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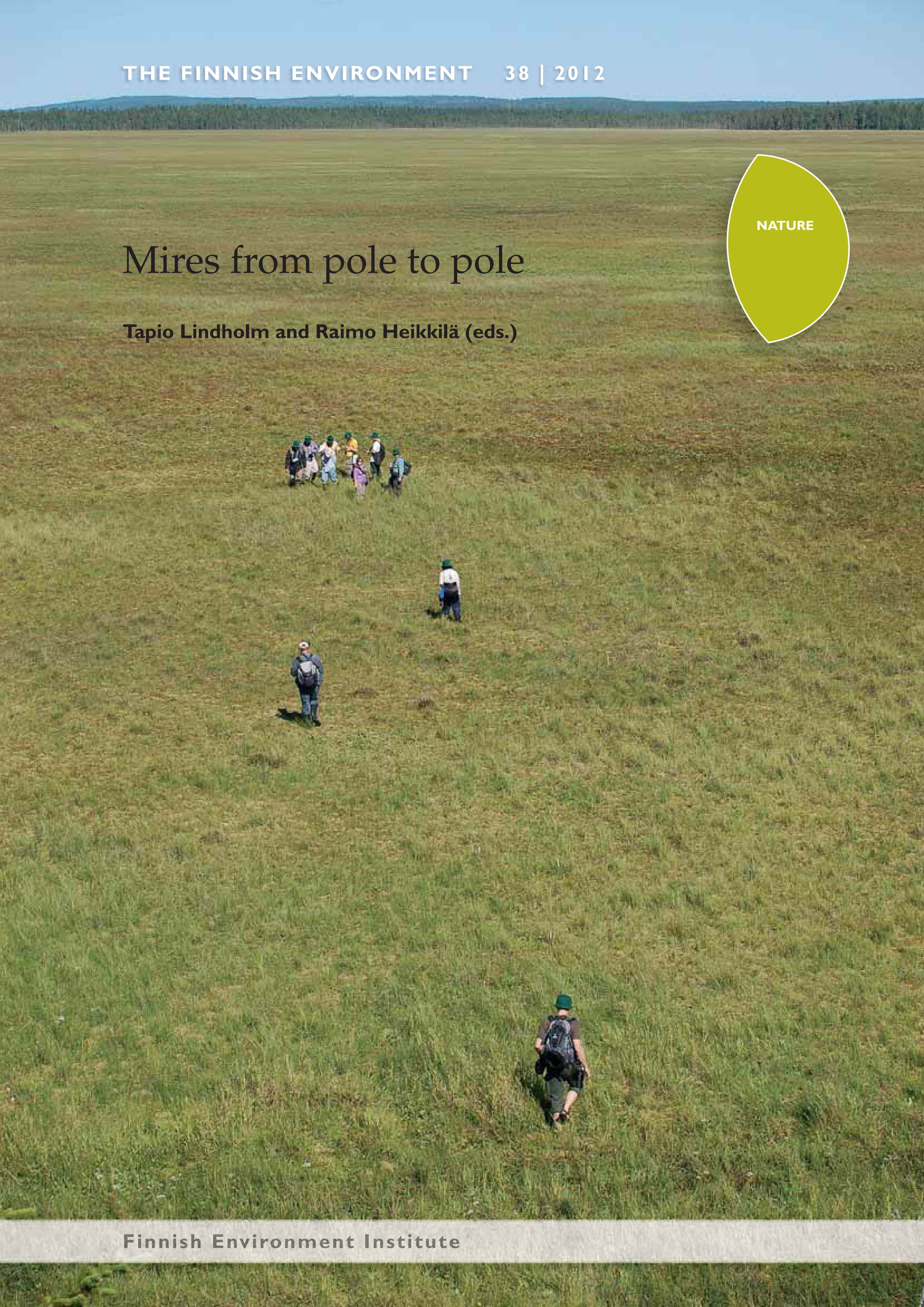
Mires from pole to pole

Tapio Lindholm and Raimo Heikkilä (eds.)



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Patterns in polygon mires in north-eastern Yakutia, Siberia: The Role of Vegetation and Water

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Introduction

Polygon mires cover large areas of the Arctic (Zoltai & Tarnocai 1975, Zoltai & Pollett 1983, Chernov & al. 1997) where the cold climate leads to polygonal frost cracking in the developing permafrost on river terraces or dry falling lake bottoms (Mackay 1999). In spring meltwater fills the frost cracks, refreezes and forms ice veins. In the course of time, these veins push up adjacent sediments as they grow laterally due to repeated cracking. This leads to the development of low-centred ice-wedge polygons (Mackay 2000) that consist of ridges surrounding deeper lying centres. This waterlogged microrelief supports a peat forming vegetation of sedges and mosses in a wetland environment where, due to climatic conditions, decomposition is anyway reduced (Billings 1987).

Since previous research related to polygon mires has largely focussed on patterned ground development (Mackay 1988, 1999) and classification (Washburn 1973, Mackay 2000), little is known about their spatio-temporal dynamics. The patterns of polygon mires are generally explained as the sole result of ice-wedge growth (Kutzbach 2000, Mackay 2000, Ellis & Rochefort 2006). This paper describes the feedback mechanisms between vegetation, water and ground ice in these mires and the hydrological connections between adjacent polygons.

Materials and methods

We studied polygon mires in the Yana-Indigirka Lowlands (north-eastern Yakutia; fig. 1). The study area (Lc05), a 5 ha large polygon mire complex composed of ca 70 low-centred polygons, is situated at a tributary of the Indigirka River 8 km south-west of Chokurdakh (70°37'N, 147°55'E). The mire complex lies between a small thermokarst lake and the approximately 10 m high plateau Boskho-Tumul that consists of yedoma sediments (Popov 1969, Ping 1995, Minke 2005). The mean annual temperature of Lc05 is -14.2°C, with a January mean of -34.3°C and a July mean of 9.7°C. The area experiences subzero temperatures from October to May. Precipitation is minimal, at only 215 mm per year (2004 data from local climate station). A representative transect (T) was studied every metre from the mire margin to the lake shore (sites 0 to 140.8), crossing seven low-centred ice-wedge polygons. For every site the vegetation was described in 1 m² plots using a percentage scale (cf. Londo 1976). Nomenclature of vascular plants follows Cherepanov (1995), and mosses are named after Abramov

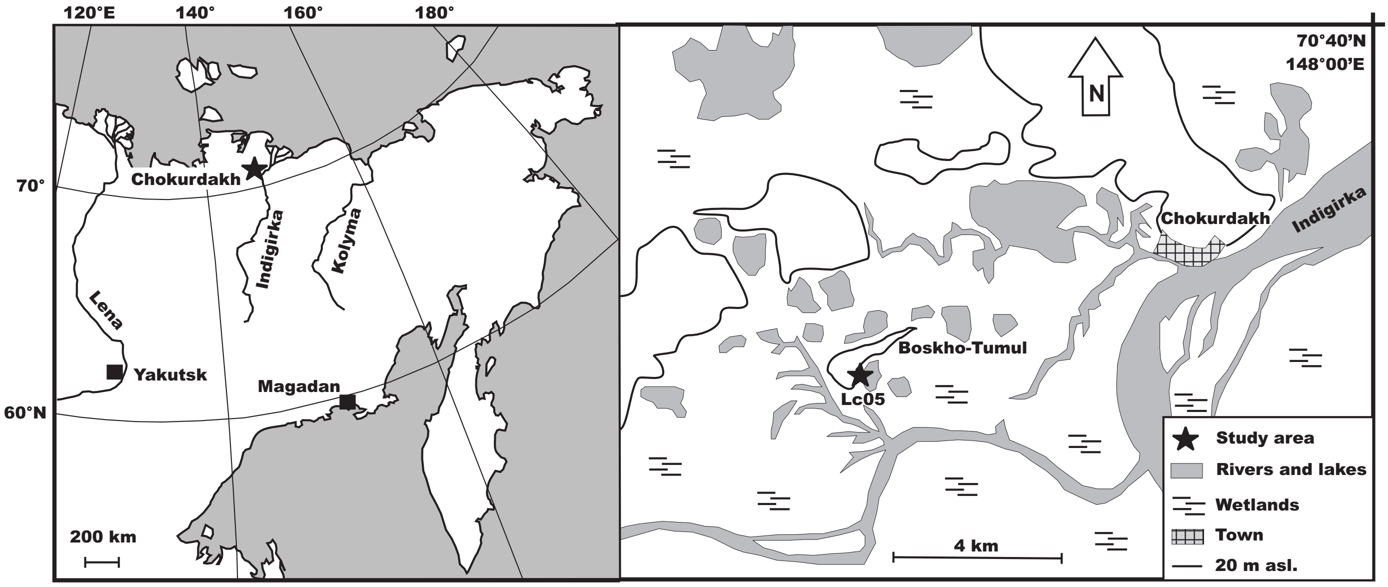

Figure 1. Location of the study area in north-eastern Yakutia, Siberia.

& Volkova (1998) (reference for *Sphagnum lenense* is USDA, NRCS 2007), liverworts after Frahm & Frey (1992), and lichens after Wirth (1995). The relevés were clustered using the software K-means2 (Legendre 2001) and the Hellinger transformation (Legendre & Gallagher 2001).

Measurements from the central spot of each transect site included ground surface height (GSH, referring to the surface of the living moss, litter, peat or bare ground), frost table height (FTH, determined with an iron rod), active layer thickness (i.e., the difference between GSH and FTH), water level, peat thickness, and depth of silt surface (recorded in excavated pits). Additionally, GSH and FTH were measured in a regular grid within an area of 26 x 135 m along transect T. All height measurements were related to a horizontal reference plane above the ground surface, established by horizontally stretched strings.

Soil temperatures were measured once at every site every 10 cm in depth down to the frost table. More detailed temperature records were taken at temperature monitoring plots with a calibrated thermistor on a 7 mm thin copper rod that allowed recurring temperature measurements every 5 cm in depth at nearly the same spot without substantial disturbance. The plots were located at a well developed polygon ridge with a dry vegetation cover of brown mosses and lichens, at a degraded ridge with a wet trench and ridge fragments covered by brown mosses and *Sphagnum* and in a polygon centre with typical wet *Carex*-lawns and irregularly spread moss-hummocks. Temperature profiles were recorded every third day during 5–19 August 2005.

At all sites, surface pH (pH-electrode HJ 98127 pHep, Hanna; with automatic temperature correction) was measured in open water or in water pressed out of wet mosses or litter. From selected soil profiles the water content was determined by weighing volumetric wet samples with a pocket balance (TCB 200-1, Kern), drying (105°C for 12 hours) and weighing again. Hydraulic conductivity (K) was measured with a piezometer (outer diameter 2.2 cm, inner diameter 1.9 cm, filter length 10 cm, perforation 20%, 10 cm falling head; Van der Schaaf 1999) at two sites of transect T and at a short transect (c) crossing a degraded ridge. As the method requires placing the filter at a minimum of 10 cm below the water table in the saturated peat (K_s), hydraulic conductivity could be measured only for some microrelief spots.

Results

Vegetation

The 141 vegetation relevés in the wetland part of transect T contain 32 vascular plant, 32 moss and 7 lichen taxa. The partitioning program K-means2 indicated to separate the relevés into two groups (Calinski-Harabazs criterion; Legendre 2001). As these groups only coarsely reflect the microrelief pattern (sites above and below the water table), a separation into five groups was chosen to reveal the finer differences in vegetation composition between the relevés (fig. 2).

The *Ptilidium ciliare-Sphagnum lenense* community covers the polygon mire margin directly adjacent to the slope with the highest ground surface and a water table below or around the frost table (fig. 2). *Ptilidium ciliare* and *Sphagnum lenense* have the highest average cover (33.50% and 40.83%, respectively) and occur in 100% of the relevés. Other species with 100% presence include *Salix pulchra, Vaccinium vitis-idaea, Ledum decumbens, Rubus chamaemorus, Carex concolor, Aulacomnium turgidum* and *Sphagnum balticum*. Of all the studied polygons, this community has a water table nearly 20 cm below surface, the lowest pH values (median 3.9), and the thinnest active layer (around 25 to 30 cm thick).

The *Carex concolor-Sphagnum balticum* community, is characterized by a high presence of *Sphagnum balticum* (100%) and *S. warnstorfii* (80%). *Carex concolor* is present in every relevé with an average cover of 12.52%, but as this species is present in 99.29% of all mire relevés it is not regarded as being characteristic of this community.

The *Dicranum angustum-Aulacomnium turgidum* community has a high average cover of *Aulacomnium turgidum* (22.57%) and *Dicranum angustum* (10.53%). Additionally, the community is characterized by a high average cover of *Sphagnum warnstorfii* and S. *subsecundum* (8.63% and 8.60%, respectively).

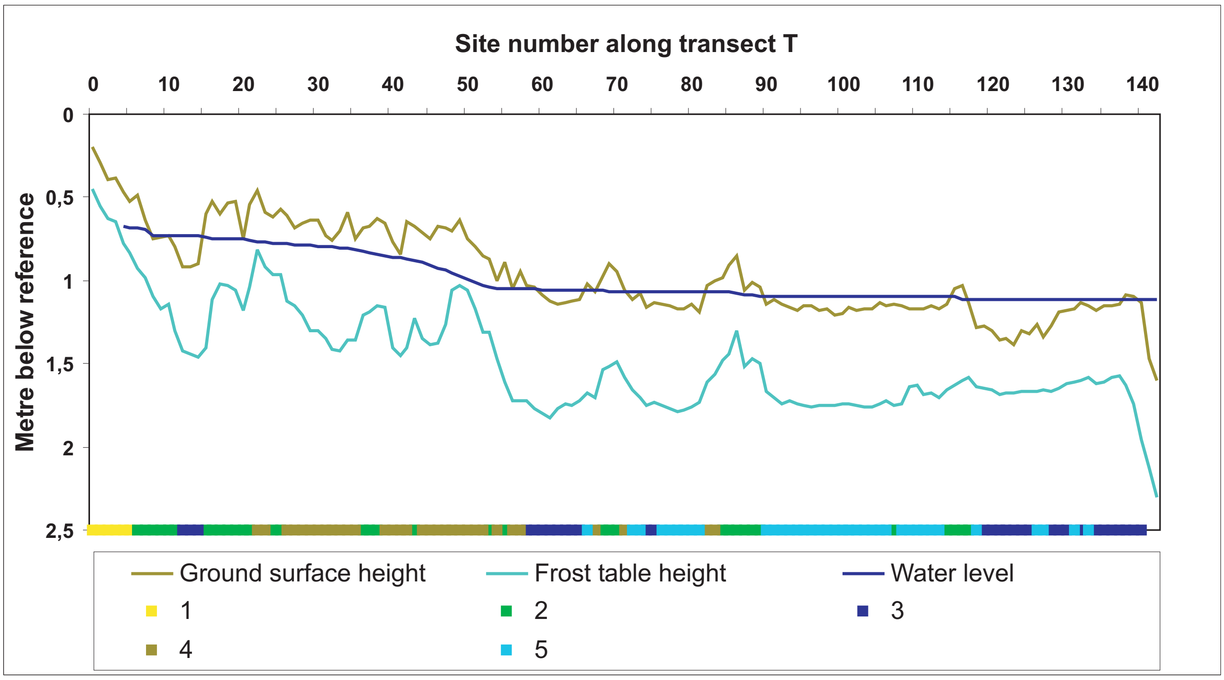

Figure 2. Vegetation types at transect T. Communities: 1) *Ptilidium ciliare-Sphagnum lenense*, 2) *Carex concolor-Sphagnum balticum*, 3) *Carex concolor*, 4) *Dicranum angustum-Aulacomnium turgidum*, 5) *Carex chordorrhiza*. Water level interpolated from average water level measurements taken in August 2005.

Sites with *Carex concolor-Sphagnum balticum* and *Dicranum angustum-Aulacomnium turgidum* vegetation are found on ridges and in hummocky centres where the water table is 4 –19 cm below the surface. The pH median is 4.4 and 4.6, respectively.

The *Carex concolor* community comprises relevés where *Carex concolor* is the dominant species (100% presence and 14.58% average cover). Also, *Carex chordorrhiza* is present in 54.84% of the sites but only covers 1.78% on average. Other species do not feature as significantly in the community.

The *Carex chordorrhiza* community is dominated by *Carex chordorrhiza* (100% presence, 13.41% average cover). *Eriophorum polystachion* and *E. scheuchzeri* are present at their highest abundance in this community.

The two latter sedge communities occur in the concave polygon centres, which are covered by open water (depth approximately 8 cm) and have the highest pH values (median of 5.6) of all the communities. The active layer of the latter four vegetation types, ranging from 40 to 65 cm, is clearly thicker than that of the *Ptilidium ciliare-Sphagnum lenense* community.

The temperature measurements show that the warmest active layer is found at areas with open water (fig. 3, sites 10-15, 60-65, 75-80, 95-115, 120-135). Here the heat is conducted to greater depths than at the ridges (site 22, 50, 69 and 85), and the frost table is deeper. Also the sparsely vegetated zone between sites 44 and 48 has a high surface temperature. On the other hand, the hummocky surface of the polygons between sites 17 and 43 yields the coldest temperature of all surveyed sites. The temperature monitoring plot of a typical dry ridge (between sites 46 and 50) carries *Dicranum angustum-Aulacomnium turgidum* vegetation with a dominance of *Cetraria laevigata*, brownmosses and some shrubs. This plot yields the largest ground surface temperature fluctuation (7.5 – 23.2°C) of all surveyed sites. The first 15 cm of the profile showed rapid cooling to below 5°C, whereas in larger depths temperature was observed to conspicuously decrease more gradually. Water level and frost table depths measure at 37 cm and 45 cm, respectively. The soil profile includes a 5 cm thick organic top layer over the silt. The volumetric water content of the dry ridge (0.38) is low compared to that of the degraded ridge and wet centre.

The degraded ridge plot (near sites 66 and 70) contains *Carex concolor-Sphagnum balticum* vegetation, with 90% moss coverage including 60% of the *Sphagnum* species. The surface temperature was noted to be a few degrees lower than at the dry ridge on the three warm and sunny days of 5, 15 and 17 August. Under cloudy and rainy conditions (other dates) the surfaces of both ridges had almost the same temperature. At the degraded ridge, the temperatures did not markedly decrease in the 15 cm thick top moss layer, which was above the water table and air-filled. In this profile the temperature decreased more gradually in the water saturated layer than in the unsaturated soil of the dry ridge. The profile includes 20 cm of living (recently grown) *Sphagnum* and around 10 cm of higher decomposed peat covering 30 cm silt above the frost table (60 cm below surface). The volumetric water content in the top layer (0-5 cm) measures at around 0.5, reaching 0.8 in the peat layer below.

The wet centre plot near site 80 is covered by a water body (depth approximately 6 cm) in which the measured water temperature did not exceed 15°C. In the open lawn of *Carex chordorrhiza, C. concolor* and *Eriophorum angustifolium* the warmest spot of each profile was the ground surface (dark brown litter or peat). Below this, temperature decreased much more gradually than at the other sites. The active layer

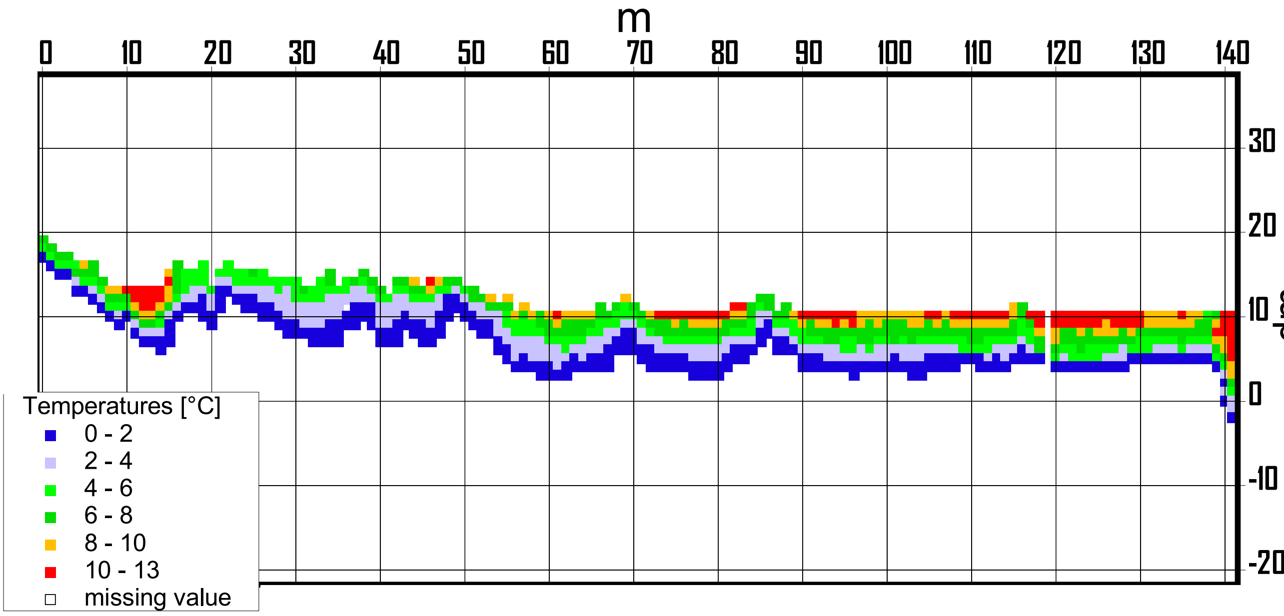

Figure 3. Temperature profile of transect T. Measurements taken at consecutive depths of 10 cm between 6 and 9 August 2005. Air temperature during measuring period was 6 – 9°C.

thickness measures 67 cm, not distinctly thicker than below the degraded ridges. The soil profile consists of 20 cm of peat over 43 cm thick silt (until the frost table). The volumetric water content in the uppermost peat layer is 0.7- 0.8.

Relief, frost table and water levels

Ground surface height and frost table are strongly correlated, with a Spearman-Rho coefficient of r^2=0.799; the active layer thickness ranges between 14 and 99 cm with a mean of 48.73 cm (N=1 573). The ground surface height (fig. 4.GSH) in the area near the slope (0 to 50 m) is characterised by an unclear polygonal pattern, small wet pools and hummocky polygon centres, whereas the area near the lake (50 to 140 m) has a regular pattern of four low-centred polygons with nearly rectangular ridges. The ridges are partly dissected and reach a depth low enough to almost match the level of the centres.

The frost table (fig. 4.FTH) shows the same pattern as the ground surface, but height differences are more explicit. Gaps in the frost table ridges are clearly visible. In the 0 – 50 m zone the frost table depressions constitute a continuous channel similar to that of a meandering brook or an erosion channel. In the zone near the lakeside, the frost table underneath the ridges is more frequently lowered and depressions appear in nearly every ridge. The polygonal pattern is less pronounced towards the lakeside.

Frozen ground above the mean water level is only found below the highest and driest ridges, and at the mire margin near the plateau slope. In general, the frost table is covered by a water-saturated layer with an average thickness of 40.41 cm.

The peat thickness averages 25.29 cm and ranges from 13 to 38 cm (N=14). The upper peat layers are highly permeable with K_s of 4.09 to 6.21 m d^{-1}; the lower peat and silt layers have lower conductivities of 0.44 to 0.06 m d^{-1} (Table 1).

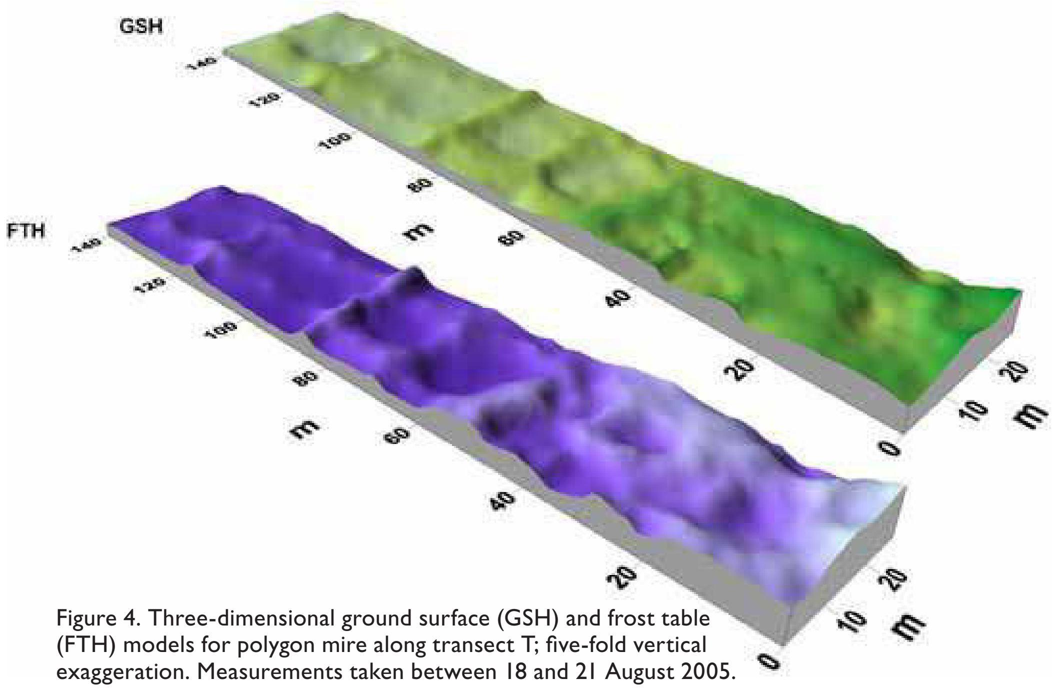

Figure 4. Three-dimensional ground surface (GSH) and frost table (FTH) models for polygon mire along transect T; five-fold vertical exaggeration. Measurements taken between 18 and 21 August 2005.

The water level decreases constantly from site 0 to 50 with a mean of 0.59 cm per metre. After site 50 the water table is nearly level. A second slight drop in the water level (4 cm) was recorded at the ridge between site 82 and 90. At the plateau slope (site 4) the water table is 44.6 cm above the lake water level (fig. 5). Water level fluctuations differ between parts of the polygon mire complex. The first 50 metres of the transect (hummocky polygons) show larger fluctuations than the following pond-like polygons (sites 50-140, fig. 5.A). The deeper the water table below the ground surface, the more pronounced the fluctuations in the water level (fig. 5.B, 5.C). A sloping water table was found between sites 35 and 50, with a fall of 24 cm over 15 m. There, a ridge of silt occurs with a thin inclined water-saturated layer over the frost table (fig. 5.A).

Discussion

Vegetation and polygon mire development

Next to peat (litter), water and ice, living vegetation is an important regulator of energy fluxes in arctic ecosystems. As insulator (especially dry moss carpets), reflector of solar radiation (light vegetation like lichens), heat conductor (especially wet moss carpets), and snow trap (e.g. stiff structures of shrubs), vegetation affects ground

Table 1. Hydraulic conductivities (K_s) in the polygon mire complex

Site	Relief type	Substrate	Depth below ground surface [m]	K_s [m d^{-1}]
T 85.5	ridge	peat	0.28	6.21
c 3.2	degraded ridge	peat	0.26	4.50 (N=3)
c 1.0	centre	peat	0.30	4.09
T 85.5	ridge	silt	0.40	0.44
T 41.3	centre	silt	0.23	0.22
c 3.2	degraded ridge	peat	0.36	0.21
c 3.2	degraded ridge	silt	0.47	0.07
c 1.0	centre	silt	0.40	0.06

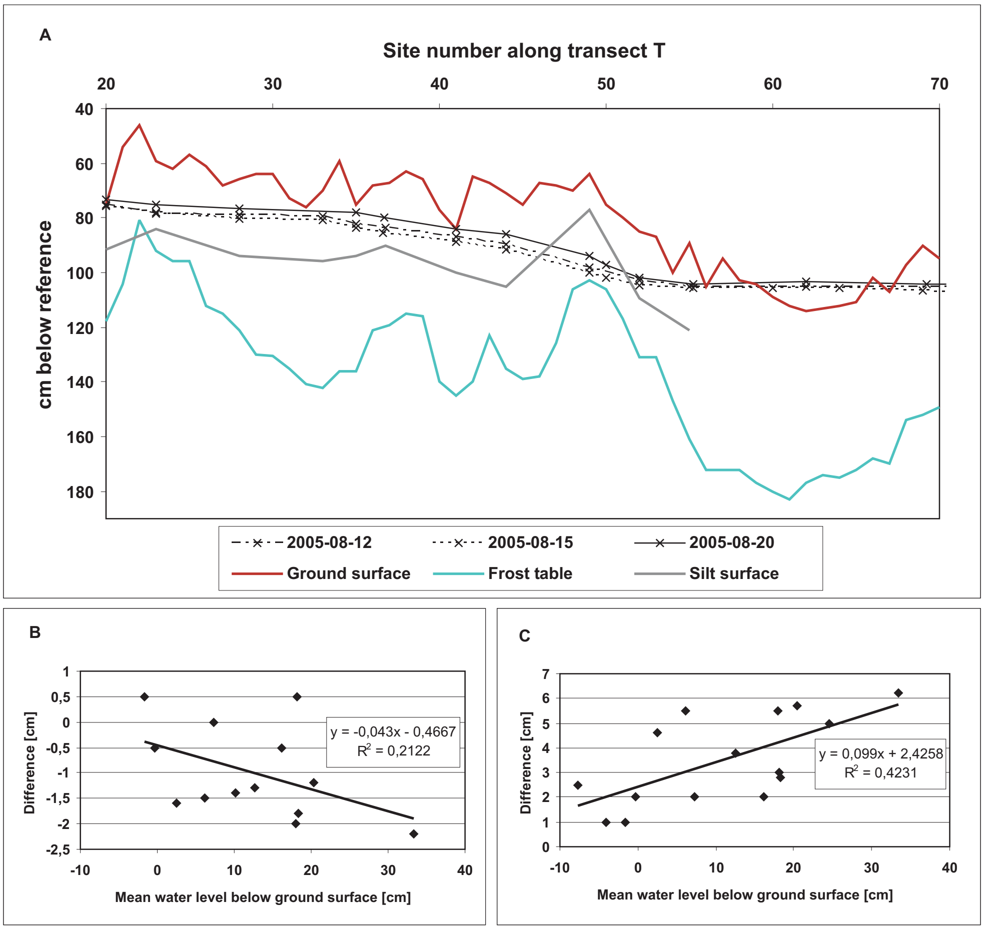

Figure 5. Three sets of water level measurements by date. A) Section of transect T with hummocky centre, ridge and wet centre. B) Water level change between 12 and 15 August 2005. C) Water level change between 15 and 20 August 2005. Mean water level averages three sets of measurements.

temperature . For an accurate interpretation of soil temperature profiles, these effects as well as substrate properties and weather have to be taken into account.

The observation that dry ridges have the largest temperature fluctuations in their upper part and experience the most rapid soil temperature decline with depth can be ascribed to the low water content of the organic surface layer and the consequent small heat conduction/convection and restricted cooling by evaporation. Largely lacking high and stiff vegetation structures, the dry ridges in the study area are susceptible to a total absence of insulating snow cover in winter (cf. Seppälä 2004). This results in strong ground cooling, frost cracking, and ice-wedge growth. Depending on the actual thermal contraction coefficient of the substrate, cracking (under frost conditions) requires a rapid temperature drop of 2°C (pure ice) to 10°C (rock) (Lachenbruch 1962). On several dry ridges of the polygon mire, 2 – 3 cm wide cracks were found. As active layer thickness strongly depends on the content of pure ice, which needs a high amount of latent heat to thaw (Woo & Xia 1996), ice-wedges and segregation ice reduce thaw speed and active layer thickness. At places were the active layer is thinner than in their near vicinity, liquid water migrates towards the frost front, thus enhancing the formation of segregation ice (Shur 1988, Shur & al. 2005). These processes constitute a positive feedback that builds up ridges (Minke 2005, Minke et al. 2007).

The degraded ridge has a water table that is ca 22 cm nearer to the surface than that of the intact dry ridge (water level 37 cm below ground surface), a totally different vegetation consisting of especially *Sphagnum* species, and a 30 cm thick peat layer. Temperatures at the top do not exceed 17°C, which is probably due to the high heat capacity and evaporation of the water in the moss layer. Constant depth temperatures for the unsaturated *Sphagnum* carpet (15 cm thick) indicate that heat is effectively conducted through the layer, probably by heat conduction in the wet mosses. Only the two warmer days (5 and 15 August) show slightly decreasing temperatures in depth in the top layer, which points to insulation of the ground. In the saturated strata of the degraded ridge, the temperature was higher than in the intact (dry) ridge at a same distance to the ground surface. Heat conduction through liquid water should be considered as the main reason for this phenomenon (cf. Boike 1997, Miller & al. 1998).

In the wet polygon centre the soil is completely water-saturated and due to heat conduction, the temperature gradients between surface and frost table are nearly linear. Temperature fluctuations in the upper part of the profile are lower than at the other sites due to the high heat capacity of the saturated substrate. The highest temperatures are reached in the dark brown litter at the bottom of the shallow ponds, where solar radiation running through the water is absorbed. The temperature of the water body itself remains low, because of its high heat capacity and the chilling effect of evaporation.

Polygon mire hydrology and hydrological windows

Large water level fluctuations were recorded at sites with a water level deep below the surface (fig. 5.B/C), indicating a lower specific yield at greater depth. Low permeable peat (probably highly decomposed and with a low proportion of large pores) was found at the bottom of these sites, whereas the highest permeability was measured in the top peat layer (Table 1). Such a steep decrease in hydraulic conductivity with depth brings to mind the acrotelm concept of hydrological self regulation (in terms of discharge control) of a mire (Joosten 1993, Couwenberg & Joosten 1999). During summer, lateral inflow to a tundra wetland is small and precipitation low, and even possibly exceeded by evaporation (Woo & Young 2006). Under such conditions the continuing existence of a wetland benefits from additional water input, resulting from snowmelt in spring, from a greater catchment (Rovansek & al. 1996, Woo & Young 2006) or from an inundation supply from rives and lakes. The vertical gradient in conductivity holds back this water since it reduces lateral runoff from the mire. The high permeability of the surface peat layers explains the level water tables over wide areas of the mire complex, especially in the polygons next to the lakeside (fig. 2). Water level steps between single polygons seem to be caused by the low hydraulic conductivity of the bottom peat and silt (Table 1, fig 5.A) that may project over the water level as a result of ice wedge or segregation ice formation. We found that in low-centred ice-wedge polygons a high correlation exists between ground surface and frost table (i.e., both surfaces being nearly parallel) but in the frost table stronger relief differences develop during the thawing season (Minke 2005). Some parts of the ridges develop an unusually thick active layer - a phenomenon also found by Minke et al. (2009). In these parts the summer frost table may be below the water table, thus facilitating subsurface water flow through the active layer. The main flow generating event in arctic wetlands is snowmelt in spring (Woo & Young 2006). In the tundra the distribution and thickness of the snowcover is strongly affected by wind redistribution. At exposed sites the snow is blown away and deposited at snow traps, such as protruding vegetation or lee sites. When the snow melts, discharge primarily takes place as surface flow because the underlying soil is still frozen (Roulet & Woo 1986).

Later, running meltwater also penetrates the active layer (Lewkowicz & French 1982, Woo & Guan 2006). The subsurface runoff is controlled by the hydraulic properties of the substratum,especially taking place in the uppermost slightly decomposed, porous organic matter (Quinton & Marsh 1998). Running water is a very powerful agent for ground frost thawing in permafrost areas: water has a high heat capacity (Woo & Xia 1996) and flowing water in the active layer enhances thawing of the frozen soil along its flow paths (Woo & Winter 1993). A rapid increase in soil temperatures after snow melt was observed by Boike (1997). In extreme circumstances, this process causes piping (i.e. formation of erosion channels within the permafrost) or gully erosion (Seppälä 1997).

When the polygon mire is flooded by meltwater in spring (Woo & Young 2006), the polygon depressions are filled with water and the lowest parts of the enclosing ridges act as thresholds for and preferential points of, further discharge. This flowing water stimulates ground thawing in spring and summer, leading to a locally thicker active layer than in the adjacent ridge parts. Such thermal erosion channels in ridges, which we term "hydrological windows", are shown in the frost table model (fig. 4).

The positive feedback of ridge uplifting causes a higher water storage capacity in the polygon centre (Minke 2005) because water is dammed by the rising frost table (Woo 1990). The larger amount of meltwater in the depression can store more latent heat received from solar radiation and as a result it enhances the thawing of the frozen ground. If the water table is below the lowest spot in the ridge frost table relief, the thaw front migrates sideward and in depth. If the water level is above the lowest part of the ridge frost table and higher than the water level of the adjacent polygon, thawing is most effective at this threshold due to continued heat input by running water. This lowers the threshold until the water level equals the level of the adjacent polygon or latent heat in the water is insufficient for further thawing (due to autumn cooling). By lowering the threshold, the water level of the polygon is lowered so that the amount of latent heat stored in the polygon depression is reduced. This slows down ground thawing and protects the remaining frost table ridges.

The model in Figure 6 summarizes the water pathways in the polygon mire landscape of thaw lake basins, which we presume to be typical for the East Siberian artic low-lands. The mire receives its water from precipitation (1), meltwater runoff from local snow melt and a catchment area (2), flooding from lakes and rivers (3) and thawing of ground ice (4), the latter being a system internal source. Pathways in the mire are overland flow (5) especially during snow melt and after storms and subsurface flow (6), which constitutes only a small part of total wetland flow, but important all the same for microrelief patterning. Flow through the frozen ground (7) is negligible. Water sinks of a polygon mire consist of internal sinks or freezing water transforming into segregation and ice-wedge ice (8), evapotranspiration (9), and outflow (10).

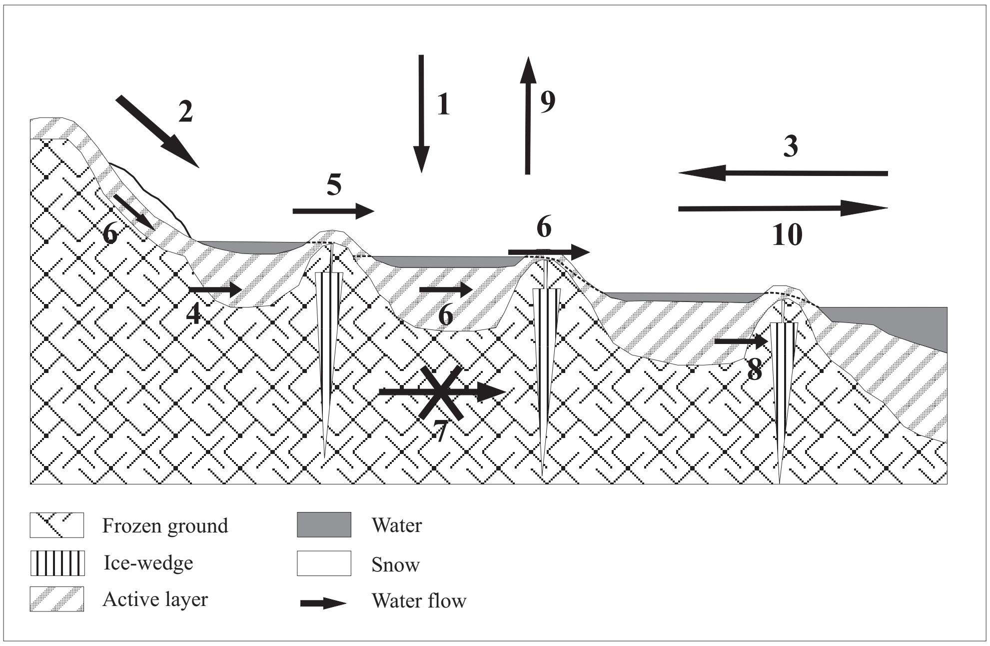

Figure 6. Water pathways in a polygon mire. Sources: 1) precipitation (rain and snow), 2) meltwater runoff from local snow melt and upland tundra, 3) flooding from adjacent lakes or rivers, 4) thawing of ground ice (internal source). Pathways: 5) overland flow, 6) subsurface flow, 7) no relevant flow through frozen ground. Sinks: 8) freezing water transforming into segregation and ice-wedge ice (internal sinks), 9) evapotranspiration, 10) outflow.

Conclusion

The vegetation distribution in the investigated polygon mire is mainly controlled by the relief and related parameters such as water level and pH. Vegetation and soil moisture strongly influence the thermal properties of the active layer, thus controlling the development of the frost table, which in turn determines the height of the microrelief. These feedback relations suggest that pattern formation in polygon mires is not merely a passive reaction to cryophysical processes, but also a result of self-organisation from the interaction of vegetation, ice and water (cf. Couwenberg & Joosten 2005).

The observed degraded ridges in the Lower Indigirka region are probably caused by thermal erosion through meltwater flow in spring and early summer. Surface and subsurface flow enhance thawing of the active layer and create deeply thawed ridge parts – hydrological windows – that facilitate water exchange between polygons during snowmelt and after intensive rainfalls. By carrying off the relatively warm water, the windows protect the remaining ridges and stabilize the polygon pattern.

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