 in the PSS profile is higher (for the depths of 10, 40, 60 cm: 0.43; 0.50; 0.26 % – PSS and 0.18; 0.27; 0.19 % – BS). The presence of geotropic mass transfer, contributing to floowing and conservation of CO_2 in the lower part of the PSS profile, seems to have a number of physical a chemical causes (greater density of peat in PSS, greater thawing depth, and the resulting migration of dissolved CO_2 in the depressions of the permafrost table under the peat spots). This assumption is stated on the basis of the works by A.V. Smagin, in which he indicates the possibility of formation of the areas of greenhouse gas accumulation in the peaty soils at a certain depth due to physical causes [*Smagin, 2005*].

The low biological activity in PSS indicates either suppression of microbiota of PSS due to hydrothermal conditions (dehydration) and cryogenic processes (cryoturbation) or totally different structural organization of the microbial communities and the soils under study. It is also to be noted that the contribution of the root systems to the CO_2 production in PSS is much lower.

Based on statistical analysis (the Fisher test), we determined the PSS to be reliably (p-level < 0.03) different from BS under vegetation for the majority of the parameters considered (pH_{H_2O}; TOC, %, TON, %; DOC, μg/g, DON, μg/g; degree of decomposition (humification) (H); volume mass, g/cm^3; BR, μg C-CO_2/(g soil·hr), C_{mic}, μg/g soil).

Thus, PSS are a unique variant of a soil cover of frozen peatlands of the northern territories of Western Siberia. Currently, the genesis of the peat spots has not been unambiguously ascertained. The existing theories explaining this [*Vasilevskaya et al., 1986; Seppälä, 2003; Marushchak, 2011*] do not fully explain their emergence. V.D. Vasilevskaya related the process of peatland soil cover degradation to the deficit condition of the major biophil elements (due to a change in their mobility), as well as to severe hydrothermal conditions on peatlands. Finnish researchers account the process of emergence of peat spots on the surface of peatlands for mechanical exogenous impacts. In their opinion, joint impact of a strong wind and of hard crystals of ice and snow destroy the surface of peatlands. In foreign literature, this process is called *iceblasting* [*Seppälä, 2003*]. Based on our observations, we believe the formation of peat spots to be caused by the impact of cryogenic processes (frost heaving, cryoturbation), boosting mineralization of the peaty profile, on the one hand, and preventing vegetation settlement, on the other. Solution of this problem remains to be a subject of further studies.

CONCLUSIONS

1. Peat spots are a characteristic and rather common landscape in the territory of research, fully devoid of the vegetation cover for dozens of years. They are associated with the top and slope parts of frozen peatlands, have an oval shape, the area from 1 to 25 m^2 and a characteristic surface of flat topped peat mounds.

2. Peat soils are determined as Typic Histoturbels, whereas the most typical soils of the frozen peatlands of the regions ate Lithic Histoturbels and Typic Hemistels.

3. The peat of the peat spot soils is significantly different from the peat of the surrounding soils for their morphological and chemical properties. The peat of the peat spots is older, more solid, and its degree of decomposition is higher. Acidity of the peat spot soils is lower, and the content of total carbon and nitrogen, as well as of their labile forms, is higher.

4. Essentially different are the parameters of functioning of the peat spot soils. The mean annual and winter temperatures of the peat spot soils are essentially higher (by 1 and 4–5 °C, accordingly). The absence of the vegetation cover accounts for greater heat penetration into the peat spot soils in the summer period and activation of cryoturbation on the soil surface in the spring period.

5. Lower biological activity of peat spot soils has been revealed. For example, emission of carbon dioxide on peat spots is on average 2 times lower than on the soils under the vegetation cover (71.2 and 155.2 mg C-$CO_2/(m^2 \cdot hr)$, respectively). The mean values of heterotrophic breathing and the content of the biomass carbon are 2–3 times lower, suggesting either suppression of microbiota of peat spot soils due to hydrothermal conditions and cryogenic processes or totally different structural organization of the microbial communities and the soils in question.

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