



Ice Lenses Beneath Hummocks in a Temperate Rich Fen

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Abstract

The study documents a process of ice lenses persistence under hummocks during spring snowmelt in a rich fen in Poland. Air temperature, as well as the temperature under vascular plant litter, *Hamatocaulis vernicosus* mat, *Tomentypnum nitens* hummocks and *Sphagnum teres* hummocks, was measured from December to March using temperature data loggers. The Capital Asset Pricing Model was adapted to analyse relationships between air temperature and temperature under litter and mosses. *Sphagnum teres* best insulated the temperature of the upper peat layer from changing air temperatures and maintained frozen peat under its hummocks the longest (for about a month after the frost had stopped). *Tomentypnum nitens* insulated similarly effectively in winter, also maintaining the ice lenses under its hummocks, but less effectively in warmer spring, which may be due to differences in hummock structure between the two species. The observed phenomenon may soon disappear due to global warming, which may affect the fen functioning.

Keywords Rich fen · Temperature insulation · Freezing · Mire microtopography · Bryophytes

Abstrakt

Praca dokumentuje proces utrzymywania się, podczas wiosennych roztopów, soczewek lodu pod kępami mchów na torfowisku niskim w Polsce. Od grudnia do marca, za pomocą rejestratorów temperatury, mierzono temperaturę powietrza oraz temperaturę pod wołokiem z roślin naczyniowych, darnią *Hamatocaulis vernicosus*, kępami *Tomentypnum nitens* i kępami *Sphagnum teres*. Do analizy zależności pomiędzy temperaturą powietrza a temperaturą pod wołokiem i mchami zaadaptowano stosowany w ekonomii model wyceny aktywów kapitałowych. *Sphagnum teres* najlepiej izolował górną warstwę torfu od wahań temperatury powietrza, pod kępami tego gatunku najdłużej utrzymywał się zamrożony torf (przez około miesiąc po ustaniu mrozu). *Tomentypnum nitens* zapewniał podobnie skuteczną izolację termiczną w okresie zimowym – pod kępami tego gatunku również utrzymywały się soczewki lodu – ale mniej skuteczną w okresie cieplejszym (wiosną), co może wynikać z różnic w strukturze kęp tych dwóch gatunków mchów. Obserwowane zjawisko utrzymywania się soczewek lodu pod kępami mchów może wkrótce zaniknąć w wyniku globalnego ocieplenia, co może wpłynąć na funkcjonowanie torfowisk.

Introduction

The reason for undertaking this study was observations I made in groundwater-fed rich fens in north-eastern Poland during spring snowmelt. When, after a frosty winter, temperatures were already high enough (March) for peat to thaw, small ice lenses remained for a longer time under hummocks of sphagna and brown mosses. I conducted temperature

measurements within the hummocks and hollows to characterize this observed phenomenon. Hummocks are typically bedded by permafrost in subarctic peatlands (large palsas with permanent ice cores (Seppälä 1986, 1990) or smaller pounu hummocks with intermittent ice (Luoto and Seppälä 2002; van Vliet-Lanoë and Seppälä 2002) or periodic ice layer in winter in boreal zone (e.g. Euroła 1968, 1975). The formation of periodic ice lenses has not yet been described from mires in the temperate zone.

Based on studies of boreal mires, Euroła (1968) indicated that ice persisted there during the thawing season longer under the hummocks than in the hollows. Although the hummocks started to thaw earlier (because they were covered with a thinner snow layer which melted faster),

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they fully thawed about 2 weeks later than the hollows (Eurola 1968). This is partly because the layer of frozen peat under the hummocks was thicker (as it was less insulated from the low air temperature in winter by the thinner layer of snow) and partly because it was in less contact with the melting water, which washing over the ice accelerates its thawing (Eurola 1968). Delayed thawing under the hummocks may be also the result of a more insulating moss layer of the hummocks than in the hollows due to the lower water content (Seppälä 1990; van der Molen and Wijnstra 1994; Soudzilovskaia et al. 2013) or the greater thickness (Soudzilovskaia et al. 2013).

The hummocks forming on a rich fen in the temperate zone are the first phase of the ombrotrophication and shrub encroachment process. The question then arises as to whether the formation of the ice lenses beneath the hummocks can affect this process and how it can be altered by climate warming. The relationship of temperature to mire microtopography has so far been diversely reported. Couwenberg and Joosten (2005) and Couwenberg (2005) explained the hummock-hollow pattern just mechanistically – by the water flow and its positive feedback with the peat structure, without pointing to temperature relevance. Hughes and Barber (2004) showed that the fen-bog transition in the Holocene in atlantic zone mires followed a large climate cooling, which may have led to an increase in effective precipitation, and if precipitation predominates over evapotranspiration, rapid peat accumulation occurs leading to the separation of the peat surface from groundwater influence and subsequent ombrotrophication. There is much evidence that boreal peatlands tend to change towards ombrotrophy with a warming climate. Väiliranta et al. (2017) suggested that the fen-bog shift in the Holocene was triggered by climate warming that enhanced plant productivity and thus accelerated peat accumulation. Similarly, Kolari et al. (2021) observed, on the mire in Finland, an expansion of *Sphagnum* hummocks at the expense of rich fen hollows during 20 years of recent climate warming.

The aim of this study was mainly to document a process of ice lenses persistence under hummocks in a temperate rich fen, which may soon disappear due to global warming, potentially affecting the functioning of temperate rich fens.

Materials and Methods

The research was carried out in the Rospuda mire located in north-eastern Poland. The average annual temperature in the region is 8.0 °C (in the coldest quarter December–February – ca. -2 °C, in the warmest quarter June–August – ca. 18 °C (c.f. Jabłońska et al. 2019)) and the average annual precipitation is 600 mm. The Rospuda mire covers about 100 ha of percolation mesotrophic rich fen. It is one of the very few

fens in Europe that has never been drained and is preserved in a near-natural state, with large areas of open moss—sedge vegetation with stable high groundwater level (Jabłońska et al. 2011, 2014, 2019). The sampling plots were located in the open moss—sedge vegetation, in a transition zone between brown moss-small sedge fen and *Sphagnum*-small sedge fen (Jabłońska et al. 2011, 2019).

In autumn 2015, we installed five iButton temperature data loggers in 10 replicates about 50 m apart (the five loggers were several metres apart in each replicate): within each replicate, one logger was installed about 1 m above the ground, attached to the trunk of a bush or tree, and the other four under a layer of different types of biomass: vascular plant litter covering bare peat hollow, *Hamatocaulis vernicosus* mat (HV), *Tomentypnum nitens* hummock (TN) and *Sphagnum teres* hummock (ST). The loggers were tightly wrapped with foil and adhesive tape. The loggers installed under the biomass layer were attached to a bamboo stick inserted into the peat in such a way that the logger was directly on the peat surface. The water level was at the same height as the peat surface when the loggers were installed. The temperature was recorded every 2 h with a resolution of 0.5 °C. The loggers were collected in spring 2016. However, some of them were damaged due to animals pulling out or biting the bamboo stick (and sometimes the logger itself). This resulted in the following number of replicates for each logger location type: air temperature – 10, litter – 5, HV – 8, TN – 6, ST – 7. When collecting the loggers, we measured the biomass thickness covering each of them. Additionally, data on daily snow depth in Suwałki were obtained from the online database of the National Climatic Data Center (US).

Data analysis was performed with the use of the Capital Asset Pricing Model (CAPM). CAPM is originally used in financial econometrics to fit a dynamic linear model for the returns on a set of assets using the overall market return as a covariate – I used air temperature as a covariate and temperature under four types of biomass took a place of assets in the model. CAPM was calculated in R (R Core Team 2016), using the dlm package (Petris 2010), following the description of the CAPM procedure presented by Petris et al. (2009).

Results

During the observed period, there was about a one-week frost in early January (-10 to -20 °C on average) without a distinct snow cover, followed by about a one-week milder frost with a snow cover of about 10 cm, and during the rest of the period, positive temperatures were observed at least during the day (Fig. 1a). During the frost period, the temperature under the litter decreased the most among the four investigated biomass types covering the peatland, whereas

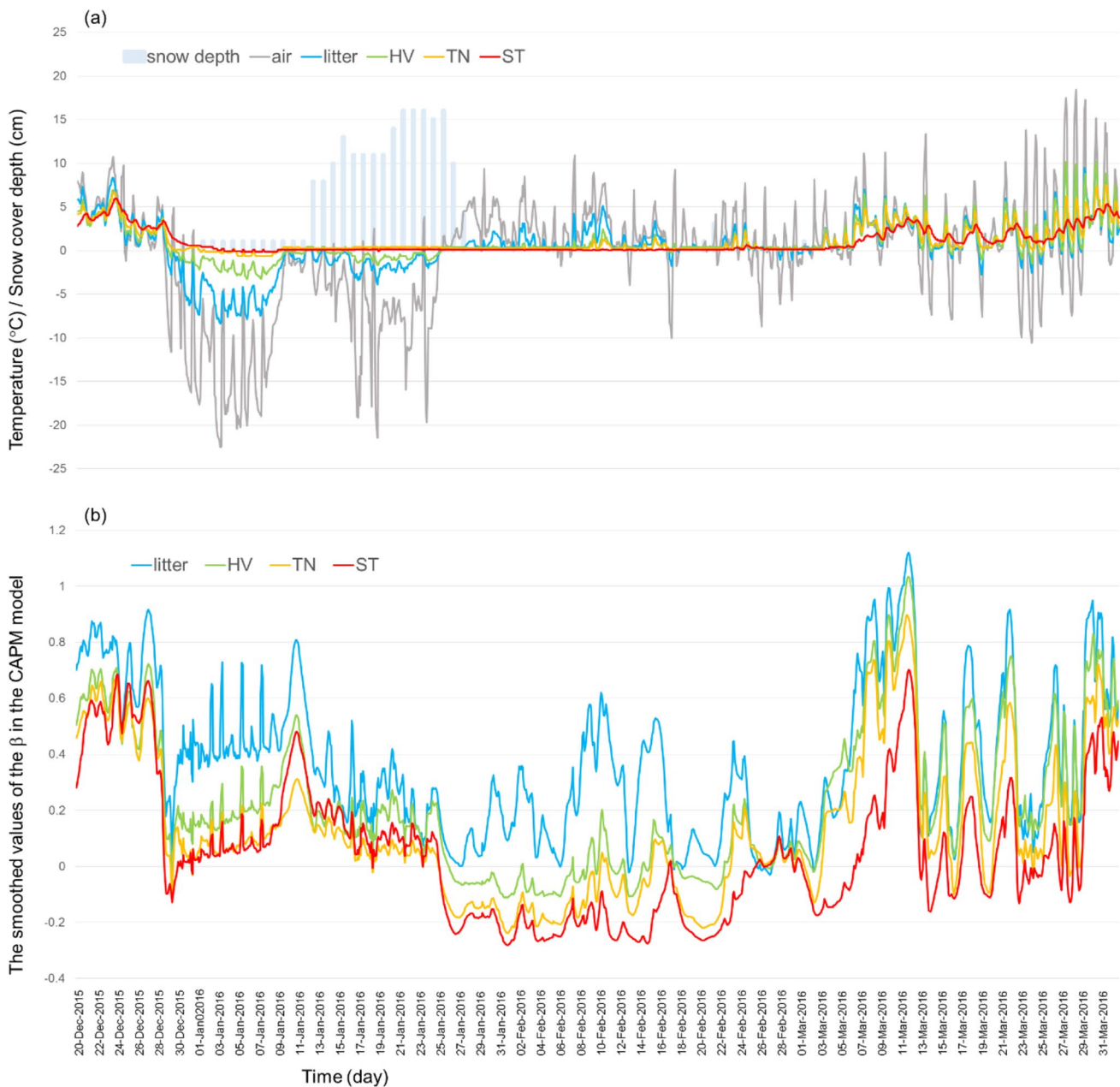


Fig. 1 The trends 20 December 2015 – 1 April 2016 for **(a)** snow cover depth (data obtained from the meteorological station in Suwałki), mean values of air temperature (measured every 2 h on 10 sampling plots) and mean values of temperature under four types of biomass covering the peat surface: i.e. under vascular plants litter (measured every 2 h on 5 plots) and under the three dominant moss species analysed: HV – *Hamatocaulis vernicosus* (measured every 2 h on 8 plots), TN – *Tomentypnum nitens* (measured every 2 h on 6 plots) and ST – *Sphagnum teres* (measured every 2 h on 7 plots); **(b)** smoothed values of β in the Capital Asset Pricing Model (CAPM) calculated on the basis of the data presented in panel a). The CAPM

model is originally used in financial econometrics to fit a dynamic linear model for the returns on a set of assets using the overall market return as a covariate – air temperature was used as a covariate and temperature under four types of biomass took a place of assets in the model. β value of less than 1.0 means that the temperature under litter/moss changes more slowly than the air temperature, the lower the β value, the slower the temperature under litter/moss reacts to changes in air temperature. A negative value of β means the reverse trend, i.e. that the temperature under the litter/moss changes in the opposite direction to the air temperature

among the mosses, the temperature under HV decreased the most. The temperature under hummock mosses (TN and ST) maintained during the whole frost period around 0 °C.

After the onset of warming up the temperature under the litter increased the fastest, whereas the temperature under the moss layer initially remained at 0 °C and then also

gradually increased. The temperature under the ST hummocks remained at 0 °C for the longest time – till the beginning of March (Fig. 1a). The time trends are more clearly differentiated when the CAPM model is applied compared to the raw temperature data (Fig. 1). The smoothed values of β in the CAPM showed that the temperature under litter reacted the most to the changes in air temperature, the temperature under HV, TN reacted more slowly to these changes, and the slowest under ST (Fig. 1b). In the case of ST, the most negative values of β were observed (Fig. 1b).

Temperature values averaged over the whole observation period are the lowest for litter, while for mosses the 95% confidence intervals do not overlap only between HV and TN (Fig. 2a). For the β value averaged over the whole observation period, clear differences were observed between all biomass types, confirming the interpretations in Fig. 1b, i.e. the highest mean β value for litter indicate that it reacted the most to the changes in air temperature, whereas temperature under HV, TN and ST reacted more slowly to these changes as indicated by increasingly lower values of β (Fig. 2b).

The thickness of the biomass layer covering the logger was the lowest for HV, while the 95% confidence intervals for the mean overlap for the other biomass types (Fig. 2c).

Discussion

Ice lenses and hummock mosses may influence each other through a positive feedback loop – the ice lenses lift the mosses above the mire surface due to frost heaving, and the mosses insulate the ice lenses allowing the lifting process to take place. The study shows that ST best insulates the temperature of the upper peat layer from changing air temperatures and maintains frozen peat under its hummocks the

longest. TN seems to insulate similarly effectively in winter, also maintaining the ice lenses under its hummocks, but less effectively in spring (Fig. 1), so that mean temperatures for the whole study period were higher under TN than ST hummocks (Fig. 2). It is noteworthy that the structure of ST and TN hummocks differs significantly (Fig. A1). Although the hummocks of these two species can be of similar height, TN has less water in them (own unpubl. data; Fig. A1), which can explain the differences between these species in warmer periods: after the mire has thawed completely, the bottom of the TN hummocks, filled mainly with air, follows the air temperature more strongly than the bottom of the ST hummocks, constantly saturated with cool groundwater maintained by *Sphagnum* shoots.

Until 23 January, most of the β values in the CAPM model ranged from 0 to 1 (Fig. 1), meaning that during frost the peat temperatures moved in the same direction as the air temperature, though with less sensitivity (Chen 2021). Later, when the air temperature began to rise, the β values beneath litter remained above 0. In spite of similar thickness (Fig. 2) the litter layer has much worse insulating properties than the moss layer. The β values under mosses dropped to negative values and the values for ST were the most negative and stayed below 0 for the longest time – until the end of February. The negative β values mean an inverse relationship between the temperature under the moss and the air temperature and may indicate the persistence of ice lenses under hummocks during the spring melt.

The results may seem contrary to the findings of Horsák et al. (2021), who showed for Western Carpathian spring fens that the peat temperature under hollow mosses (growing close to spring water outlet) was better buffered than under hummock mosses (growing further from the spring) – i.e. peat under hollow mosses was much colder than

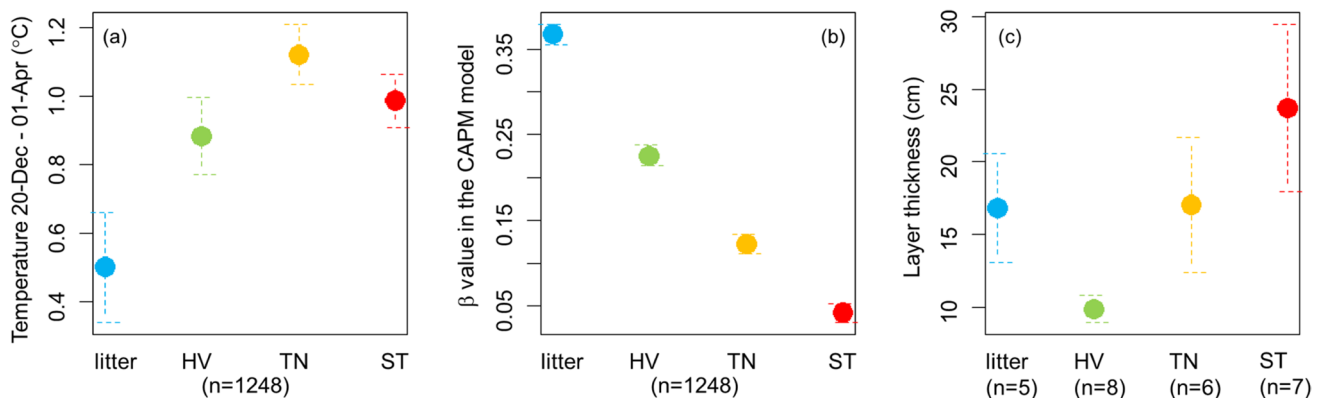


Fig. 2 Means and 95% confidence intervals for (a) temperature in the period 20 December 2015 – 1 April 2016, (b) β values in the CAPM model (compare Fig. 1 for more detailed explanations) and (c) layer thickness. The values in a) and b) are the average values for the trends shown in Fig. 1a and 1b respectively. The samples are grouped

according to the type of biomass covering the peat surface: i.e. vascular plants litter and the three dominant moss species analysed: HV – *Hamatocaulis vernicosus*, TN – *Tomentypnum nitens* and ST – *Sphagnum teres*

air than under hummocks in the warm period and much warmer in the cold period. The main difference that may account for these apparently inconsistent results is in the winter air temperatures – the minimum reported by Horsák et al. (2021) was -3.8 °C, whereas during my study the air temperature dropped to -20 °C. Thermal buffering by groundwater in cold periods occurs up to a certain frost level, until the mire freezes over. Once the mire has frozen, the thermal buffering by groundwater disappears, and the control of the temperature of the upper peat layer is taken over by insulation by mosses and snow.

The snow accumulated in the second half of January reduced peat freezing in spite of low air temperatures (the temperature under the litter was distinctly higher during the time of snow cover than during the preceding snow-free period, despite the fact that in both periods the air temperature dropped to around -20 °C, Fig. 1). The snow cover, like the moss layer, has insulating properties (Eurola 1968, 1975), particularly when it is new, fluffy snow (Seppälä 1990; Benoy et al. 2007).

The growth rate of mosses is hampered by frost (Campbell and Rydin 2019) but still, they continue to grow not only in the warmer season of the year but also in winter when the mire is at least temporarily frozen (Küttim et al. 2020). Snow cover partially alleviates the physiological stress associated with freezing (Cooper et al. 2019; Küttim et al. 2019). Vascular plants do not begin to grow when the mire is frozen. Although thermal buffering by groundwater generally mitigates the negative effects of cold on fen plants (Fernández-Pascual et al. 2015), the hummocks sustaining the ice lenses are microhabitats where the growing season may be slightly shorter than in the hollows. With concurrent lower access to groundwater, this may create conditions for competitively weak vascular plant species with a northern range, such as *Carex dioica*, *C. chordorrhiza* (Fig. A2), as well as *Liparis loeselii*, *Parnassia palustris*, *Saxifraga hirculus* (Peterka et al. 2017). In a study covering the whole vegetation of the Rospuda valley (Jabłońska et al. 2019), the affinity of *C. dioica* and *C. chordorrhiza* to *S. teres* hummocks, as well as of *P. palustris* and *S. hirculus* to *T. nitens* hummocks was confirmed. In a comprehensive study by Singh et al. (2019) on the relationship between vascular plants and mosses in rich fens in central and eastern Europe, *C. dioica*, *C. chordorrhiza* and *L. loeselii* were associated with intermediate values of brown moss/*Sphagnum* ratio, indicating a substantial share of *Sphagnum* in the sites where the species occur. Singh et al. (2019) showed that *P. palustris* and *S. hirculus* were significantly positively correlated with the brown moss/*Sphagnum* ratio, but did not specify whether the brown mosses dominating in the sites are hollow or hummock species. It cannot therefore be ruled out that they also show a relationship between these species and *T. nitens* hummocks. The species discussed are increasingly rare in central European peatlands.

Due to climate warming, harsh winters in central Europe will become scarce (IOŚ 2022). The phenomenon described here may, with great probability, become a thing of the past within the next couple of years, as a frost that is too weak and of short duration will not cause the groundwater-fed fen to freeze. Studies of peatlands in northern Europe reveal consistent trends towards ombrotrophication of fens with climate warming (Väliranta et al. 2017; Granlund et al. 2021; Kolari et al. 2021), but in northern Europe winters are still cold enough for hummocks to preserve frosted peat longer during spring melt. It is therefore not possible to directly transpose the trends observed currently in northern peatlands to the temperate zone. It cannot be ruled out that the decline of the phenomenon described in this article, may contribute (in addition to falling groundwater levels, reduced precipitation, increased peat decomposition leading to an increased supply of nutrients, as well as the more severe impact of the increasingly shorter and thinner snow cover on the hummock than hollow mosses (Küttim et al. 2019)) to the retardation of ombrotrophication on rich fens in central European lowlands and to the disappearance of *Sphagno-Tomentypnion* and *Saxifrago-Tomentypnion* vegetation (Peterka et al. 2017; Hájek et al. 2021) and its characteristic plant species.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13157-022-01586-y>.

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Author Contributions EJ conceived and designed the research, performed the research, analysed the data and wrote the manuscript.

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Data Availability The datasets analysed during the current study are available from the corresponding author on reasonable request.

Code Availability Capital Asset Pricing Model (CAPM) was calculated in R (R Core Team 2016), using dlm package (Petris 2010), following the description of CAPM procedure presented by Petris et al. (2009).

Declarations

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of Interest The authors declare that they have no conflict of interest.

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