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Distribution, diversity, development and dynamics of polygon mires: examples from Northeast Yakutia (Siberia)

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The typical peatlands of the arctic zone are polygon mires. The interplay of vegetation, peat, water, and ice makes polygon mires highly dynamic, diverse and interesting ecosystems.

Polygon mires are the typical mire type of the Arctic where rapidly falling temperatures in winter lead to the formation of cracks in the shrinking permafrost. Similar to drying clay, these cracks form a polygonal pattern. The dimensions and shapes of the polygons are determined by the type of substrate and the position in the landscape. In spring, water from melting snow trickles into the open cracks, refreezes, and forms ice-veins (Fig. 1 - left side). Since they are the weakest spots in the permafrost body, these veins of pure ice are the preferential zones for further cracking. In the course of time the veins thus grow wider and wider and become ice-wedges (Fig. 1 - right side). As the thickening ice-wedges occupy more and more space, adjacent soil material is pushed aside and heaps up in a polygonal pattern of low ridges that enclose wet depressions (Mackay 2000, Fig. 2).

Distribution

Polygon mires mainly form in an arctic climate with less than 250 mm annual precipitation, because too much insulating snow would prohibit rapid permafrost cooling and crack formation. On the other hand, the climate must be wet enough to support plant growth. Polygon mires furthermore - like all mires - require flat, wet areas.

Because of these criteria, polygon mires are not as common as often thought. They occur abundantly in the Arctic coastal plains of Alaska, in the Canadian Mackenzie delta, and especially in northern Siberia: in the Yenisey lowlands, in the southern, low-lying parts of the Taymyr peninsula, in the Lena delta and in the Yana-Indigirka and Kolyma lowlands (Botch & Masing 1983; Tarnocai & Zoltai 1988; Naumov 2004; Ping et al. 2004; Fig. 3). There they are found on watersheds, bottoms of drained lakes, river terraces, and floodplains (Boch 1974). Incidentally polygon mires also occur outside these main regions. We estimate that worldwide polygon mires effectively cover 250,000 km^2, i.e. 3% of the Arctic land mass, being an area equivalent to that of the United Kingdom. The main concentrations are located in Taymyr and Yakutia. Our examples are from that last area.

Diversity

The classical and most common polygon peatlands are "low-centred polygons" consisting of elevated ridges that enclose central depressions (Fig.

Fig. 1: Thin ice-veins (left) in the course of time develop to huge ice-wedges (right).

Fig. 2: Landscape with polygon mires near Chokurdakh (NE Yakutia).

4, part a). Their shape may vary from strictly rectangular, via pentagonal or hexangular to almost circular. Under not always clearly understood conditions, the ice-wedges may melt and the ridges collapse to form trenches surrounding the polygon centre: the relief inverts and "high-centred polygons" originate (Fig. 4b, Billings & Peterson 1980). High-centred polygon peatlands are actually erosional phenomena: their surface dries out, peat accumulation stops and the peat is oxidized or blown away (Zoltai & Pollett 1983).

In areas with discontinuous permafrost, a mire type occurs that is often confused with polygon mires sensu stricto. This "peat plateau bog" or "flat palsa" is an elevated bog landform in which permafrost has developed in peat that was originally deposited under non-permafrost conditions (Zoltai & Tarnocai 1975). This may happen locally in a fen when vegetation (often *Sphagnum* mosses) that start to grow dries out in summer. The air cushion then protects the underlying peat against melting. In autumn, the plants become wet again, the insulation is annulled, and frost penetrates deeper in the peat. In the course of time, the growing ice body raises the mire surface and stimulates the spreading of the insulating moss carpet: a positive feedback that leads to the expansion of permafrost both in width and in depth. The ice-wedges that may subsequently develop in such

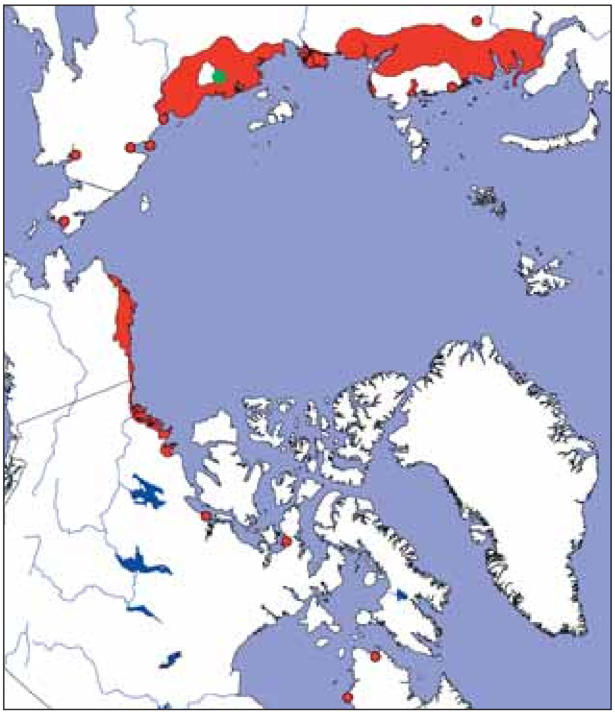

Fig. 3: The distribution of polygon mires worldwide, based on Quickbird satellite images. Red: extensive occurrences, red dots: incidental occurrences. Green point: Chokurdakh, NE Yakutia.

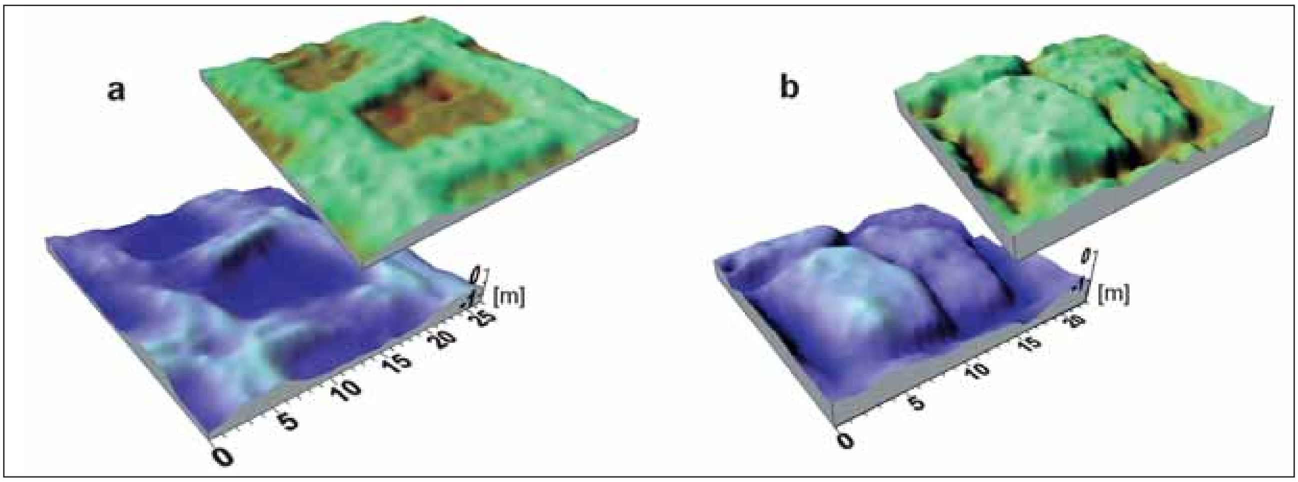

Fig. 4: The ground surface (green) and the top of the frost table (blue) of a low-centred (a) and a high-centred (b) polygon peatland near Chokurdakh (NE Yakutia) (after Minke 2005).

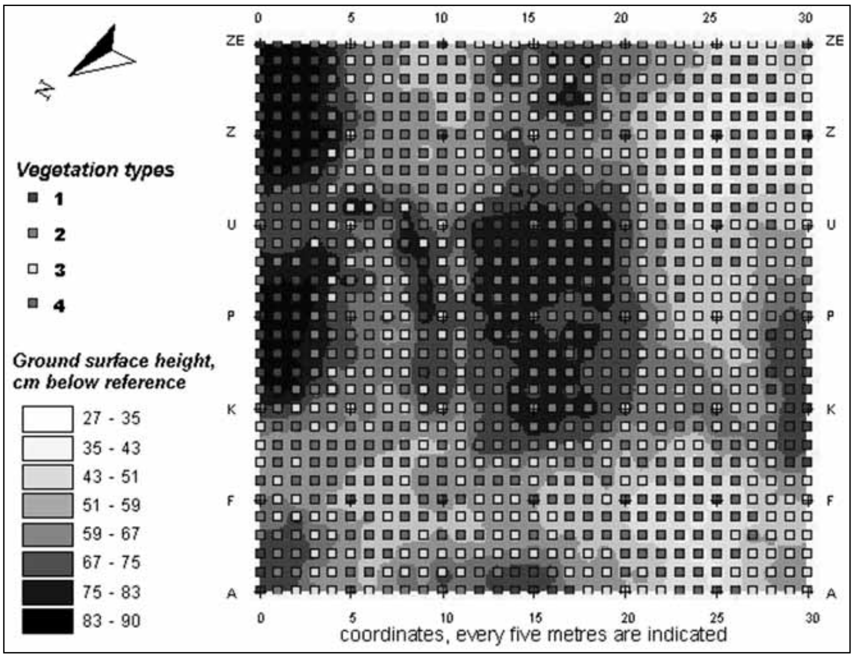

Fig. 5: The vegetation types of low-centred polygon Lc04 in relation to the ground surface height (after Minke 2005). 1 – *Carex chordorrhiza*-type, 2 – *Carex chordorrhiza-Drepanocladus revolvens*-type, 3 – *Tomentypnum nitens-Aulacomnium turgidum-Sphagnum squarrosum*-type, 4 – *Hylocomium splendens-Aulacomnium turgidum*-type.

"polygonal peat plateaus" form a less regular pattern of trenches than that of "real" polygon mires.

The vegetation in polygon mires is strongly related to the microrelief and is, for Arctic conditions, often rather diverse. The investigated low-centred polygon Lc04 (70°37'N, 147°55'E), on an area of 30 x 30 m, contains 40 vascular plant, 38 moss and eight lichen species. These occur in four major vegetation types (Fig. 5). *Carex concolor* occurs at all sites with high frequencies. In type 1 in the deepest parts of the depressions the moss cover includes *Scorpidium scorpidioides, Sphagnum subsecundum*, *Rhizomnium punctatum* and *Drepanocladus revolvens*, with *Carex chordorrhiza* as dominating vascular plant species accompanied by *C. rariflora* and *C. rotundata*. Type 2 - in the shallow parts of the wet depressions - is rather similar but has a higher abundance of *Drepanocladus revolvens*, whereas also most other taxa occur in higher frequencies. Type 3 covers the sides and lower parts of the ridges and is dominated by the mosses *Tomentypnum nitens*, *Aulacomnium turgidum*, and many *Sphagnum* species, whereas *Drepanocladus* is largely absent. Type 4 on the highest parts of the ridges includes *Hylocomium splendens*, *Aulacomnium turgidum*, *Betula exilis*, *Calamagrostis*, and *Pyrola rotundifolia*; *Sphagnum* and *Tomentypnum nitens* are also typical, but less frequent than in type 3.

Also the abiotic parameter shows prominent patterns related to the microrelief. The thickness of the active layer (the ground layer that thaws and freezes annually) is much thinner on the ridges than in the polygon depressions, whereas the C/N-ratio indicates poorer trophic conditions on the ridges.

Development

Only in young wetland soils, do the necessary conditions for polygon mire development coincide. In dry flat mineral soils, the active layer thaws up too deep in summer for the soil to remain wet and for ridges to develop. Furthermore, the wind clears these flat areas from snow and insufficient water remains for the formation of peat. Under deeper water, on the other hand, no permafrost can persist because the water stores too much summer warmth due to its large heat capacity. Only on new wet land, e.g. on the bottom of drained thermokarst lakes, on floodplains and in deltas, do the insulating effects of vegetation and the first peat keep the active layer over the newly forming permafrost sufficiently shallow to enable ice-wedges to develop and ridges to form. Besides, these low-lying landscapes receive additional water from melting snow or from flooding, which facilitates peat formation.

After the young ice-wedges have created the first relief differences by soil displacement, ridge formation is further controlled by the complex interplay of vegetation, peat, ice, and water. In winter the prominent parts are swept clean from the protecting snow by wind and the ice becomes colder. In summer, the drier vegetation/peat on those spots protects the underlying ice from melting which results in water migrating from the wetter, lower areas towards the cold ice under the ridges.

This leads to the formation of segregation ice with a high latent heat (Shur et al. 2005) that further slows down thawing of the ridges in summer and that further lifts the soil. This positive feedback mechanism causes the ridges to grow in height and width much more rapidly than would be possible by only ice-wedge expansion. When the ridges grow too high they become too dry for peat formation. The height difference between ridges and depressions may further be enlarged when warmth-conducting open water in the depressions results in ground subsidence. The latter process is again counteracted by rapid peat accumulation in the wet depressions (Tarnocai & Zoltai 1988, Minke 2005).

Although all these effects and their complex mutual influences are not yet sufficiently understood, the feedback relations suggest that pattern formation in polygon mires is not merely a passive reaction on cryophysical processes, but also results from self-organisation by the interaction of vegetation, ice, peat and water.

Hydrological dynamics

Many of the low-centred polygons we studied show parts of ridges with a conspicuously lowered frost table in summer (Fig. 4a, Fig. 6, Fig. 7). We explain these phenomena as the result of water flow especially during spring and call them "hydrological windows"

(Donner 2007). Ice-wedge polygons are obviously hydrologically open systems, a conclusion also drawn in recent studies from Canada (Woo & Guan 2006). The question only is: Are these windows the result of ice-wedge degradation under the influence of rising global temperatures, or are they a natural characteristic of polygon mires?

In order to address this issue, we made a detailed study of peat sections from low-centred polygon Lc04 (Fig. 7). The pollen/spores and macrofossil content and the geochemistry showed that the present polygon centre (A in Fig. 7) had almost continuously been covered by a wet hollow vegetation. A current hydrological window (B) appeared to have been present on the same spot during almost the complete existence of the polygon in the last 1000 years. This shows that windows are natural phenomena and not the result of recent global warming. For the duration of some hundred years, however, the spot was covered by dry ridge vegetation, i.e. the window was "closed". In contrast, a present-day closed ridge (C) was shown to have had a temporal collapse by which means a new window was opened. Later, this window closed again. This supports the observations of Romanovskij (1977) who also describes alternating growth and collapse of ridges.

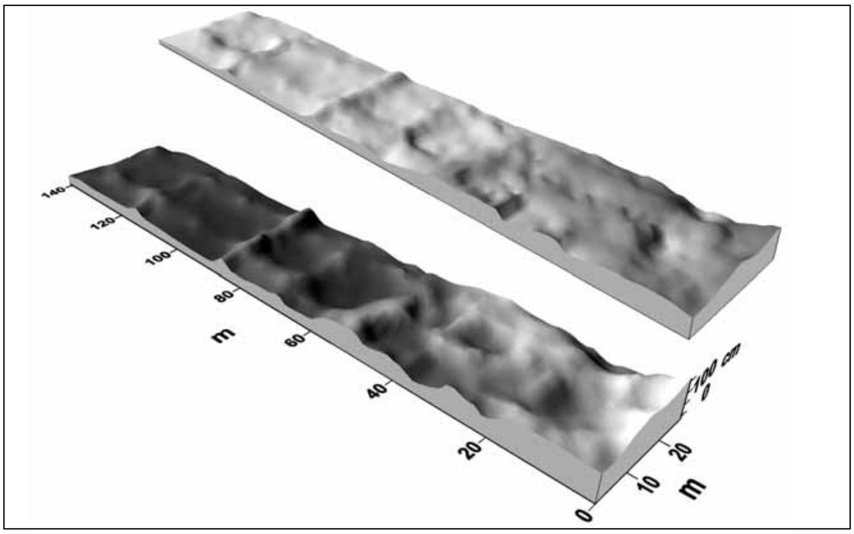

Fig. 6: Ground surface (green, above) and frost table height (blue, below) in polygon mire transect Lc05 near Chokurdakh (after Donner 2007).

Such rapid changes cannot be explained by the local disappearance and regrowth of ice-wedges. Most probably they reflect the effects of the described feedback mechanisms between vegetation, ice and water that may rapidly alter the volume and ice content of frozen soil covering and surrounding the ice-wedge.

Windows can therefore be explained as "natural" components of polygon mires in terms of self-regulation. The hydrological windows facilitate water discharge from the polygons during snowmelt and after intensive rainfalls. By carrying off the relatively warm water, the windows protect the remaining ridges from melting completely and in this way stabilise the polygon pattern.

Although polygon mires play an important role in the carbon and methane budgets of the arctic tundra (Hobbie et al. 2000; Wagner et al. 2005), a zone with over 15% of the world's soil-carbon (Lal & Kimble 2000) and the largest expected climate change (Arctic Climate Impact Assessment 2005), we are only starting to understand the functioning of these fascinating ecosystems.

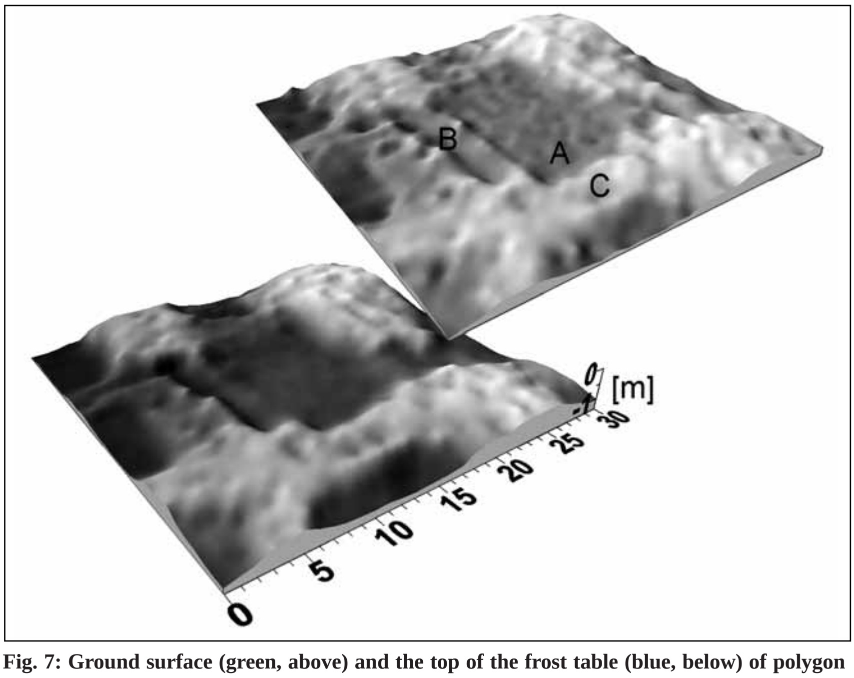

Fig. 7: Ground surface (green, above) and the top of the frost table (blue, below) of polygon Lc04 (after Minke 2005), showing hydrological windows and the location of the analysed peat sections A, B and C.

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