CORRELATION OF ACTIVE LAYER THICKNESS AND LANDSCAPE PARAMETERS OF PEATLAND IN NORTHERN WEST SIBERIA (NADYM STATION)

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Active layer thickness and landscape parameters (elevation, volumetric soil moisture, and soil surface temperature) of frozen peatland at the CALM R1 site in the Nadym area, northern West Siberia, are highly variable in space. Thaw depths are controlled jointly by soil and vegetation patterns related to elevations and winter temperatures of soil surface. The spatial variability of soil moisture and surface temperatures depend on snow depths which are greater in microtopographic lows and shallower in relatively elevated areas.

Permafrost, permafrost-affected soils, peat, soil moisture, soil temperature, statistics

INTRODUCTION

The international program of Circumpolar Active Layer Monitoring (CALM) is developed as a leading edge in comprehensive efforts to study active layer and permafrost responses to climate change in the long-term perspective. Started in 1990, the CALM network currently consists of more than 200 active sites in fifteen countries (www.gwu.edu/~calm/data/north.html), mostly in Arctic and Subarctic areas. Multiple active layer parameters have been monitored on 100 × 100 m^2 or 1000 × 1000 m^2 grids in Alaska [*Brown, 1967; Hinkel and Nelson, 2003; Streletskiy et al., 2014*], Canada [*Nixon and Taylor, 1994; Nixon et al., 1995*], Greenland [*Christiansen, 1999*], Antarctica [*Pablo et al., 2014*], and at 64 sites in Russia [*Mazhitova et al., 2004; Melnikov et al., 2005; Vasiliev et al., 2008; Melnikov, 2012; Bobrik et al., 2014; Grebenets et al., 2014; Khomutov et al., 2014; Malkova et al., 2014*].

Thirteen out of sixty four CALM sites in Russia are located in West Siberia. The reported data are from CALM R1 (Nadym station), the southernmost West Siberian site lying in the zone of sporadic permafrost. The site has been run since 1997, with measurements of thaw depths, air and soil temperatures, vegetation, and elevations.

Spatial variations in active layer thickness in peatland within discontinuous (sporadic) permafrost are discussed in the paper in correlation with landscape parameters. The specific objectives of the study are (1) tracing the local patterns of soil, vegetation, and elevations (microtopography); (2) estimating thaw depths, volumetric soil moisture contents, and soil surface temperatures; (3) correlating thaw depth variations to the landscape patterns.

STUDY AREA

The CALM R1 site is located at 65°20′ N, 72°55′ E in northern West Siberia (Nadym area, Tyumen region, Yamal-Nenets Autonomous District), at the northern boundary of the northern taiga subzone, in the margin of the third limnic-alluvial plain of the Nadym River, in the Kheigiyakha–Levaya Khetta interfluve (Fig. 1) [*Moskalenko, 2012*]. The site belongs to the zone of sporadic permafrost, where patches of frozen ground occupying 50 % of the surface area

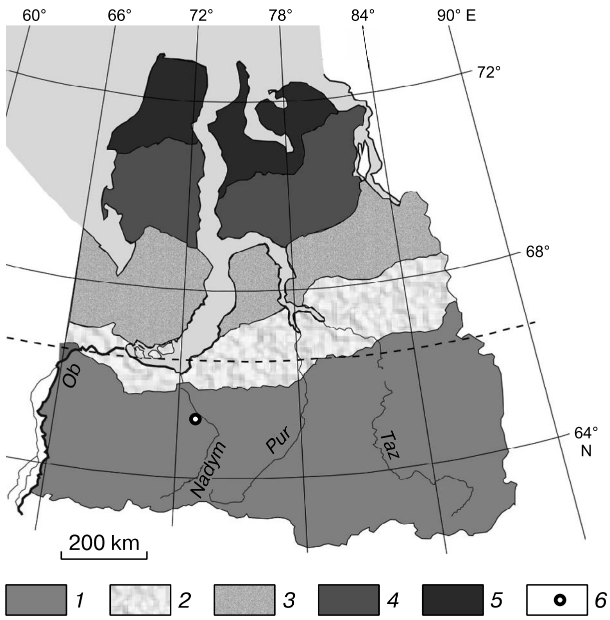

Fig. 1. Study area.

1 – boreal taiga, *2* – forest tundra, *3* – southern tundra, *4* – typical tundra; *5* – Arctic tundra; *6* – Nadym station.

correspond to peatland, marshy, and heaving terrains [*Pavlov and Moskalenko, 2001*]. The climate is severe, with long cold winters, low mean annual temperatures (–5 °C), and 450 to 650 mm annual precipitation.

The landscapes are of two groups according to soil conditions and presence or absence of permafrost: (i) automorphic forest landscapes free from permafrost and (ii) hydromorphic landscapes of oligotrophic bogs or peatlands with low or high peat mounds, where permafrost table lies at a depth of 1–2 m [*Vasilievskaya et al., 1986; Matyshak, 2009*].

We studied a typical peatland area, which is a flat or gently sloping surface with large mounds rising above the base level of bog ecosystems, as well as a piece of swampy land nearby.

METHODS

Active layer thickness and other related parameters have been monitored continuously within a 100 × 100 m plot on a regular 10 m grid, at 121 measuring points.

In August 2014, soil, vegetation, and microtopography patterns were documented at all points of the site, with relative elevations measured by leveling surveys [*Simonov, 2005*]. Peat thickness was estimated using an *Eijkelkamp* gouge auger designed for sampling wet clay and peat with minimal disturbance of soft cohesive soils. Volumetric soil moisture was measured in triplicate at each point in the upper 15 cm of soil by a *Spectrum TDR-100* soil moisture meter. Thaw depths were determined in late August and early September [*Melnikov et al., 2005*] by inserting a 10-mm diameter graduated steel rod into the soil to the point of refusal [*Methods of Estimating Thaw Depth, 1984*].

Air temperatures were sampled at 1 m above the surface, every four hours, from August 2013 to July 2014 with *Thermochron iButton*™ loggers. The loggers for soil surface temperatures were placed at a depth of 2 cm to avoid biases from direct sunlight and to estimate effects of vegetation on the thermal regime [*Goncharova et al., 2015*]. The mean annual and mean monthly (July and February, the warmest and coldest months, respectively) temperatures were analyzed statistically.

The collected data were processed by correlation and regression methods using *Excel* and *Statistica 6.0* software. The spatial variations of measured parameters were imaged in maps using *Golden Software Surfer 8* modeling.

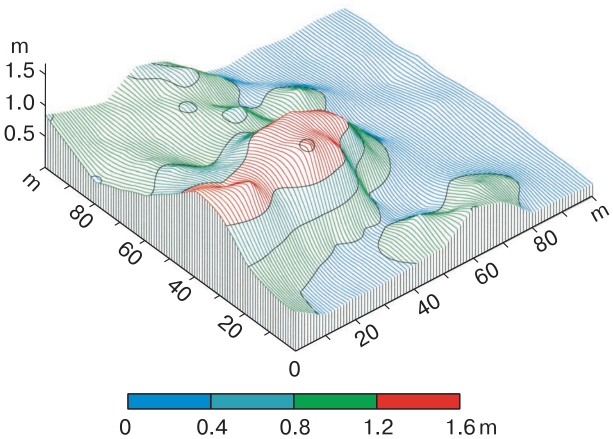

Fig. 2. Digital elevation model of Nadym CALM site (August 2014).

RESULTS AND DISCUSSION

1. Topography, vegetation and soil

Site background. The sampling points are located mostly in peatland (over 60 %) and in a swampy terrain nearby (40 %). According to leveling, the difference between the maximum and minimum elevations is 1.68 m (Fig. 2), mean relative elevation being 0.54 ± 0.07 m (hereafter the 95 % confidence interval is quoted as mean ± 1.96 × SD). A half of the territory is below 0.5 m. Mean elevations are 0.73 m and 0.23 m for the peatland and swampy areas, respectively.

Peatland microtopography consists of flat surfaces and relative highs (peat mounds) and lows (hollows): 27.5 %, 45 %, and 27.5 % of points, respectively. The swampy terrain is flat, with mounds.

The plant communities are diverse *Cladonia* lichens and mosses (*Sphagnum*, *Pleurozium*, *Politri-*

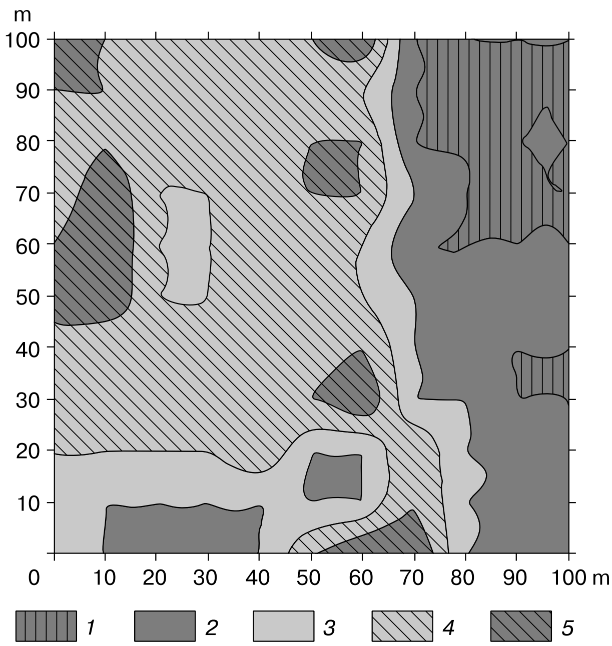

Fig. 3. Map of plant communities (August 2014).

1 – Sphagnum with sparse Carex; *2 – Sphagnum*; *3 – Cladonia*; *4 – Cladonia* with sparse moss and shrubs; *5 – Sphagnum* with sparse shrubs and grasses.

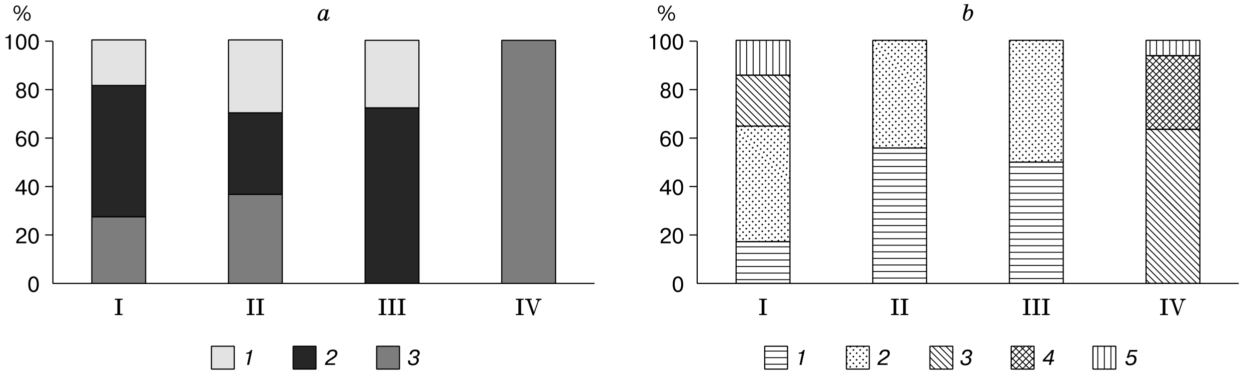

Fig. 4. Elevations (*a*) and vegetation (*b*) in different microtopogaphic forms.

a: elevations of 0–0.50 m (*1*), 0.51–1.00 m (*2*), >1.01 m (*3*); *b*: plant communities of *Cladonia* (*1*), *Cladonia* with sparse moss and shrubs (*2*), *Sphagnum* (*3*), *Sphagnum* with sparse *Carex* (*4*), *Sphagnum* with sparse shrubs and grasses (*5*). Roman numerals denote microtopogaphic forms of relative highs (I) and lows (II), flat peatland (III), and flat swampy terrain (IV).

chum), shrubs of dwarf birch (*Betula nana*), billberry (*Vaccínium myrtíllus)*, bog billbery *(Vaccínium uliginósum)*, red billberry (*Vaccínium vítis-idaéa*), and wild rosemary (*Ledum palustre*); and grasses of sedges (*Carex* sp.), cotton grass (*Eriophorum* sp.), and andromeda (*Andromeda*). Sphagnum and reindeer moss communities (with and without scarce shrubs, grasses, and sedges) grow at 50.5 and 49.5 % of points, respectively. Sedges and shrub-free sphagnum with reindeer mosses grow at 20 % of points. Reindeer mosses (with and without shrubs) and sphagnum with shrubs are common to peatland while sphagnum and sedge-sphagnum communities more often grow in the swampy terrain.

Although being rather small, the site comprises six soil types [*Matyshak, 2009*]: cryoturbated gley, peat-gley, and cryogenic soils in peatland (peat-cryogenic and peat-gley soils at 37 and 21 % of points, respectively) and oligotrophic peat in the swampy area [*Shishov et al., 2004*].

Peat in peatland is from 0 to 0.57 m thick (0.28 m on average), being the thinnest in microtopographic highs and lows (0.20 ± 0.05 m). Generally, the peat thickness varies strongly over the peatland area (56 % of difference). In the swampy terrain, peat is as thick as 0.50 ± 0.05 m.

Correlations between microtopogaphy, vegetation, and peat thickness. All points within the swampy terrain have elevations under 0.50 m, and mostly sphagnum vegetation, with sphagnum and sedge communities growing at 30 % of points (Fig. 3).

The flat surface of peatland, with a mean elevation over 0.50 m, is generally elevated above the swampy terrain. The elevation difference is 0.5 to 1.0 m at 70 % of points and exceeds 1 m at 30 % of points (Fig. 4). Microtopographic lows in peatland have elevations below 0.5 m (Fig. 4) and their vegetation is limited to reindeer mosses.

According to regression analysis, elevations correlate with soil moisture ($r = -0.70$, p-level significance <0.05), thaw depth ($r = -0.30$, p-level <0.05), and vegetation patterns ($r = 0.65$, p-level <0.05). Vegetation types also show statistically significant correlations with relative elevations (highs or lows, $r = 0.35$, p-level <0.05) and soil moisture ($r = 0.57$, p-level <0.05).

2. Active layer thickness

Active layer thickness is an important characteristic of permafrost soils. Permafrost, as a confining bed on one hand and a low-temperature rock on the other hand, influences the evolution of ecosystems and soils, especially as a control of the moisture and temperature regimes [*Makeev, 1999*]. The mean active layer thickness at the CALM R1 site varies from 1.01 to 1.43 m (September 1997 through September 2010), but shows no distinct time trends [*Melnikov, 2012*].

In September 2014, thaw depths varied from 0.55 to 2.0 m and more being 1.66 ± 0.08 m on average. The average was the greatest over the period of observations [*Melnikov, 2012*], being less than 1.5 m at 35.5 % of points and more than 2 m at 56.2 % of points, mainly within the swampy terrain and within microtopographic lows in peatland (Fig. 5). Shallow thaw depths (within 1 m) were measured at 11 % of points, with 27 % variance. The thaw depth patterns were analyzed in correlation with other monitored parameters, on order to study the variations in more detail.

Active layer thickness and microtopography. Average thaw depths within zones of 0–0.5, 0.51–1.0 and >1 m elevations are 1.80, 1.54 and 1.37 m, respectively. At lower elevations, the percentage of points showing thaw depths greater than 2 m increased from 23.5 to 71.6 % (Fig. 6). Active layer is the thinnest (>1 m) only at elevations exceeding 0.5 m.

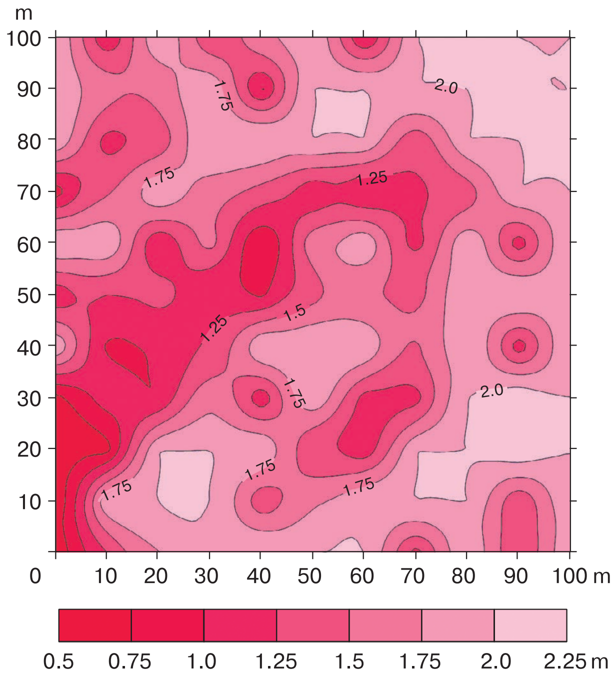

Fig. 5. Map of active layer thickness (August 2014).

The thaw depths are 1.45 m, 1.59 m, and 1.64 m on average in flat peatland, highs, and lows, respectively, and exceed 2 m in a half of points within microtopographic lows and highs (Fig. 6).

In the swampy terrain, thaw depths are more than 2 m at 70 % of points and the average is 1.78 m, or greater than in peatland, due to the warming effect of water.

According to regression analysis, the correlation between active layer thickness and elevations is at $r = -0.30$, p-level <0.05; thaw depth [m] = 1.54 [m]– 0.34 [m/m] × elevation [m].

Thus, thaw depths are shallower in more elevated areas and deeper at lower elevations, which is especially prominent in peatland where microtopographic lows are prone to warming from snow (in cold seasons) and water.

Active layer thickness and vegetation. Average thaw depths under reindeer mosses and sphagnum communities are 1.56 m and 1.68 m, respectively. The active layer is thicker than 2 m mainly under areas of sphagnum and sedge vegetation. However, the correlation of thaw depths is statistically significant neither with vegetation types (regression analysis) nor with peat thickness in peatland (statistical analysis of the data total and of separate groups).

3. Soil surface temperatures

Temperature and topography. According to regression analysis, mean annual soil temperatures show statistically significant correlation with elevations ($r = -0.48$, p-level <0.05; T [°C] = 2.0 [°C]– 0.71 [°C/m] × elevation [m]). Monthly means for February likewise correlate with elevations ($r = -0.60$, p-level <0.05; T [°C] = –0.50 [°C]–1.63 [°C/m] × elevation [m]).

The coldest annual means are measured at elevations above 1.01 m (Table 1). The reason is in the distribution of snow cover over different landforms: snow depths are shallower in relative highs and deeper in relative lows. The surface lying below 0.5 m is the warmest, while the warm annual means are due to the winter component related to larger snow depths.

Temperature and active layer thickness. Thaw depths correlate with winter and mean annual temperatures of soil surface: $r = 0.38$, p-level <0.05; thaw depth [m] = 1.63 [m] + 0.17 [m/°C] × T_{Feb} [°C] and $r = 0.33$, p-level <0.05; thaw depth [m] = 0.94 [m] + 0.26 [m/°C] × T_{ann} [°C], respectively, but there is no correlation with summer soil temperatures. These correlation patterns are consistent with mean temperatures for zones of different thaw depths (Table 2).

Thus, the spatial variations of soil surface temperatures depend mostly on elevations, but the effect is implicit, via snow depths that differ in microtopogaphic highs and lows.

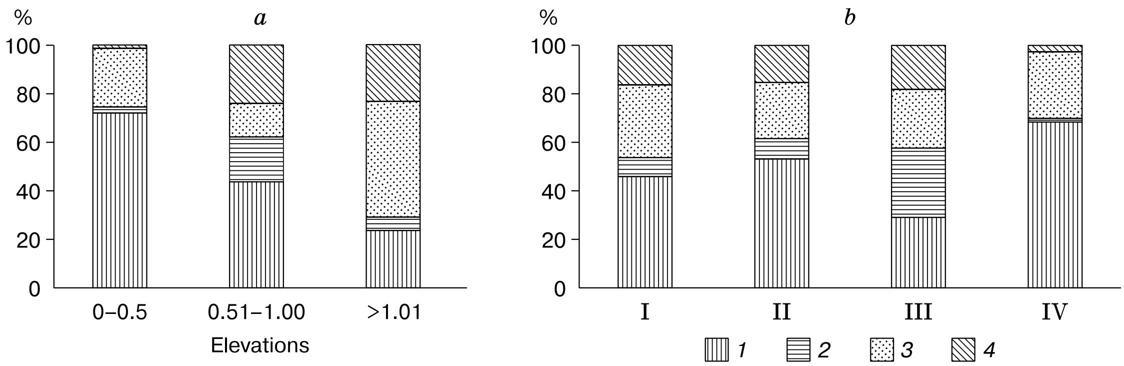

Fig. 6. Thaw depth frequency in different elevation intervals (*a*) and microtopogaphic forms (*b*).

Thaw depths (m): >2 (*1*), 1.51–2.00 (*2*), 1.01–1.50 (*3*), 0.51–1.00 (*4*). Roman numerals denote microtopogaphic forms of highs (I) and lows (II), flat peatland (III), and flat swampy terrain (IV).

Table 1. **Temperatures of soil surface in zones of different thaw depths**

T_s, °C	Thaw depths, m					T_a, °C
	0–0.50*	0.51–1.00	1.01–1.50	1.51–2.00	>2.00	
Mean annual	1.4	1.5 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	–6.1
Mean monthly (February)	–2.8	–1.8 ± 0.1	–2.5 ± 0.2	–2.1 ± 0.2	–1.4 ± 0.1	–29.7
Mean monthly (July)	10.3	8.5 ± 0.5	9.7 ± 0.5	7.7 ± 0.4	8.7 ± 0.3	12.8

Note. T_s is soil surface temperature; T_a is air temperature.
* Only two measurement points within 0–0.5 m zone, no confidence interval estimated.

Table 2. **Temperatures of soil surface in zones of different elevations**

T_s, °C	Elevations, m		
	0–0.50	0.51–1.00	≥1.01
Mean annual	1.6 ± 0.1	1.5 ± 0.1	1.0 ± 0.1
Mean monthly (February)	–1.3 ± 0.2	–1.8 ± 0.2	–2.4 ± 0.3
Mean monthly (July)	9.2 ± 0.6	9.4 ± 0.3	8.2 ± 0.7

4. Soil moisture

Volumetric soil moisture varies strongly over the area, with 35.9 % variance: from 8.5 to 66.1 vol.%, 42.2 ± 2.5 vol.% on average, exceeding 50 vol.% at about 60 % of points (Fig. 7). Soil in the swampy terrain with sphagnum plant communities contains more than 56.0 ± 3.5 vol.% of moisture, and the average moisture in peatland soil, grown with reindeer mosses, is 41.0 ± 2.5 vol.%.

According to regression analysis, soil moisture shows statistically significant correlation with elevations (r = –0.70, p-level <0.05), microtopogaphy (relative highs or lows, r = 0.27, p-level <0.05) and vegetation (r = 0.57, p-level <0.05), but does not correlate with other monitored parameters.

Soil moisture and elevations. Soil moisture correlates with elevations (Fig. 8): moisture [%] = = 93.3 [%]–38.0 [%/m] × elevation [m]; r = –0.70, p-level <0.05.

Microtopographic lows in peatland are the wettest, with mean moisture contents about 45 vol.% on average, while the highs are the driest (35.5 vol.% of water) due to better ventilation. Soils in the flat surface of peatland contain medium amounts of moisture (about 40 %).

The soil moisture values are the highest and the lowest (56.3 vol.% and 34.1 vol.%) at points with the lowest (below 0.50 m) and highest (over 1 m) elevations, respectively.

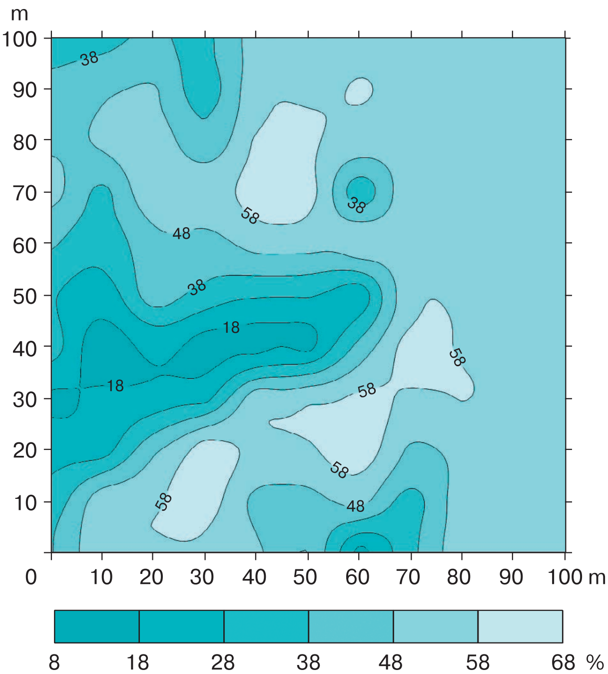

Fig. 7. Map of volumetric soil moisture (August 2014).

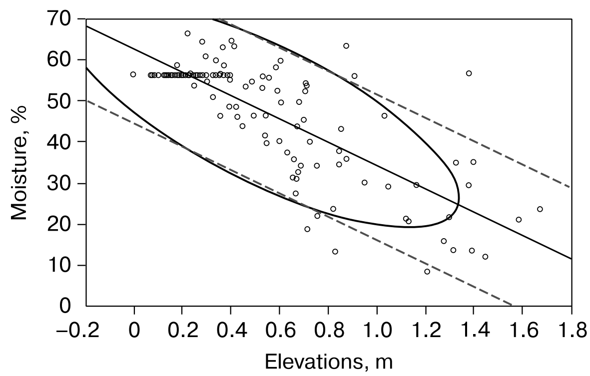

Fig. 8. Regression relationship between soil moisture and elevations (August 2014).

Dash lines show confidence interval; ellipses contour 95 % confidence of mean values.

Soil moisture and active layer thickness show no correlation, possibly, because the active layer is thick enough (more than 1 m) or because the permafrost table is laterally variable.

CONCLUSIONS

Active layer thickness is presumed to depend mostly on snow depth in the cold season and on thickness of the organic layer in the warm season [*Zimov et al., 1993; Mazhitova et al., 2004*].

The peatland CALM site we studied is remarkable by a large thickness and high spatial variability of the active layer. It is measured in late August and represents the peatland state at this specific time, unlike peat thickness or vegetation types which evolve for tens to hundreds of years. Furthermore, peat is rather thin within the monitoring site. More exact constraints on correlations of active layer thickness with other monitored parameters require the use of thaw depth means over many years and comparisons with data from other peatland sites with shallower thaw depths or larger peat thicknesses.

Periglacial processes control landscape formation in the hydromorphic conditions of the R1 site and are favorable for peatlands. Thus permafrost zoning is more relevant to the area than the conventional physiographic division [*Matyshak, 2009*]. Combinations of several factors, primarily depending on elevations, produce high variability of soil and vegetation patterns.

CONCLUSIVE REMARKS

1. All parameters monitored at the CALM R1 peatland site are highly variable over the area. Thaw depths are controlled by interplay of soil and vegetation patterns related to microtopography.
2. Thaw depths at the site are 166 ± 8 cm on average (variance 27 %, September 2014) and exceed 2 m at more than a half of measuring points, mostly within the swampy terrain and microtopographic lows.
3. The spatial pattern of active layer thickness depends on elevations ($r = -0.30$, p-level <0.05) and winter soil surface temperatures ($r = 0.38$, p-level <0.05) due to snow depth variations.
4. Elevations are mostly responsible for the spatial variations of soil moisture and soil surface temperatures in peatland.

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