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TEMPERATURE REGIME OF THE TUNDRA SOILS AND UNDERLYING PERMAFROST (NORTHEAST EUROPEAN RUSSIA)

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The temperature regime was investigated in seven permafrost soils formed in mineral and peaty soil-forming deposits in various landscapes of the southern tundra in the northeast European Russia. Seasonal and multiannual temperature dynamics was revealed within the active layer and underlying permafrost horizons. Soil temperature regimes were analyzed according to the Russian and American classification systems. The frozen soils differentiation is shown through key temperature indicators.

Temperature regime, frozen soils, perennially frozen rocks (permafrost), seasonally thawing layer

INTRODUCTION

Climate change is one of the most important global challenges of XXI century. Degradation of permafrost followed by the forest boundary gradually advancing northward is expected to have dramatic effect on soils and vegetation growth. Soils represent by themselves a major carbon storage medium, with its appreciable reserves conserved in the permafrost layers [*Hugelius et al., 2011*]. Due to the effect of global climate change on soils previously serving as a reservoir for carbon, they may convert into its source and produce additional input of carbonaceous greenhouse gases into the atmosphere, which in turn will promote the ground warming [*Davidson and Janssens, 2006*].

Subarctic northeast European Russia is one of the regions, most sensitive to climate change [*Mazhitova et al., 2004; Oberman and Shesler, 2009*]. Specifically, the highest rates of permafrost degradation are attributed to the eastern Timan-Pechora region [*Oberman and Shesler, 2009*]. The fairly unstable in the conditions of global warming insulars and massifs of relatively high-temperature perennially frozen rocks (PFR) are distributed within the limits of the tundra and forest tundra southern extents.

The studies of the tundra soils temperature regime in the area were conducted by *A.V. Kononenko* [*1986*] and *G.G. Mazhitova* [*2008*]. The work [*Kononenko, 1986*] consisted in the analysis of summer hydrothermal regime of two virgin soils, lacking, however, the winter and annual characteristics, as well as the relation of regimes diversity at the landscape level. The temperature regime of eleven soils formed in various landscapes of the flatland and mountain tundra confined to frozen and thawed areas is discussed in detail in [*Mazhitova, 2008*]. The paper highlights a drastic difference between the winter and annual temperature indicators for frozen and nonfrozen soils, given the summer temperatures in the root zone are much similar. The investigations of the temperature regime in frozen soils were restricted to the seasonally thawing layer, STL (active layer) thickness.

Since 2007, the Institute of Biology, Komi Scientific Centre (SC) employees launched the long-term temperature monitoring of main types of frozen soils profiles in the southeast Bolshaya Zemlya tundra. The temperature monitoring was carried out within the extents of active layer and in the permafrost table (to a depth of 120 cm). This allows to assess the current ecological condition within the soil-geocryological complex, and its response both to the interannual air temperature dynamics, and to future climate changes, provided a longer series of observations is available.

The purpose of the article consists in analyzing key temperature parameters of the tundra frozen soils and the underlying permafrost, in order to classify the temperature regimes.

THE OBJECTS AND METHODS OF THE STUDY

The area's environmental conditions. The soil temperature study was carried out in two sites in the southern subzone (shrub tundra) in the catchment basins of the Bolshaya Rogovaya and the Vorkuta rivers, and in the northern forest tundra area (the Seida river basin). The study area falls within the Usa Rv. basin, a tributary to the Pechora river (northeast European Russia). Given that these sites reflect all the diversity of frozen soils in the southeastern tundra sector, they were subsumed into the study area, which also belongs to the discontinuous permafrost zone [*Geocryological map..., 1998*] with the PFR mean annual temperature varying from 0 to −2 °C. Among them, predominate the complexes of surface-gleyed (frozen and non-frozen), peaty gley and boggy frozen soils [*State... map..., 2000*].

Table 1. **Climatic indicators (the Vorkuta meteorological station)**

Hydrogeological year (01.10–31.09)	Mean annual air temperature, °C	Degree days thaw, °C·day		Total annual precipitation, mm	Total precipitation, mm	
		>0 °C	>10 °C		June–September	December–February
2007/08	–3.6	1126	802	525	195	132
2008/09	–4.5	1046	701	613	252	124
2009/10	–7.0	995	602	776	376	129
2010/11	–4.1	1002	558	668	215	88
Average, over the period 2007–2011	–4.8	1042	666	645	259	118
Normal annual (1947–2011)	–5.7	1015	536	523	225	106
Range (1947–2011)	–2.8...–9.9	647–1310	0–1059	294–762	86–393	16–303

Climatic parameters. According to the Vorkuta weather station, the nearest to the study area, the flatland tundra is characterized by mean annual air temperature –5,7 °C (1947–2011 yy.). The 2007–2011 temperature readings fall within the limits of long-time average values (Table 1). However, the average annual precipitations during the observation period exceeded the long-term annual averages (645 mm/year). When calculating the mean annual values both for air temperature and precipitations, we relied on the data for the hydrological year (October 1–September 30).

Characterization of the studied soils. The study aimed to investigate frozen soils developed in clay loam and peat sediments in different landscapes of the southern tundra in the northeast European Russia. The so-called "merging" permafrost typifies the studied soils, meaning that it reaches the permafrost table during the soil seasonal freezing [*Geocryology..., 1988*]. The names of soil horizons and codes for the types of soil structures are consistent with the classification of Russian soils [*Shishov et al., 2004*]. Table 2 provides the list of shorter names of soils, used hereafter in the text.

In the southern tundra conditions, mineral frozen soils form mainly on the massifs of clay loam (windward slopes and tops of ridges; terraces, mounds, etc.), beneath the shrub and moss-lichen vegetation. The group of these soils are mainly peaty gleyzem with active layer depth from 50 to 200 cm. Peaty frozen (dry-peaty, peaty oligotrophic) soils are widely distributed within the plain-mound marshes and form above the peat deposits with the thickness ranging from 40 cm to several meters. The seasonal thaw depth in peaty soils, normally, does not exceed 40–60 cm.

The temperature regime was investigated in three profiles for loamy and four profiles for frozen peaty soils (Table 2). The soil temperature was measured using HOBO digital logger, installed at depths of 0, 20, 50, 100 (120) cm, and set to eight measurements per day. The loggers sensors were fixed on a wooden stick, lowered in the well (hole) of 3 cm in diameter at a depth of 100–120 cm. Seasonal thaw depth was measured with a graded metal probe at the end of the growing season, while the snow thickness was measured in March. The air temperature data required for the calculations was provided by the Vorkuta weather station. The soil temperatures investigations were carried out during the period 2007–2011.

WINTER SOIL TEMPERATURE REGIME

Seasonal freezing of the top-most horizon of the tundra frozen soils begins in October in this area when negative air temperatures become stable, with long-term annual average date falling on October, 16 (the period over 2007–2011) according to the Vorkuta weather station. The soil begins to freeze mostly from the top. In November, the average monthly temperature of the upper STL is, normally, sub-zero (negative) (Fig. 1). The greater is the depth, the lower are the rates of frost penetration into the middle (20–50 cm) and lower (50–120 cm) horizons of the soil, with the "zero veils" effect documented at this point, lasting from two to six months. The "zero veils" are stable temperatures (close to 0 °C) preserved for a long time at a certain depth [*Geocryology..., 1988*]. The greatest length of the sub-zero temperatures period characterizes the STL–PFR contact boundary.

The total negative surface temperatures of the studied soils range from –171...–2508 °C·day (Table 3), whereas the summation of this indicator for mineral soils is overlapped by the temperature range for peaty soils. Nevertheless, the differences in the freezing events ingress are defined by comparing soil of mounds and that of relatively flat areas. Soils of profiles 1, 6, 7 developed in fairly flat or low areas with 30–45 cm thick snow cover. Profiles 2 and 5 are confined to peaty and clay-loam permafrost mounds (palsas) 2–5 meters high. A shallow snow cover (0–30 cm) on the mounds promotes strong cooling of the soil. Given that the differences in temperature regimes are dictated by landscape positions of soils, we

Table 2. **Characterization of the objects of study**

Number and index of soil profile	Coordinates	Landscape	Active layer depth, cm	Average max. snow cover thickness, cm	Soil profile structure	Name of soil type	
						[*Shishov et al., 2004*]	This paper
1. CALM R2 Profile	67°35′ N 64°10′ E	Circumpolar Active Layer Monitoring (CALM) program/ Site R2. The Vorkuta Rv. basin. Slight sloping stream bank. Shrub-moss spotted (medallion) tundra	110	42	TO (0-12) – BG (12-70) – CG (70-110) – CG (110-120+)	Peaty gley soil subject to cryoturbation in medium silty clay loam	Cryoturbation-affected peaty gleyzem
2. U58 Profile	67°19′ N 62°24′ E	The Bol. Rogovaya Rv. basin. Mineral mound (palsa). Shrub-moss –lichen tundra	100	≤30	T (0-20) – B (20-37) – Bf (37-53) – BC (53-70) – Cg (70-85+)	Cryogenic – ferruginized peaty gleyzem on stratified loamy clays	Cryogenic – ferruginized peaty gleyzem
3. U71 Profile	67°20′ N 62°20′ E	The Bol. Rogovaya Rv. basin. Flat top of mineral mound (palsa), shrub-moss –lichen tundra	110	≤20	T (0-6) – I (6-12) – II (12-17) – III (17-20) – IV (20-32) – V (32-50) – VI (50-71) – VII (71–80) – VIII (80-89) – IX (90-110) – X (110+)	Stratified alluvial on clay loamy-sandy lacustrine-alluvial sediments	Stratified-alluvial soil
4. S3 Profile	67°03′ N 62°56′ E	The Seida Rv. basin. Flat top of peat mound, shrub-moss –lichen vegetation, denuded peat patches	52	≤10	O (0-7) – TJ (7-40) – T2 (40-52) – T3 (52-100+)	Dry peaty soil	Dry peaty soil (Seida site)
5. U92 Profile	67°19′ N 62°23′ E	The Bol. Rogovaya Rv. basin. Cambered (raised) top of peat mound, shrub-moss vegetation	45	≤10	O (0-5) – TJ (5-26) – T2 (26-41) – T3 (41-57) – T4 (57-100+)	Dry peaty soil	Dry peaty soil (Bol. Rogovaya site)
6. S7 Profile	67°03′ N 62°57′ E	The Seida Rv. basin. Low lacustrine beach of flat peat mounds, shrub-moss vegetation	40	45	TO (0-21) – T2 (21-41) – T3 (41-70) – T4 (70-100+)	Peaty oligotrophic soil (intermediate)	Peaty intermediate soil
7. U71/1 Profile	67°20′ N 62°20′ E	The Bol. Rogovaya Rv. basin. Swampy hollow, sedge-sphagnum bog	55	40	TO (0-12) – TO2 (12-19) – TO3 (19-30) – T (30-55) – T (55-60) – G (60-100+)	Peaty oligotrophic soil	Peaty oligotrophic soil

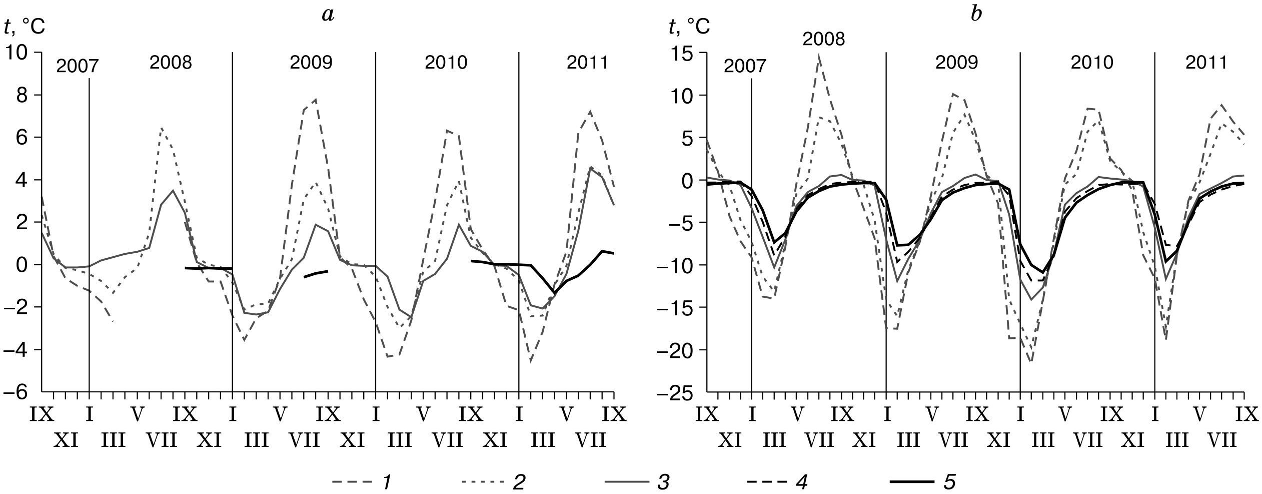

Fig. 1. Average monthly temperatures of peat-gleyzem cryogenic soil subjected to cryoturbation (*a*) and of dry peaty soil in Seida site (*b*).

Depth: *1* – 0 cm; *2* – 20 cm; *3* – 50 cm; *4* – 80 cm; *5* – 120 cm.

introduced names for soils in these two groups: flatland soil and mound soil. When comparing the two groups we could see that the below 0 °C surface temperatures summations are overlapped to a lesser extent.

The summations of negative soils temperatures both in flat areas and mounds at a depth of 20 cm are overlapped also slightly (Table 3, Fig. 2). The perennially frozen rocks are subject to cooling to the greatest extent in peat mounds, at a depth of 100–120 cm. The permafrost underlying peaty intermediate and peaty oligotrophic soils appear much warmer than in peat mounds. The peaty gleyzem soils evidenced cryoturbation are characterized by the least summations of negative temperatures throughout the profile (Table 3).

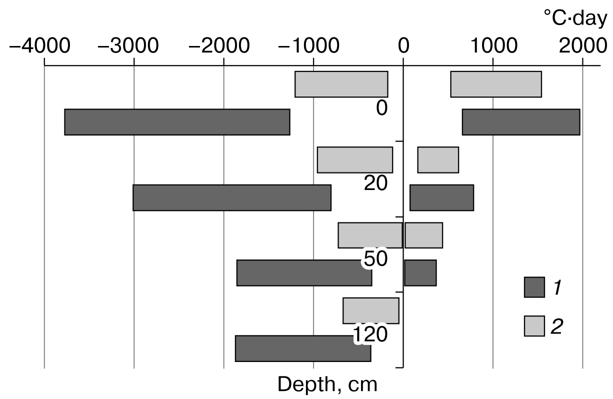

Fig. 2. The ranges of negative and positive soil temperatures sums in the mounds (*1*) and flatlands (*2*).

Any month from January to March may turn out the coldest at depths of 0 and 20 cm (Fig. 1). Given that soil of the windward mounds is more sensitive to winter temperature fluctuations, this period is most likely to fall for January and February (Fig. 1, *b*). The PFR evidence the lowest freezing temperatures peak in the period from February through April. The coldest month mean temperatures in the permafrost layers vary from −0.1 to −12 °C. The PFR composing the base of mineral and peaty mounds (Fig. 1, *b*) are subject to the greatest freezing degree.

SUMMER TEMPERATURE REGIME

Seasonal thawing of the upper soil horizons begins in May, with May 27 as the date of establishing of mean daily positive air temperatures and the commencement of stable snow cover degradation. Either July or August appear the warmest month in the surface soil horizons (Fig. 1). The temperature maximums in lower subsurface horizons are recorded in the period from August through October in the active layer, and from September through December, in PFR.

The positive temperatures sums (>0 °C) on the surface (depth: 0 cm) over all years of observations in all the soils constituted 529...1312 °C · day (Table 3, Fig. 2). The heat ingress to the surface of mineral and peaty soils proved approximately the same, with their ranges overlapping. When comparing soil groups of flat land and mounds we should bear it in mind that soils of the first group are exposed to less heat, which is most likely associated with their surface being shaded to a greater extent by shrub vegetation.

The positive temperature sums are 1.5–3 times lower at a depth of 20 cm, compared with the surface temperature (Table 3, Fig. 2). The sums maximum of

Table 3. **Parameters of thermal soil regime in perennially frozen rocks**

Depth, cm	Total mean negative daily temperatures, °C·day				Total mean positive daily temperatures, °C·day						Mean annual temperature, °C			
					>0 °C			>10 °C						
	2007/08	2008/09	2009/10	2010/11	2008/09	2009/10	2010/11	2008/09	2009/10	2010/11	2007/08	2008/09	2009/10	2010/11
	Cryoturbation-affected peaty gleyzem													
0	–171	–394	–474	–385	721	529	743	207	88	123	–0.9	0.9	0.2	1.0
20	–118	–226	–253	–206	311	255	452	0	0	0	1.1	0.2	0.0	0.7
50	–13	–278	–202	–197	122	93	419	0	0	0	0.9	–0.4	–0.3	0.6
120	–	–49	–	–106	0	0	43	0	0	0	–0.2	–0.3	–	–0.2
	Cryogenic – ferruginized peaty gleyzem													
0	–1289	–1843	–1720	–1409	906	755	970	554	317	388	–0.4	–2.8	–2.6	–1.2
20	–943	–	–1405	–	118	175	76	0	0	0	–2.5	–2.6	–3.7	–
50	–803	–802	–1149	–	85	90	43	0	0	0	–1.7	–2.2	–3.2	–
120	–647	–	–970	–	4	1	3	0	0	0	–2.2	–	–2.9	–
	Stratified-alluvial soil													
0	–1036	–1324	–1628	–1246	1272	1138	1312	898	720	814	0.8	–0.2	–1.7	–0.1
20	–805	–858	–1260	–1030	708	594	612	230	108	9	–0.4	–0.4	–2.2	–1.3
50	–606	–644	–1049	–847	325	276	316	0	0	0	–0.7	–0.9	–2.5	–1.6
80	–457	–484	–865	–	191	105	–	0	0	0	–0.7	–0.8	–2.3	–
120	–362	–	–	–	0	0	0	0	0	0	–1.3	–	–	–
	Dry peaty soil (Seida site)													
0	–1753	–1974	–2508	–1559	911	719	917	415	211	213	–1.8	–2.9	–4.6	–2.0
20	–1418	–1684	–2204	–1364	568	497	628	49	49	12	–2.3	–3.1	–4.4	–2.2
50	–1017	–1273	–1709	–1032	29	18	29	0	0	0	–2.7	–3.4	–4.6	–2.8
80	–922	–1145	–1599	–981	0	0	0	0	0	0	–2.5	–3.1	–4.4	–2.6
120	–858	–1068	–1507	–1020	0	0	0	0	0	0	–2.3	–2.9	–4.1	–2.7
	Dry peaty soil (Bol. Rogovaya site)													
0	–1304	–	–2183	–1731	–	658	740	90	126	265	–2.5	–	–4.8	–
20	–1127	–1411	–	–	189	–	–	0	0	0	–2.1	–3.8	–4.2	–3.1
50	–897	–1081	–1505	–1223	0	0	0	0	0	0	–2.5	–3.0	–4.1	–3.3
100	–730	–	–	–1207	0	0	0	0	0	0	–3.0	–	–	–3.3
	Peaty intermediate soil													
0	–804	–838	–1186	–1264	532	541	902	25	82	275	0.5	–0.7	–1.6	–1.2
20	–440	–662	–841	–816	193	164	237	0	0	8	–0.7	–1.3	–1.8	–1.7
50	–350	–533	–713	–684	0	0	0	0	0	0	–1.0	–1.5	–2.0	–1.9
80	–357	–515	–	–	0	0	0	0	0	0	–1.0	–1.4	–	–1.7
120	–349	–477	–	–	0	0	0	0	0	0	–1.0	–1.3	–	–1.5
	Peaty oligotrophic soil													
0	–	–	–999	–938	–	901	101	–	378	313	–	–	–0.6	–0.1
50	–	–	–642	–615	–	21	38	–	0	0	–	–	–1.9	–1.6
100	–	–	–609	–620	–	0	0	–	0	0	–	–	–1.8	–1.7

Note. Dash “ – ” means that the temperature was not measured.

positive temperatures at a depth of 20 cm were recorded in the stratified alluvial and dry peaty soils (the Seida river reach). A thin peaty mat within the stratified alluvial soil (6 cm) and relatively light granulometric textures promotes a deeper penetration of positive temperatures, as evidenced by a greater thickness of the active layer (110 cm). An appreciable warming of the dry peaty topsoil horizons is accounted for a sparse moss-lichen vegetation on the mounds, as the rates of the solar radiation absorption grow higher due to the black color of the denuded peat.

In terms of surface positive temperatures sums (>10 °C) the situation appears similar, with the surface of mounds receiving more heat, unlike that of flat lands (Table 3). At a depth of 20 cm, however, high temperatures are documented only in the stratified alluvial and peaty soils (the Seida river site).

Thus, the penetration of temperatures higher than 10 °C to a depth of 10–15 cm (basic root zone) is characteristic of the frozen soils in the study area, which agrees well with the results of the analysis of soils temperature series in that same area over the period of 1997–2004. The penetration of such temperatures is hindered by the presence of thick organogenic layer, the proximity of the cooling permafrost shield, and by large heat losses during the thawing season in the active layer development.

ANNUAL CHARACTERISTICS OF THE SOILS TEMPERATURE REGIME

The aggregate range of mean annual temperatures at depths 0, 20, and 50 cm in the studied soils constituted 1.1...–4.8 °C in the active layer, and –0.2...–4.4 °C in the permafrost layer (Table 3). The mean annual temperatures of the active layer were negative in six of seven profiles, and they tend to gradually decrease down the profile. The mean annual negative temperatures in frozen soils and positive in non-frozen soils for the most part is a normal situation [*Kudryavtsev, 1981; Burn, 2004*]. The coldest mean annual soil temperatures are attributed to peat mounds (Table 3). Relatively warm temperatures are assigned to flat land sites, as their temperature regime is the closest to non-frozen tundra soils. The mean annual positive temperatures were documented during the observation period in peaty gleyzem soils subjected to cryoturbation at depths of 0, 20 and 50 cm in the active layer.

The depth of seasonally thawing layer progressively increased within the extents of the monitoring site, comprising the cryoturbation-affected peaty gleyzem soils underpinned by the following statistics: totally, 400 measurements were done with a grid cell measuring 10 × 10 m in size, averaging out at 62 cm in 1997, and 88 cm in 2011. A gradual increase of the mean annual temperatures in the active layer, accompanied by the permafrost thaw, was due to the temperatures growth in the summer and, especially, in the winter. The positive mean annual temperature in the upper soil horizons, while remaining negative at other depths (temperature offset), is one of the signs of the permafrost degradation [*Burn, 2004*].

The seasonal temperature fluctuations range tend to gradually decrease from the topsoil down the profile, comprising the upper parts of the permafrost stratum, to a depth of temperature zero fluctuations. Seasonal temperature fluctuations are more clearly expressed in the studied frozen soil horizons at a depth of 50–120 cm, which is often consistent with the zone of the intermediate layer formation.

CORRELATION OF THE ATMOSPHERIC AND SOIL TEMPERATURES

Frozen soils in the region develop at relatively windward areas where maximum thickness of snow is usually not greater than 50 cm [*Mazhitova, 2008*]. In seasonal temperature variations of the investigated frozen soils winter temperatures differ much greater than summer temperatures. The summations of positive temperatures (>0 °C) at a depth of 20 cm constituted 708 °C, whereas the negative temperatures sums amounted to 2204 °C, i.e. 3.1 times greater (Fig. 2). Among the tundra soils varieties in the area, this ratio proves the highest for the frozen soils profiles with the harsh winter environment. That said, the soils experiencing a sharp difference during the winter season are formed in immediate neighborhood, at uniform air temperatures. The differences stem mostly from nonuniform depths of the snow cover. Given the acknowledgeable regional differences, the role of snow in shaping the soil temperature regime is admittedly appreciable [*Shamanova, 1970; Dimo, 1972; Oberman, 1998; Yli-Halla and Mokma, 1998; Pavlov and Moskalenko, 2001*].

The differentiated thickness of the snow cover directly affects winter temperatures of both active layer and the underlying PFR. With normal rate of 60 cm, the decade maximum snow depth over a year varied from 10 to 45 cm in the vicinities of the Vorkuta weather station. A relatively low (0–30 cm) depth of snow cover facilitates the soils cooling in winter conditions, and is favorable for conservation of the near surface permafrost. Shrubs and trees, choosing only snowy areas to be their habitat, retain more snow, which promotes the formation of relatively warm, including non-frozen, soils.

The degree of warm or cold air penetration into soils can be expressed through the ratio of the sums of positive and negative temperatures on the soils surface to air temperatures of similar type over the same period. In the English-language literature, this value is termed N-factor [*Lunardini, 1978*]. The winter N-factor, ie. the ratio of the sums of the soil surface negative temperatures to those of the air, largely depends on the snow depth. The winter N-factor values for six of seven investigated profiles ranged within 0.28–0.76, which is, generally, characteristic of the frozen soils [*Mazhitova, 2008*]. The exception is the cryoturbation-affected peaty gleyzem soil with the values of 0.07–0.15. In this case, the extremely low winter N-factor in the area with the mean annual air temperature –5.7 °C accounts for the presence of frozen soils within the active layer with average annual temperature above 0 °C.

TEMPERATURE REGIMES CLASSIFICATION

Classification of soil temperature regimes was elaborated in detail by *V.N. Dimo* [*1972*] for the entire area of the former Soviet Union. The temperature values were taken at a depth of 20 cm. Unlike in the American classification [*Soil Taxonomy, 1999*], where the adopted depth is 50 cm, the Russian classification focuses on the root zone temperature characteristics. The criteria for the regimes types differentiation are: the presence/absence of permafrost, and if there is – whether its boundary is merging/non-merging; the mean annual temperature. The criteria for the subtypes classification are: the sum of average daily temperatures above 10 °C, the summation of mean daily temperatures below 0 °C, average temperatures of the coldest and the warmest months at a depth of 20 cm. Subtypes of the annual cycle were specified both for summer and winter seasons, and continentality. Inside the subtypes the combinations of the parameters values are provided in 4 °C increments, based on the coldest month temperature.

In terms of annual parameters, the temperature regimes for six of seven investigated soils are related to very cold subtype within the cryogenic soils type. On the basis of the mean annual temperature only the cryoturbation-affected peaty gleyzem soil falls into the cold subtype, intended for seasonally frozen soils (Table 4).

The classification clearly reflects a relative homogeneity of the summer temperature conditions in the upper layer. In terms of the summer temperature measurements, all the investigated soils belong to a very cold subtype of the cryogenic soils type (Table 4).

The soils significantly differ in winter indicators and are attributed to various temperature types (Table 4). The studied soils are not always classified, as the profiles of cryogenic soils type. In terms of the negative temperatures sum and the coldest month temperature, the peaty gleyzem cryogenic soil subjected to cryoturbation are ranked as the cold subtype within long-term seasonally frozen type. With regard to winter regime, the profile is close to the type of soils extending far beyond the cryolithozone. This uncertainty (or, inconsistency between the low negative temperatures sums and the presence of the merging permafrost) is greatly accounted for the fact that the classification makes no provision for a particular niche for "warm" permafrost soils of the East European tundra. These "off-sets" in taxonomic relat-

Table 4. **Correlation between soil thermal regime parameters (at a depth of 20 cm) and thermal types and subtypes according to Dimo [*1972*]**

<table>
<tr><th rowspan="2">Soil</th><th>Year</th><th colspan="2">Summer</th><th colspan="2">Winter</th><th>Continentality</th></tr>
<tr><th>Mean annual temperature</th><th>Degree days thaw (>10 °C)</th><th>Mean temperature of the warmest month</th><th>Freezing degree days</th><th>Mean temperature of the coldest month</th><th>The difference between the warmest and the coldest mean monthly temperatures</th></tr>
<tr><td>Cryoturbation-affected peaty gleyzem</td><td>Cold
Long-term seasonally frozen</td><td colspan="2" rowspan="6">Very cold
Cryogenic</td><td colspan="2">Cold
Seasonally frozen</td><td>Mild</td></tr>
<tr><td>Cryogenic – ferruginized peaty gleyzem</td><td rowspan="5">Very cold
Cryogenic</td><td rowspan="3">Cold
Long-term seasonally frozen</td><td rowspan="4">Cold
Cryogenic</td><td rowspan="3">Moderately continental</td></tr>
<tr><td>Stratified alluvial soil</td></tr>
<tr><td>Dry peaty soil (Bolshaya Rogovaya site)</td></tr>
<tr><td>Dry peat (Seida site)</td><td>Cold
Cryogenic</td><td>Continental</td></tr>
<tr><td>Peaty intermediate soil</td><td colspan="2">Moderately cold
Long-term seasonally frozen</td><td>Mild</td></tr>
</table>

Note. The thermal regime subtype is over the thermal regime.

Table 5. **The soils thermal regimes classification (at a depth of 50 cm) according to [*Soil Taxonomy, 1999*]**

Name of soil types: This paper	Name of soil types: [*Soil Taxonomy, 1999*]	Permafrost occurrence depth, m	Mean annual temperature, °C	Mean summer temperature, °C	Difference between mean winter and summer temperatures, °C	Temperature class
Cryoturbation-affected peaty gleyzem	Ruptic-Histic Aquiturbel	<1	−1...1	<6	<6	Subgelic
Cryogenic-ferruginous peaty gleyzem	Ruptic-Histic Aquiturbel		−4...−2			
Stratified alluvial soils	Lithic Psammorthels	1–2	−3...0		4–8	
Dry peaty soil (Seida site)	Typic Folistel	<1	−5...−2		>>6	Pergelic, Subgelic
Dry peaty soil (Bolshaya Rogovaya site)	Typic Folistel		−4...−2		2–7	Subgelic
Peaty intermediate soil	Typic Hemistel		−2...−1		<6	
Peaty oligotrophic soil	Lithic Fibristel					

edness of soils can be attributed to climate changes, accompanied by the permafrost degradation along the southern boundary of the cryolithozone [*Oberman and Shesler, 2009*].

In this context, when establishing the sub-types of permafrost soils formed on the southern edges of the cryolithozone in the north European Russia [*Dimo, 1972*], it is necessary to extend the range of temperature indicators to a depth of 20 cm, in the national system of temperature regimes classification. The parameters of very cold subtype in the annual cycle should include average annual temperatures within the ranges of 0...−4 and −8...−4 °C. For more accurate classification of frozen soils with a milder winter regime it is recommended to include additional subtype for moderately cold regimes with the ranges of negative temperatures summation from −500...−1000; the mean daily temperatures from −1000...−1500 °C·day, and the mean temperature of the coldest month within the ranges of −4...−8 and −8...−12 °C.

To distinguish a group of soils with the degrading permafrost, it is recommended to additionally introduce the combination of: the mean annual temperatures at 20 cm depth from 2 to 0 °C; the summations of negative temperatures within the range of 0...−500 °C; the temperature of the coldest month 0...−4 °C; the “merging/non-merging” criterion for the permafrost strata characterization within the extent of 2 m from the surface.

Less criteria are used in [*Soil Taxonomy, 1999*] for the temperature regimes classification: the presence/absence of permafrost within 2 m from the surface; the mean soil summer temperature at a depth of 50 cm. The classification of regimes [*Soil Taxonomy, 1999*] is shown in Table 5. The investigated soils are characterized by Subgelic regime (average annual temperature: −4 °C; permafrost), dry peaty soil (the Seida river reach); in 2009–2010 yy. characterized by Pergelic regime (average annual temperature of the soil: less than −4 °C; permafrost).

Gradations of the mean annual temperatures above and below −4 °C account for different degrees of the permafrost stability. The investigated soils are relatively unstable, with the mean annual temperatures exceeding −4 °C at a depth of 50 cm.

The annual amplitude of the investigated surface soils temperatures is based on two indicators: the difference between the mean temperatures of the coldest and warmest month (continentality) at a depth of 20 cm [*Dimo, 1972*], and the difference between the mean summer and winter temperatures at a depth of 50 cm [*Soil Taxonomy, 1999*].

Based on the national classification of the soil climates continentality, the cryoturbation-affected peaty gleyzem and peaty intermediate soils are related to mild (oceanic) subtype (amplitude: <16 °C), while the dry peaty soil of mounds (the Seida river reach) is classified as continental (24–28 °C), and the rest of the soils belong to moderately continental subtype (16–20 °C) (Table 4).

In terms of difference between the mean summer and winter temperatures at a depth of 50 cm the largest amplitudes represent soil windward areas. Soils of flat areas are aligned with lower temperature ranges (Table 5).

The resolution of the Russian temperature regimes classification as applicable to discontinuous permafrost zone of the northeast European Russia is slightly higher than that of the American classification. At the lowest taxonomic level, the first one differentiates eight combinations of subtypes based on indicators, covering: year, summer, winter and continentality, while the latter comprise two temperature classes. The values of indicators included both in the Russian and American classifications reflect differences in landscape conditions of the investigated The Russian classification index values reflect: snow cover thickness (depth), groundcover characteristics, etc. The American classification index values reflects to a greater extent the influence of the subsurface (including cryogenic) conditions down the soil profile.

CONCLUSIONS

Frozen soils with different mean winter and annual temperatures develop in the immediate neighborhood with the zones of discontinuous and insular permafrost in the northeast European Russia. The winter temperatures differences are caused by the variable snow cover depth in the area, dictated by the landscape features. The summer temperature measurements appear relatively leveled in the upper horizons (0–20 cm) of the investigated soils, and the subsurface differentiation is conditioned by the varying permafrost strata occurrence depths.

The cold frozen soils with harsh winter temperature regime form on the peat and mineral mounds. Fairly low mean annual temperatures in the upper horizons of the permafrost, given their shallow occurrence, indicate relative stability of the permafrost in the soils of peat mounds.

Soils of shallow, low and flat areas constitute a group of warm profiles characterized by relatively mild winter and annual thermal regimes. Loamy soils of this group are underlain by the fairly warm permafrost layer, particularly sensitive to climate changes. When consistently positive, the mean annual temperatures in the active layer in the cryoturbation-affected peat-gleyzem soils evidence and diagnose the permafrost thawing in mineral soils, monitored in the region in the past two decades.

Both the national and American classifications of temperature regimes reflect different landscape conditions of frozen soils regardless of their composition. The Russian classification of temperature regimes has a higher resolution, though, but it should be supplemented with parameters allowing to make provisions for the block of “warm” permafrost soils of the east European tundra.

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