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THE IMPACT OF TRANSFORMATION IN VEGETATION AND SOIL COVER ON THE SOIL TEMPERATURE REGIME UNDER WINTER ROAD OPERATION IN BOLSHEZEMELSKAYA TUNDRA

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The impact of transformation in the vegetation and soil cover on the soil temperature regime under winter road operation in Bolshezemelskaya tundra has been studied. Winter, summer and mean annual temperature parameters of tundra peat and mineral soils were revealed at the road section in the North Khosedau oil field. The main differences in the temperature regime of upper soil horizons (0–40 cm) at anthropogenically disturbed (tracks of the winter road) and undisturbed sites in different tundra ecosystems affected by continuous permafrost have been revealed.

Vegetation and soil cover, winter road, soil temperature regime, tundra ecosystems

INTRODUCTION

Construction of roads and of their infrastructure in development of hydrocarbon fields of Arctic is one of the major factors of anthropogenic impact on the tundra ecosystems. In the territory of the cryolithozone of Russia, the warming impact of filled-up motorways and railways on soil has been studied [*Ananyeva (Malkova), 1997; Moskalenko, 2012; Grebenets and Isakov, 2016*]. Certain studies are devoted to the impact of the traffic of cross-country caterpillar vehicles on soil in the summer period [*Gruzdev and Umnyakhin, 1984; Iglovsky, 2007*]. However, winter roads widely used for transportation of staff and cargo in the Russian Arctic in construction and operation of the infrastructure sites of the oil and gas complex account for the major part of the linear structures there [*Bykov, 1977*]. From the engineering viewpoint, the operation of winter roads causes the least damage to the tundra ecosystems, compared to the roads of other types [*Design..., 1991*]. Yet, the studies of the recent years have shown essential impact of winter roads on the ecosystems in the cryolithozone. As winter road tracks cross frost peat plateaus, the upper permafrost layers thaw, taliks are formed and degradation of peat mounds intensifies. On mineralized soils, laying of winter roads intensifies the erosion processes, leading to changes in the seasonal processes of freezing and thawing [*Minayeva, 2016*].

The goal of this research was to assess the impact of the transformation of the vegetation and soil cover on the temperature regime of soils at operation of a winter road under conditions of winter road operation in Bolshezemelskaya tundra (the area of the North Khosedau oil field).

THE LOCATION AND THE CHARACTERISTIC OF THE AREA UNDER STUDY

The field works were conducted in the Nenets autonomous district in the territory of the North Khosedau oil field (3 km southwest from the central point of oil collection). The study area is situated on the boundary between the southern and typical tundra, 55 km northeast of the Horey-Ver meteorological station (Fig. 1). The area is within the natural boundaries of the Yzyamlylk tract in the bogged valley of the Izyamykshor River (the left tributary of the Kolva River). The territory is characterized by alternating drained uphill sites and flat boggy poorly drained sites. According to the meteorological station data, in 2014, the mean annual temperature was –4.5 °C. The long-term mean annual rate of precipitation is 500 mm, with 350 mm falling in the warm period. The long-term maximum annual snow depth was 45 cm [*Fedorov, 1976*]. In the area under study, the winter road crosses natural tundra territorial complexes (NTC) with tall shrub and dwarf shrub vegetation on sandy and sandy loamy soils and a peat plateau on permafrost-affected peat soils under dwarf shrub-lichen vegetation (Fig. 2). The dwarf shrub vegetation is primarily associated with well-drained areas, whereas the tall shrub vegetation and flat mound peat soils occupy poorly drained areas. The tall shrub vegetation, unlike the dwarf shrub vegetation, is characterized by the presence of a tall (more than 40 cm) and

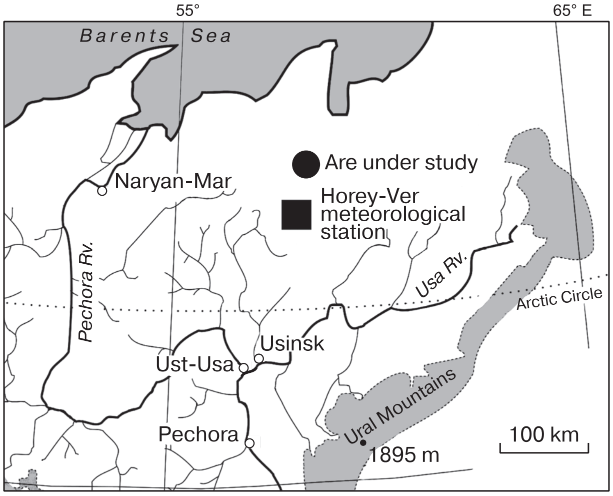

Fig. 1. The geographical location of the area under study.

closed shrub layer (more than 18 %), mainly consisting of *Salix* sp. and *Betula nana*.

The winter road was put into operation in 2007 and was actively operated until 2010, in the period of building infrastructure facilities in the oil field. In the subsequent years, the road was irregularly used in winter to transport cargo and equipment to the oil production site. The track ruts are characterized by the trough shape, 5–15 cm deep and 60–100 cm wide. Making the road resulted in disturbing the conditions for the vegetation growth (Table 1).

STUDY METHODS

During the study in the tundra NTC, differing by the character of the vegetation and soil covers, 5 sites were initiated (Tables 1 and 2). The sites 50 × 50 m in size consisted of 6 rows having 6 grid nodes each. All the sites were crossed by the winter road, 80–90 % grid nodes were on undisturbed surfaces.

At each grid node, the height and the projective coverage of willows (*Salix* sp.), dwarf birch thickets (*Betula nana*), dwarf shrubs (*Empetrum hermaphroditum*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Rubus chamaemorus*), wild rosemary (*Ledum* sp.), marsh cinquefoil (*Comarum palustre*), sedge (*Carex* sp.), moss (*Polytrichum* sp.) and lichens (*Cladonia rangiferina*) were determined. The following characteristics of the soil cover were investigated: thickness of the peat horizon, cm; depth of ground water, cm, and thickness of the active layer, cm. A steel rod was used to measure the thickness of the active layer and the ground water depth on August 15–16, 2014.

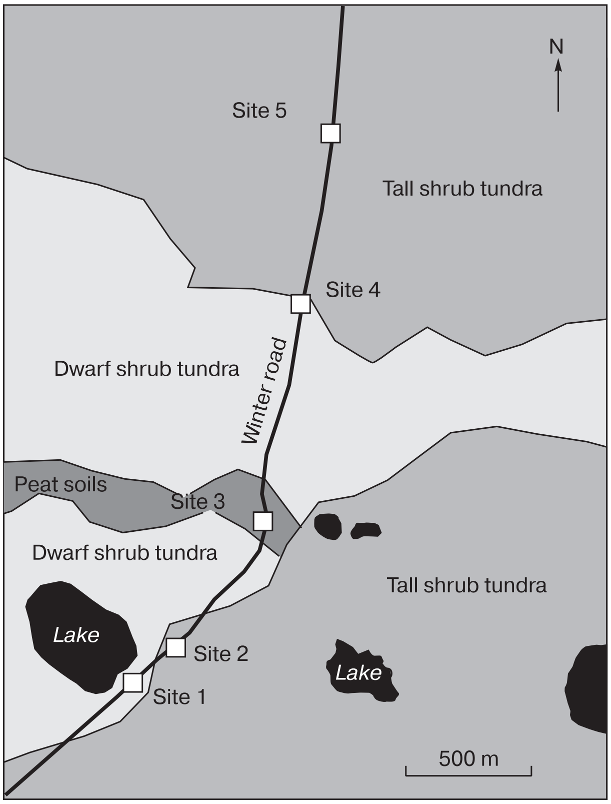

Fig. 2. The schematic map of the area under study.

Within each site, detailed studies of the morphological structure and of the soil temperature regime were conducted in two points located at the distance of 10–15 m from each other: in the anthropogenically disturbed soil under the track of the winter road and in the virgin soil in the adjacent undisturbed area (Table 1). The term ‘virgin soil’ is used in this study to characterize undisturbed soils under natural vegetation [*Rode, 1975*]. Altogether, 10 soil profiles were studied, and 140 *I-button* temperature loggers were installed at the depths of 0, 2, 5, 10, 15, 20 and 40 cm. Continuous temperature measurements were conducted in the period from 15.08.2014 to 15.07.2015.

Statistical analysis of the parameters of the vegetation and soil covers, calculation of the thaw and freezing degree days, followed by visualization of the results, were performed using the Microsoft Excel 2010 and IBM SPSS software programs and the R package. The characteristics of the vegetation and soil covers do not comply with the normal law of distribution; therefore, to compare them under normal conditions and under the road track, the non-parametric Mann–Whitney U test was used [*Moskalev and Novakovsky, 2014*]. The relation between the characteristics of the vegetation and soil covers and the thaw and freezing degree days was evaluated with a non-parametric method, Spearman’s rank correlation [*Lakin, 1990*].

The values of the mean annual soil temperature were calculated in the Matlab 7.0 software package. As the period of monitoring soil temperatures did not

Table 1. **Characteristics of the object under study**

Site	Conditions	Landscape characteristics	Vegetation	Average height of shrub tier, cm	Soil*	Thickness, cm		Track size, cm	
						organogenic horizon	active layer	depth	width
1	Undisturbed	Moderately drained surface of a flat lacustrine terrace	*Betula nana*, *Vaccinium vitis-idaea*, *Empetrum hermaphroditum*, *Rubus chamaemorus*, *Polytrichum* sp., *Cladonia rangiferina*	8	Stratified alluvial soil on layered sands	2	110	–	–
1	Disturbed		*Salix* sp., *Betula nana*, *Vaccinium vitis-idaea*, *Rubus chamaemorus*, *Carex* sp., *Eriophorum vaginatum*, *Polytrichum* sp., *Cladonia rangiferina*	7		4	>130	5	60
2	Undisturbed	Poorly drained surface of a flat depressed runoff band	*Salix* sp., *Betula nana*, *Vaccinium vitis-idaea*, *Carex* sp., *Comarum palustre*, *Polytrichum* sp.	40	Alluvial gleying soil on layered sands	8	120–130	–	–
2	Disturbed		*Salix* sp., *Carex* sp., *Comarum palustre*, *Eriophorum vaginatum*, *Polytrichum* sp.	16		5	>150	10	60
3	Undisturbed	Hummocky peat soil	*Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Ledum* sp., *Empetrum hermaphroditum*, *Rubus chamaemorus*, *Polytrichum* sp., *Cladonia rangiferina*	10	Olygotrophic frozen peat soil	100	45	–	–
3	Disturbed		Vegetation is absent on the tracks	0		100	45	15	100
4	Undisturbed	Gley soil of the top of the watershed slope	*Salix* sp., *Betula nana*, *Ledum* sp., *Empetrum hermaphroditum*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Polytrichum* sp., *Cladonia rangiferina*	20	Cryometamorphic gley soil on dusty loams	5	>150	–	–
4	Disturbed		Vegetation is absent on the tracks	0		2	>150	15	60
5	Undisturbed	Poorly drained surface of the top of the watershed slope	*Salix* sp., *Betula nana*, *Equisetum* sp., *Carex* sp., species of families Poacea, *Polytrichum* sp.	129	Cryometamorphic peat gley soil on dusty loams	20	>150	–	–
5	Disturbed		*Salix* sp., *Comarum palustre*, *Carex* sp., *Eriophorum vaginatum*	9		15	>150	10	60

Note. Parameters of soil and vegetation are provided immediately for the thermometric well locations.

* Soil names are provided after [*Shishov et al., 2004*].

Table 2. **Mean values of the vegetation and soil covers for undisturbed and disturbed areas in the sites under study**

Parameter	Site 1		Site 2		Site 3		Site 4		Site 5	
	undisturbed	disturbed	undisturbed	disturbed	undisturbed	disturbed	undisturbed	disturbed	undisturbed	disturbed
Vegetation cover parameters (numerator: height, cm; denominator: coverage, %)										
Willows	$\frac{0.0\pm0.0^*}{0.0\pm0.0^*}$	$\frac{2.5\pm2.5}{0.8\pm0.8}$	$\frac{40.3\pm7.1}{18.1\pm3.6}$	$\frac{16.0\pm7.5}{4.0\pm1.9}$			$\frac{14.6\pm1.6}{9.6\pm1.4}$	$\frac{7.5\pm7.5}{5.0\pm5.0}$	$\frac{128.8\pm10.3^{**}}{57.3\pm4.7^{**}}$	$\frac{0.0\pm0.0^*}{0.0\pm0.0^*}$
Dwarf birches	$\frac{8.0\pm1.6}{4.6\pm1.0}$	$\frac{7.5\pm2.5}{6.7\pm2.8}$	$\frac{11.9\pm3.9}{4.4\pm1.7}$	$\frac{9.0\pm9.0}{4.0\pm4.0}$	$\frac{13.0\pm3.4}{5.7\pm1.7}$	$\frac{5.0\pm5.0}{1.0\pm1.0}$	$\frac{17.9\pm0.9}{13.9\pm1.0}$	$\frac{20.0\pm0.1}{15.0\pm0.1}$	$\frac{15.0\pm5.2}{8.6\pm2.9}$	$\frac{8.8\pm8.8}{5.0\pm5.0}$
Ledum					$\frac{4.1\pm1.4}{2.8\pm1.2}$	$\frac{5.0\pm5.0}{1.7\pm1.7}$	$\frac{3.8\pm1.3^*}{3.1\pm1.2^*}$	$\frac{12.5\pm2.5}{15.0\pm10.0}$		
Marsh cinquefoil			$\frac{32.1\pm4.4^*}{21.0\pm3.6^*}$	$\frac{7.0\pm4.4}{2.0\pm1.2}$					$\frac{10.2\pm3.0}{6.9\pm2.6}$	$\frac{10.0\pm5.8}{3.8\pm2.4}$
Dwarf shrubs	$\frac{4.0\pm0.9}{7.3\pm1.8}$	$\frac{4.0\pm1.1}{15.0\pm4.7}$			$\frac{5.3\pm0.9}{10.4\pm2.6}$	$\frac{7.3\pm1.5}{5.7\pm2.3}$	$\frac{8.8\pm0.7}{17.8\pm1.8}$	$\frac{10.0\pm0.1}{32.5\pm2.5}$	$\frac{1.5\pm0.7}{2.7\pm1.5}$	$\frac{1.3\pm1.3}{1.8\pm1.8}$
Sedges	$\frac{11.3\pm2.3}{4.5\pm1.3}$	$\frac{16.2\pm4.3}{9.2\pm3.0}$	$\frac{74.8\pm5.9^{**}}{56.0\pm5.6}$	$\frac{29.0\pm1.9}{60.0\pm10.5}$	$\frac{10.1\pm1.4}{12.0\pm3.3}$	$\frac{16.7\pm3.3}{36.7\pm20.5}$	$\frac{14.6\pm1.3}{8.8\pm1.4}$	$\frac{15.0\pm0.1}{20.0\pm15.0}$	$\frac{28.5\pm5.6}{20.9\pm4.8}$	$\frac{25.0\pm11.0}{33.8\pm19.1}$
Lichens	$\frac{2.0\pm0.3^{**}}{42.9\pm6.6^{**}}$	$\frac{0.2\pm0.2}{2.5\pm1.7}$			$\frac{0.5\pm0.2}{15.9\pm4.4}$	$\frac{0.3\pm0.3}{26.7\pm26.7}$	$\frac{2.1\pm0.2}{30.4\pm4.2}$	$\frac{1.5\pm0.5}{17.5\pm7.5}$	$\frac{0.2\pm0.2}{2.7\pm2.5}$	
Mosses	$\frac{1.8\pm0.4}{12.5\pm2.4}$	$\frac{0.7\pm0.1}{20.8\pm4.2}$	$\frac{7.6\pm1.5}{61.2\pm6.7}$	$\frac{0.7\pm0.2}{54\pm12.1}$	$\frac{2.2\pm0.6}{24.5\pm5.6}$	$\frac{4.0\pm3.0}{41\pm29.9}$	$\frac{2.6\pm0.3}{38.3\pm3.8^*}$	$\frac{6.0\pm4.0}{82.5\pm7.5}$	$\frac{4.2\pm0.8}{38.8\pm4.7}$	$\frac{2.0\pm1.0}{45.0\pm18.6}$
Soil cover parameters										
Peat thickness, cm	5.6 ± 0.7	5.4 ± 1.3	50.2 ± 6.9**	3.9 ± 1.7	97.6 ± 2.4	100.0 ± 0.0	4.8 ± 0.7	13.5 ± 6.5	24.1 ± 2.2	30.8 ± 9.9
Ground water depth, cm	44.3 ± 3.3**	22.5 ± 6.3	4.5 ± 3.9*	16.4 ± 5.7	9.8 ± 3.1	21.7 ± 16.9	37.2 ± 6.0	30.0 ± 30.0	15.6 ± 5.0	11.3 ± 11.3
Active layer thickness, cm	78.3 ± 3.9	89.3 ± 11.0	117.8 ± 4.3*	106.6 ± 8.6	46.9 ± 2.9	54.3 ± 4.7	90.3 ± 3.1	55.0 ± 20.0	108.8 ± 4.9**	57.8 ± 11.3

According to Mann–Whitney U test: * $p < 0.05$, ** $p < 0.01$.

fully cover a calendar year, values of the mean annual soil temperature at different depths obtained by data processing were approximated with the formula

$$T_{\text{year}}(z) = C \exp(-\gamma z) + d, \qquad (1)$$

where γ is the parameter characterizing attenuation of temperature fluctuations related to the depth, cm^{-1}; C is the constant of the mean annual temperature on the soil surface; d is the soil temperature at the depth of attenuation of the soil temperature fluctuations, °C; z is the depth of measurements of the soil temperature, cm. The values of d in formula (1) with a fixed value of γ were determined by the least squares method [*Korn and Korn, 1977*]. The choice of this function for approximating the mean annual soil temperature was caused by the necessity of finding asymptotic properties of the decision, namely, the temperature at lower depths (about 10 m) tending towards a certain constant value (d) at attenuation of the temperature fluctuations.

STUDY RESULTS

The vegetation and soil covers. The correlation analysis showed that at all the sites, the increase in the presence of *Salix* sp. was accompanied by a rise in the height of *Betula nana* (the correlation coefficient $r = 0.5$), *Comarum palustre* ($r = 0.6$), *Carex* sp. ($r = 0.6$), *Polytrichum* sp. ($r = 0.3$). In its turn, the rise in the height of the dwarf shrubs is comparable to the increased presence of *Cladonia rangiferina* ($r = 0.6$), *Ledum* sp. ($r = 0.9$) and decreased presence of *Comarum palustre* ($r = -0.8$) and *Carex* sp. ($r = -0.7$) (Fig. 3).

The increase in the active layer thickness is accompanied by the rise in the height of *Salix* sp. ($r = 0.9$), *Carex* sp. ($r = 0.7$) and *Comarum palustre* ($r = 0.7$). Reduction in the active layer thickness was observed as the height of the dwarf shrubs ($r = -0.7$), *Ledum* sp. ($r = -0.7$) rose and the thickness of the peat horizon increased ($r = -0.4$). Increased active layer thickness agrees both with increased sums of positive temperatures ($r = 0.4$) and with warming of the winter temperature conditions in soils ($r = 0.7$) (Fig. 3).

The operation of the winter road resulted in significant damages of *Salix* sp., *Betula nana*, *Cladonia rangiferina*; in the road tracks, their mean height decreased essentially (Tables 1, 2). The height and the plant cover of the dwarf shrubs increased practically on all the sites (Table 2). In the tracks, the upper organogenic horizon became destroyed completely (site 3) or partly (sites 1, 2, 4, 5). In the disturbed soils, the active layer thickness and the depth of the ground water table varied on a case-by-case basis depending on the type of NTC. In disturbed sites 2 and 3, the ground water level was found to be 11 cm lower than that in undisturbed sites. This is related to the increase in the depth of seasonal thawing in the track soils (site 3) and laying of the road on the most drained part of the bog (site 2). On sites 2, 4, 5, the damage of the shrub and dwarf shrub tiers contributed to the 10–50 % increase of the active layer thickness (Table 2). On sites 1 and 3, the active layer thickness increased by 14–16 %. On site 1, the mean height of the natural dwarf shrub vegetation was found to be minimal (4–8 cm); therefore, the transformation of the soil cover became the determining factor of the increase in the thickness of the active layer here. On peat soil (site 3), the upper organogenic horizon became destroyed, the lower horizons of black peat with low albedo outcropped.

The soil temperature regime. Freezing of the upper part of the studied tundra soils begins in October. The fastest freezing rates were recorded on the virgin soils of sites 3 and 4, located in the windward locations, where intense wind-driven removal of snow takes place. In the track soils, freezing occurs slower (Fig. 4), which is explained by filling of the winter road track with snow and by a longer freezing period.

During November, freezing actively involves the entire upper 40-cm soil layer. The lowest freezing rates are found in the virgin soils under tall shrub vegetation (sites 2 and 5, Table 2). Intense snow accumulation on sites under tall shrub vegetation contributed to slow seasonal freezing with a long period of around-zero temperatures (Fig. 4). The soils of the winter road tracks freeze for a longer period on sites with prevailing dwarf shrub vegetation (sites 1, 3, 4), whereas destruction of tall shrub vegetation on sites 2 and 5 increased freezing of the disturbed soils due to reduced snow accumulation. Complete freezing of the upper layer (0–40 cm) in virgin soils under tall shrub vegetation was observed only in late December (Fig. 4).

The minimal sums of the negative temperatures on the soil surface were recorded on flat-mound peat soil (site 3, Table 3). The soils of the permafrost-affected peat mounds are characterized by intense winter cooling of the active layer [*Kaverin et al., 2014*]. Among the mineral soils (sites 1, 2, 4, 5) the soils of site 4, located on the windward top of a steep loamy slope, are the coldest ones. The soils of site 5, established under tall willows on a relatively flat surface, have the mildest winter temperatures. The soils of site 2 under tall shrub vegetation are also characterized by high winter temperatures (Table 3). The soils of site 1 occupy an interim position for the winter parameters between windward surfaces with shallow snow (sites 3, 4) and sites with intense snow accumulation (sites 2, 5). At the depth of 40 cm, differentiation of the soils for the winter temperature regime is similar to that on their surface (Table 3).

In total, expected differences were recorded between the soils of disturbed and undisturbed area in the winter temperature regime. For the sums of negative temperatures, the sections of the winter road

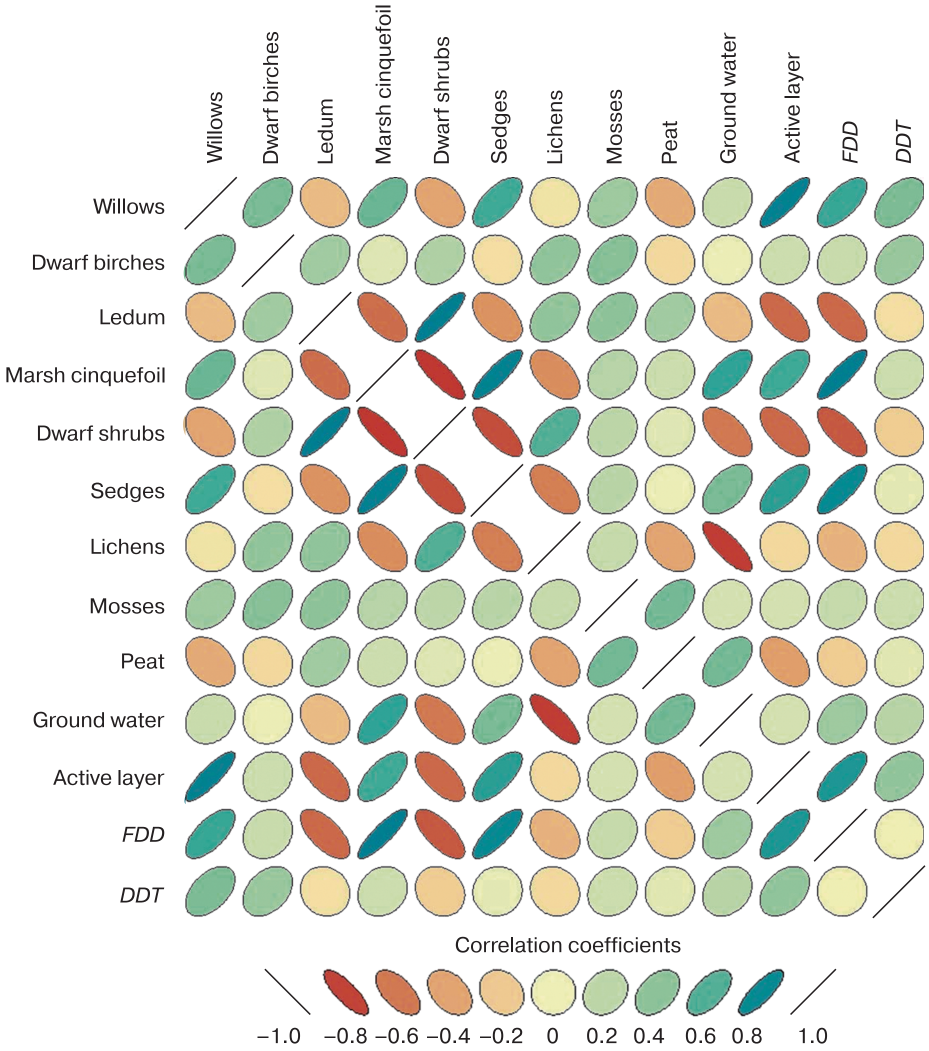

Fig. 3. Mean values of the correlation coefficients by Spearman between the soil cover parameters, the average height of the plants and the sums of soil temperatures at the depth of 20 cm.

The average height of the plants: willow (*Salix* sp.), dwarf birch (*Betula nana*), ledum (*Ledum* sp.), marsh cinquefoil (*Comarum palustre*), dwarf shrubs (*Empetrum hermaphroditum*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Rubus chamaemorus*), sedges (*Carex* sp.), lichens (*Cladonia rangiferina*), and mosses (*Polytrichum* sp.). Characteristics of the soil cover: peat – thickness of the upper peat horizon (cm); active layer – thickness of the active layer (cm); ground water – the depth of the ground water in the period of study (cm). The temperature parameters: *DDT* – sums of positive temperatures (°C·day), *FDD* – sums of negative temperatures (°C·day).

track proved to be colder than those of the virgin soils on sites 2 and 5. This is related to the warming effect of the shrub layer, intensely accumulating snow in winter. The maximum cooling effect of the section of the winter road was recorded on site 5 (Table 3), where the winter road crossed the willow community with a tall closed shrub layer (Table 2). The track surface of the winter road here is colder than the surface of the virgin soil by 261 degree-days. Whereas on virgin soil, only the upper 2-cm deep soil layer was seasonally frozen, in the road track, freezing embraced the entire part of the soil profile under study. On site 2, similar differences are less expressed, which is related to the lower height of the shrub layer (Tables 2, 3).

An opposite pattern was observed on sites 1, 3 and 4, where the track soils in winter were warmer than the virgin soils (Table 3). This is explained by the low height of the dwarf shrubs, which accumulate less snow than tall shrubs. More snow is accumulated in the road tracks. The maximum warming effect of the winter road was found on site 4, where the soil under the track became cooled 2 times less than its virgin counterpart. The monitoring data confirmed

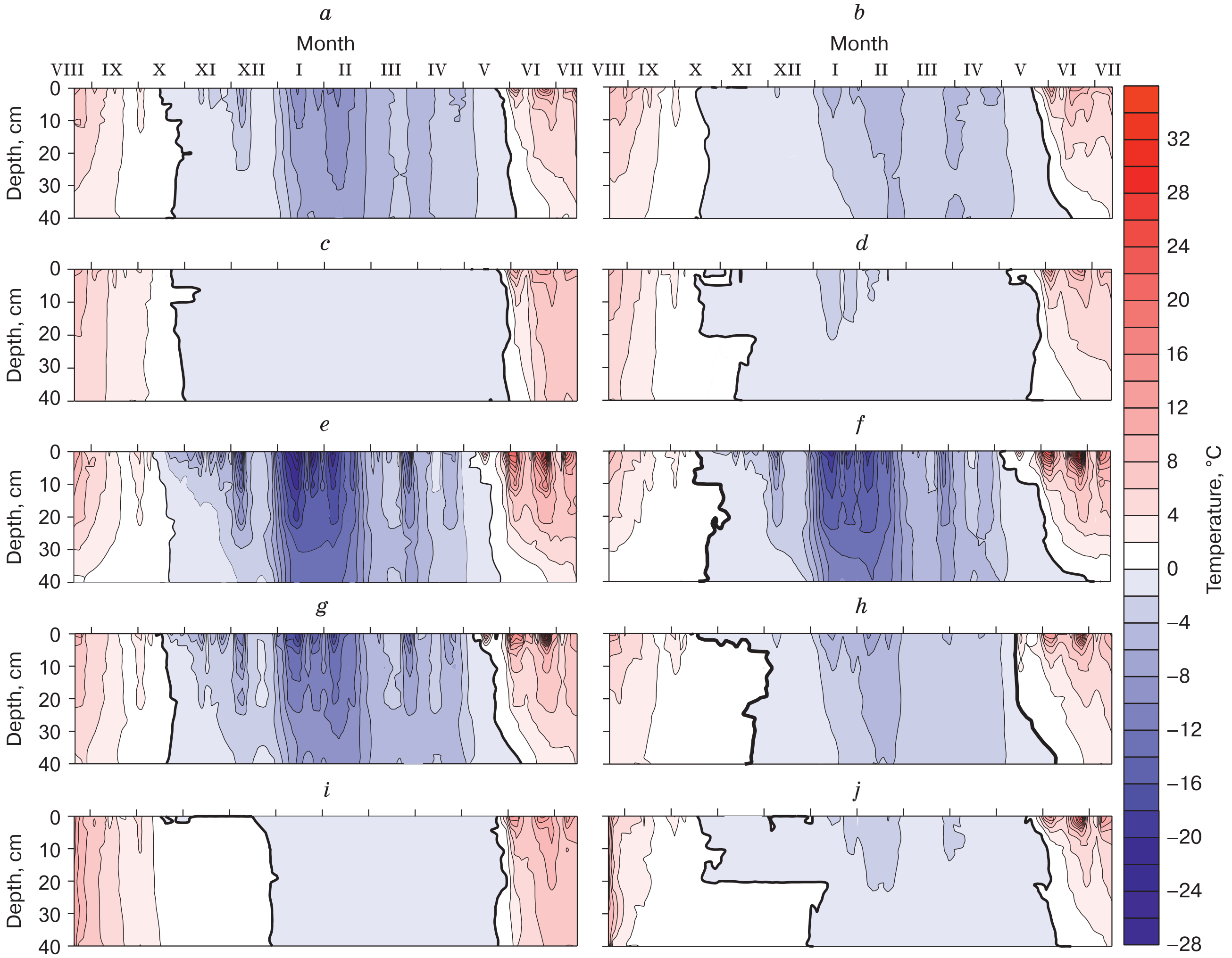

Fig. 4. Soil isothermobaths in the upper layer (0–40 cm) for 2014–2015 for undisturbed and disturbed conditions.

a, *b* – site 1; *c*, *d* – site 2; *e*, *f* – site 3; *g*, *h* – site 4; *i*, *j* – site 5; *a*, *c*, *e*, *g*, *i* – virgin soil; *b*, *d*, *f*, *h*, *j* – track soil.

Table 3. **Sums of negative mean daily soil temperatures (°C·day) in 2014–2015**

Site	Soil	Depth, cm					
		0	2	5	10	20	40
1	Undisturbed	–967	–936	–895	–830	–811	–690
	Disturbed	–538	–	–502	–493	–	–487
2	Undisturbed	–	–138	–	–125	–124	–51
	Disturbed	–206	–196	–197	–	–176	–75
3	Undisturbed	–1865	–1730	–1595	–1491	–1360	–1054
	Disturbed	–1551	–1357	–1359	–1283	–1269	–1017
4	Undisturbed	–1485	–1374	–1212	–1169	–1070	–918
	Disturbed	–641	–572	–475	–453	–449	–362
5	Undisturbed	–18	–6	0	0	–	0
	Disturbed	–280	–	–279	–258	–164	–124

Notes for Tables 3–5: dash – not determined.

the special vulnerability of the tundra mineral soils, compared to peat soils, not only to climatic changes but also to anthropogenic impact [*Mazhitova, 2008*]. Minimal differences between the sums of negative temperatures are recorded in the hummocky peat soils. This may be explained by intense wind-caused removal of snow from the hummocks' surface and by increased heat conductivity of the frozen peat horizons in winter.

The lowest winter temperatures on the soil surface (–26...–22 °C) were recorded on site 3 (the hummocky peat soil) (Fig. 4). In the "warm" soils of site 5, the minimum temperatures of the surface were –0.5...–4.5 °C. The temperature minimum in the upper soil horizons (0–40 cm) were recorded in January–February. In the virgin soil of site 5, a shift of the temperature minimum to April (the depth of 40 cm) was observed, due to the heat insulating effect of the deep snow cover.

Seasonal thawing of the tundra soils begins in May (Fig. 4). In the first half of May, positive temperatures on the soil surface were recorded on sites 3 and 4. This is related to the earlier disappearance of the snow cover from the surface of the hummocky peat soil and of the drained steep slope. The other soils begin to thaw in the second half of May. The maximum sums of positive temperatures on the soil surface were recorded on site 3 (Table 4), which is related to the low albedo of the peat soil surface [*Kaverin et al., 2014*]. However, in peat soils, rather fast attenuation of temperatures is observed, and already at the depth of 40 cm, these soils are the coldest. In general, soils under the shadowing tall shrub vegetation get warmed less, compared to areas under dwarf shrub vegetation (Table 4).

The summer temperature parameters of virgin and disturbed soils vary (Fig. 3). The surface of the track soil is warmer than that of its virgin counterparts on sites 1 and 3, characterized by the minimum height of the dwarf shrub vegetation (4–13 cm) (Table 4). In addition, on the soil surface of site 3 outcropping black peat was excavated, characterized by the low albedo.

From the depth of 20 cm, the track soils on all the sites are characterized by the relatively low sums of positive temperatures, compared to their virgin counterparts. Decrease of the summer temperatures depending on the depth in disturbed soils is explained by the greater "accumulation of the winter cold" (sites 2 and 5) and later dates of snow thawing in the tracks (sites 1, 3, 4).

The total range of the mean annual temperatures in the soils under study at the depths of 0–40 cm was equal to +2.7...–2.6 °C (Table 5). The mean annual

Table 4. **Sums of positive mean daily soil temperatures (°C·day) in 2014–2015**

Site	Soil	Depth, cm					
		0	2	5	10	20	40
1	Undisturbed	613	513	427	395	323	159
	Disturbed	646	529	499	411	295	139
2	Undisturbed	673	574	519	470	437	389
	Disturbed	637	543	461	393	338	198
3	Undisturbed	891	836	744	625	481	118
	Disturbed	912	836	618	427	301	16
4	Undisturbed	934	764	565	479	441	209
	Disturbed	753	651	554	414	284	149
5	Undisturbed	769	717	709	623	570	567
	Disturbed	691	584	400	282	246	123

Table 5. **Mean annual soil temperatures (°C) in 2014–2015**

Site	Soil	Depth, cm					
		0	2	5	10	20	40
1	Undisturbed	–0.4	–0.6	–0.8	–0.8	–1.0	–1.2
	Disturbed	0.9	–	0.5	0.2	–0.1	–0.8
2	Undisturbed	2.2	1.7	1.6	1.4	1.2	1.3
	Disturbed	1.7	1.4	1.2	–	0.8	0.5
3	Undisturbed	–1.7	–1.5	–1.5	–1.6	–1.7	–2.3
	Disturbed	–0.8	–0.5	–1.3	–1.7	–2.1	–2.6
4	Undisturbed	–0.6	–0.9	–1.1	–1.3	–1.2	–1.6
	Disturbed	1.0	0.9	0.8	0.3	–0.2	–0.4
5	Undisturbed	2.7	2.5	2.5	2.2	–	2.0
	Disturbed	1.7	1.4	0.7	0.3	0.5	0.1

temperature parameters reflect primarily the impact of winter. Positive mean annual temperatures, characteristic of soils under tall shrub tundra vegetation (sites 2 and 5), demonstrate a mild winter regime in these soils. The minimum mean annual temperatures (–0.8...–2.6 °C) were recorded in permafrost peat soils of site 3 (Table 5).

According to the annual parameters, disturbed soils are warmer than virgin soils in the sites with prevailing dwarf shrub vegetation (sites 1, 3, 4, Table 5). Positive mean annual temperatures in the upper horizons of the mineral soils of the track (sites 1 and 4) demonstrate the warming impact of the winter road. The track soils in the sites with prevailing tall shrub vegetation (sites 2, 5) proved to be colder than their virgin counterparts. The mean annual temperatures decrease as the depth increase, and maximum gradients of the temperature reduction (⩾1.0 °C/40 cm) are recorded in anthropogenically disturbed soils. In virgin soils, the gradient was 0...0.8 °C/40 cm.

CONCLUSION

The correlation analysis of the quantitative parameters of the vegetation and soil covers allows interactions between them and the main indicators of spatial differentiation of the active layer thickness in disturbed and undisturbed conditions to be revealed. The increase in the active layer thickness is accompanied by the increase in the height of *Salix* sp. ($r = 0.9$), *Carex* sp. ($r = 0.7$) and *Comarum palustre* ($r = 0.7$). Reduction of the active layer thickness is observed as the height of the dwarf shrub ($r = -0.7$) and ledum ($r = -0.7$) rises and the thickness of the peat horizon ($r = -0.4$) grows.

Operation of the winter road partly damages the vegetation cover, enhancing the spatial differentiation of its quantitative parameters in the areas under study. In the road tracks, mostly tall shrubs (*Salix* sp., *Betula nana*) and lichens (*Cladonia rangiferina*) are destroyed, and their average height and coverage reduce dramatically. At the same time, the height and the coverage of the dwarf shrubs increased in the tracks.

Operation of the winter road influences the parameters of the soil cover. Transformation or complete destruction of the upper coarse humus horizon takes place in the track soils. The active layer thickness and the depth of the ground water in disturbed conditions vary differently, depending on the combination of factors on the given NTC. The active layer thickness in the track soils versus to virgin soils decreases by 10–50 % under conditions of prevailing shrub or dwarf shrub vegetation taller than 18 cm. An increase in the active layer thickness (14–16 %) was recorded for the peat soil and on that of site 1, characterized by the minimum height of the dwarf shrub vegetation (4–13 cm).

Resulting from transformation of the vegetation and soil covers, the temperature regime of the soils changes, too. Winter road construction across tundra vegetation communities with the average height of the tall shrubs exceeding 40 cm contributes to the increase of the winter cooling on the soil surface by 50–200 %. This is caused by destruction of tall shrub vegetation, which contributes to snow accumulation under undisturbed conditions. For low dwarf shrub communities (4–18 cm), construction of the winter road, on the contrary, contributes to reduction of the sums of negative soil temperatures by 40–80 %. In the summer period, the warming influence of the track of the winter road is expressed on sites with the average height of the dwarf shrub vegetation equal to 4–13 cm.

The mean annual temperatures of the soils, primarily reflecting the specific features of their winter climate, under conditions of disturbed tall shrub tundra vegetation, are on average 0.4...1.4 °C lower, and those under conditions of the dwarf shrub tundra are higher by 0.3...1.8 °C than on virgin sites.

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