Ground temperature and snow depth variability within a subarctic peat plateau landscape

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Abstract
Subarctic permafrost peatlands cover extensive areas and store large amounts of soil organic carbon that can be remobilized as active layer deepening and thermokarst formation increase in a future warmer climate. Better knowledge of ground thermal variability within these ecosystems is important for understanding future landscape development and permafrost carbon feedbacks. In a peat plateau complex in Tavvavuoma, northern Sweden, ground temperatures and snow depth have been monitored in six different landscape units: on a peat plateau, in a depression within a peat plateau, along a peat plateau edge (close to a thermokarst lake), at a thermokarst lake shoreline, in a thermokarst lake and in a fen. Permafrost is present in all three peat plateau landscape units, and mean annual ground temperature (MAGT) in the central parts of the peat plateau is \(-0.3^\circ C\) at 2 m depth. In the three low-lying wetter or saturated landscape units (along the thermokarst lake shoreline, in the lake and the fen) taliks are present and MAGT at 1 m depth is \(1.0 - 2.7^\circ C\). Topographical differences between the elevated and low-lying units affect both local snow depth and soil moisture, and are important for ground thermal patterns in this landscape. Permafrost exists in landscape units with a shallow mean December–April snow depth (<20 cm) whereas snow depths >40 cm mostly result in absence of permafrost.

KEYWORDS
landscape unit, peatland, permafrost, small-scale morphology, subarctic, temperature regime

1 INTRODUCTION

Permafrost peatlands are widespread in the sporadic and discontinuous permafrost zones around the circum-Arctic and store \(\sim 300 \times 10^{15}\) g carbon (C), which is nearly 25% of the total soil organic carbon (SOC) in the northern circumpolar permafrost region. Because most permafrost peatlands are located in the southern parts of the permafrost region they are already near thawing and very sensitive to future warmer conditions. Extensive landscape changes have already started to take place in subarctic peatlands in recent decades as a result of permafrost thaw. As long as the ground stays frozen, these environments are net carbon sinks through uptake of carbon dioxide (CO2) by plants and peat accumulation. Under changing climatic conditions increased emissions of greenhouse gases (CO2, methane [CH4] and nitrous oxide [N2O]) can be expected as deepening of the active layer, thermokarst processes and changes in the surface hydrology can cause increased remobilization of previously frozen soil carbon and nitrogen.

Peatlands cover extensive lowland areas in the northern circumpolar permafrost region (\(-13\%)\). Despite an overall relatively flat landscape, their small-scale topography can vary considerably. Permafrost peatland ecosystems are often characterized by a complex...
mosaic of different features, or landscape units, such as dry surface peat plateaus and palsas uplifted by frost heave, wet collapse scar fens or bogs and thermokarst lakes in depressions. In this study, landscape units are defined as a portion of the landscape with similar morphological characteristics, largely uniform in terms of topography, vegetation and water table.

Ground temperatures in permafrost peatlands are controlled by both air temperature and snow depth.16-21 Because of topographical differences, winds can redistribute snow within these landscapes. Elevated palsas and peat plateaus typically have a thin snow cover, <30 cm, which allows extensive heat loss from the ground in winter, promoting permafrost development and persistence.21-23 In low-lying landscape units, a thick snow cover can reduce heat flux from the soil, because snow has very low thermal conductivity.24,25 For example, Seppälä26 and Johansson et al19 have shown that artificially increased snow depths on palsas and peat plateaus result in higher ground temperatures.

Several studies have discussed temporal changes in ground temperature and active layer depth in palsa mires, and the impacts of vegetation and snow depth on ground thermal properties and palsa formation.17,19-23,26,27 However, few studies have focused on spatial variation in ground thermal regimes across landscape units in peat plateau ecosystems. The projected global warming and Arctic amplification will continue to cause permafrost thaw and ground subsidence in regions with extensive permafrost peatland coverage.3 Therefore, a better understanding of climate–permafrost–hydrology interactions, and variability across landscapes and scales is essential for model projections of the future carbon balance in these morphologically heterogeneous environments. The objectives of this study are to (a) increase our knowledge of small-scale spatial ground thermal variability within subarctic peat plateau landscapes, and (b) discuss drivers of ground thermal regimes in different landscape units.

2 | STUDY AREA

Tavvavuoma is a widespread permafrost peatland area in northern Sweden, surrounded by low mountains (up to ~750 m a.s.l.). In the peat plateau complex (68°28′N, 20°54′E, ~555 m a.s.l.) a mosaic of landscape units are found: peat plateaus, palsas, thermokarst lakes, streams and fens (Figure 1). Dome-shaped palsas can reach up to around 6 m in height. The peat plateau surfaces are generally lower and flatter, and are characterized by small hummocks and depressions, formed as a result of ground collapse following thaw of the ice-rich substrate. Shorelines along shallow thermokarst lakes (<1 m deep) can be either gently sloping, stable and covered with vegetation (cotton

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**FIGURE 1** (a) Map showing the location of the study area in northern Sweden. Inset map with circum-Arctic permafrost zonation, adapted from Brown et al.28 (b) IKONOS image from 2003 of a section of the peat plateau complex in Tavvavuoma with palsas, fens, streams and thermokarst lakes. The white rectangle shows the study area with ground temperature and snow depth monitoring in different landscape units [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 2  (a) Map showing landscape units and locations of thermistor cables within the study area in Tavvavuoma. (b) Thermistor cable locations. (c) Ground thermal snapshot (minimum, mean and maximum temperatures) in different landscape units within the peat plateau complex in 2007 (2008 for T8 and T9) [Colour figure can be viewed at wileyonlinelibrary.com]
3 | METHODS

3.1 | Ground temperature

Ground temperature monitoring started in the peat plateau complex in Tavvavuoma in September 2005. Additional thermistor strings were installed in 2006, 2007 and 2008 to better cover the topographic variability within the peatland. Ground temperatures were recorded in nine 1–2 m deep boreholes (T1–T9): in the central peat plateau (T2, T3), in a depression in the peat plateau (T4), at the peat plateau edge (T1, T7), at the thermokarst lake shoreline (T5, T6), in the thermokarst lake (T8) and in the fen (T9) (Figure 2; Supporting Information Figure S1). Organic layer depth at the boreholes, and vegetation cover within a 20 cm radius from the borehole centers are presented in Table 1. The thermistors (Fenwal UNI curve type, 192-502LET-A01) have a curve tolerance of ±0.2°C. The accuracy was improved to ±0.05°C by calibration in an ice–water bath at 0°C before installation.22 The land-based thermistors were mounted on cables at 0.02, 0.1, 0.25, 0.5 and 1.0 m depth, and for T2–T4 and T9 also at 1.5 and 2.0 m depth. The cables were installed in 38 mm diameter boreholes, made by hammering down steel pipes into the ground 5–10 cm at a time before pulling them back up until 1 or 2 m depth was reached. Before installation the thermistor cables were attached to 30 mm diameter plastic rods to avoid air circulation in the hole, and at the surface peat and moss were packed around the rod. The thermistor cable installed in the lake (T8) was also attached to a plastic rod, and pushed down into the sediments, with the thermistors 0.3, 0.7, 1.1, 1.5, 1.9 and 2.3 m down in the bottom substrate. At the time of installation, water depth at T8 was 70 cm. A Campbell Scientific CR1000 data logger connected to a Campbell Scientific Multiplexer AM16/32 was used to record ground temperatures every 3 h (starting at 00:00 Central European Time). This study presents a temporal snapshot from the year 2007 (2008 for T8 and T9, as these thermistor cables were not installed until in spring/summer 2007). The years 2007/2008 are the only ones with soil temperature records that are complete for all landscape units, and that are not biased due to permafrost collapse. Since then some thermistors have failed (e.g., T4) and many of the upper thermistors (e.g., at T1 and T5) have been recording air or lake temperatures, rather than soil temperatures, due to extensive ground collapse as a result of permafrost thaw along the lake shoreline and slow continuous ground subsidence on the peat plateau (Supporting Information Figure S1).

3.2 | Thaw depth

Thaw depth was measured in late August/early September at three locations within 25 cm radius from each thermistor cable by probing a 1 m long steel rod (10 mm diameter) into the soil until it reached the permafrost table. Mean values were calculated. As thaw depth was not systematically measured at all thermistor cables in 2007/2008,
mean values for 2010–2012 (recorded 2010-09-02, 2011-09-03 and 2012-08-23) were used. Other studies suggest that the maximum thaw depth in this region is reached later in September or even in October.\textsuperscript{16,17} Therefore the term late-season thaw depth is used in this study instead of active layer depth.

### 3.3 | Snow depth

Snow depth in the different landscape units was monitored by a stationary digital camera overlooking the peat plateau complex. Adjacent to each thermistor cable, snow depth stakes (S1–S9) were mounted (38 mm diameter steel pipes painted in 10 cm wide red and white bands) (Figure 3). When analyzing the pictures, measuring accuracy was ±2.5 cm. Because of irregular recordings and two camera failures there was very limited data available for the time period 2005–2009. In December 2009 a time-lapse package from Harbortronics (Fort Collins, CO, USA) with a Pentax K200D camera was installed, and since then pictures have been recorded much more frequently. However, there were still periods of days in winter when it was difficult to see the snow depth at the various stakes because it was too dark or the camera box was partly covered with snow. For this study, data recorded approximately every 2 weeks from three winters (October 2010 to May 2013) were used to assess seasonal snow depth.

**FIGURE 3** (a) Mean winter (December–April) snow depth distribution within the study area. (b) Location of snow depth stakes installed in different landscape units within the peat plateau complex. The stakes (S1–S9) are installed close to, and numbered in accordance with, the thermistor cables presented in Figure 2 (SX is an extra snow depth stake, originally close to T5 at the lake shoreline, but over time inundated by water due to thermal erosion – see Figure S2). (c) Snow depth variability in different landscape units (S1–S8) during three winter seasons (2010/11–2012/13). The data are derived from pictures recorded approximately every 2 weeks. No data are available for S9 because the stake is partly hidden from the camera [Colour figure can be viewed at wileyonlinelibrary.com]
variability and to calculate mean December–April snow depths in different landscape units.

3.4 | Statistical analysis

Spearman’s rank correlation coefficient was used to determine if there was a statistically significant correlation between snow depth and ground temperature at the thermistor cable sites on the peat plateau and along the thermokarst lake shoreline (T1–T7). Because of the small sample size the p-value was calculated with Monte-Carlo permutation (100,000 permutations), using the statistical software Stata version 15. The thermokarst lake and fen landscape units (T8 and T9) were excluded from this analysis because the thermal properties were probably not just affected by snow depth but also by overlying water/ice. Moreover, no snow depth data were available for T9.

4 | RESULTS

4.1 | Ground temperature

MAGT values just below 0°C were recorded at 1 m depth in the central parts of the peat plateau (T3, T2) and at the peat plateau edge close to the thermokarst lake shoreline (T7, T1) (Figure 2 and Table 2). In the small depression within the peat plateau (T4), MAGT was just above 0°C (0.3°C) at 1 m depth. However, at 2 m depth permafrost was present and MAGT was the same at T4, T3 and T2 (−0.3°C). MAGT values >0°C (permafrost-free conditions) were recorded at 1 m depth at the lake shoreline (1.0 and 1.6°C at T6 and T5, respectively), with a slightly higher MAGT at T5 where the shoreline was actively eroding. Permafrost-free conditions also prevailed in the fen and in the lake sediments (MAGT 1.1 and 2.3°C at 2 m depth at T9 and T8, respectively). In the lake sediments, the minimum recorded ground temperature at 0.3 m depth was below 0°C (−0.03°C), supporting the observation during cable installation that the shallow lake freezes to the bottom in winter.

4.2 | Thaw depth

In the elevated peat plateau and peat plateau edge landscape units (T1–T3, T7), late-season thaw depth was typically around 50–70 cm (Table 2). In the depression within the peat plateau (T4) late-season thaw depth was 75 cm in 2005 when the thermistor cable was installed, and between 100 and 150 cm in 2007 (Table 2 and Figure 2).

4.3 | Snow depth

Mean December–April snow depth was shallowest on the peat plateau (12–17 cm), both in the central parts (S2, S3) and at the peat plateau edge (S1, S7) (Table 2 and Figure 3). Snow cover duration was also shorter on the elevated peat plateau and along the peat plateau edge compared to the other landscape units. The timing of onset was similar in all units, but because snow cover was thinner on the peat plateau, spring snowmelt occurred on average 3–4 weeks earlier here compared to on the low-lying landscape units, including the depression in the peat plateau (around 5 May at S1–S3 and S7, and around 29 May at S4–S6 and S8) (Figure 3c). The deepest mean snow depth was found at the lake shoreline and in the depression within the peat plateau, whereas an intermediate snow depth was recorded on the thermokarst lake (Table 2 and Figure 3).

### TABLE 2  Mean annual ground temperature (MAGT), mean late season thaw depth and mean December–April snow depth at the thermistor cable sites

| Thermistor cable/snow depth stake | T1/S1 | T2/S2 | T3/S3 | T4/S4 | T5/S5 | T6/S6 | T7/S7 | T8/S8 | T9/S9 |
|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| MAGT at 0.02 m depth (°C)         | no data | 0.45  | no data | 2.26  | 2.66  | 2.53  | no data | no data | 1.76  |
| MAGT at 0.1 m depth (°C)          | 0.58  | −0.01 | 0.51  | 2.08  | 2.49  | 2.19  | 1.40   | no data | 1.63  |
| MAGT at 0.25 m depth (°C)         | 0.11  | −0.25 | −0.32 | 1.40  | 2.51  | 1.24  | 0.19   | no data | 1.37  |
| MAGT at 0.5 m depth (°C)          | 0.11  | −0.62 | −0.29 | 0.66  | 2.58  | 1.13  | 0.27   | 3.13   | 1.28  |
| MAGT at 1 m depth (°C)            | −0.44 | −0.44 | −0.26 | 0.26  | 1.57  | 0.99  | −0.01  | 2.67   | 1.26  |
| MAGT at 1.5 m depth (°C)          | no data | −0.39 | −0.20 | −0.10 | no data | no data | no data | 2.34   | 1.28  |
| MAGT at 2 m depth (°C)            | no data | −0.35 | −0.26 | −0.33 | no data | no data | no data | 2.29   | 1.14  |
| Mean late season thaw depth 2010–2012 (cm) | >100b  | 56    | 52    | >100c | >100c | >100c | >100c | 69    | >100c |
| Mean December–April snow depth 2010/11–2012/13 (cm) | 13    | 12    | 13    | 60    | 90    | 79    | 17    | 41    | no data |

*Due to ground subsidence the sensor depths for T1 are 9 cm shallower.
*Due to active block erosion, thaw depth at installation 2005-09-23: 75 cm.
*Data from 2010 only, since then in water.
*Due to ground subsidence the sensor depths for T7 are 4 cm shallower.
*Linearly interpolated value based on data from 0.3 and 0.7 m depth.
*Linearly interpolated value based on data from 0.7 and 1.1 m depth.
*Linearly interpolated value based on data from 1.9 and 2.3 m depth.
4.4 | Statistical analysis

Snow depth had an important impact on ground temperatures. There was a statistically significant correlation between mean December–April snow depth and MAGT at 1 m depth at T1–T7 (Spearman’s rho = 0.9727, p = 0.0016).

5 | DISCUSSION

The six landscape units in the peat plateau complex in Tavvavuoma display different ground thermal characteristics. Because air temperature and precipitation regimes are similar across the landscape, other environmental parameters must account for the local differences in ground temperatures. Permafrost is present in three of the units – in the central parts of the peat plateau, along the peat plateau edge and in the depression within the peat plateau – but their ground thermal patterns are partly dissimilar. On the elevated, central parts of the peat plateau (T2, T3) MAGT is ~−0.3°C at 2 m depth. Late-season thaw depths of 52–56 cm imply that the permafrost is relatively stable.23 In both the central elevated parts and along the peat plateau edge, mean December–April snow depth is shallow (~20 cm). A thin snow cover, <30 cm, generally preserves the permafrost in elevated palsas and peat plateaus as it facilitates extensive heat flux from the peat in winter.21,22,27 However, along the peat plateau edge late-season thaw depth is greater (>69 cm) compared to in the more central parts, despite an equally shallow snow cover. The relatively deep active layer at the peat plateau edge implies that the permafrost has started to thaw, possibly as a result of more lateral exposure to warm air and proximity to the thermokarst lake promoting lateral heat flux from the water into the adjacent peat plateau in summer. This is particularly evident at T1 where extensive block erosion and ground collapse has taken place since the thermistor cable was installed in 2005 (Supporting Information Figure S2).

In the depression within the peat plateau (T4) where mean December–April snow depth is 60 cm, late-season thaw depth is even greater (100–150 cm) than along the peat plateau edge (Table 2). Despite a similar MAGT at 2 m depth as in the central parts of the peat plateau (~0.3°C as at T2 and T3), maximum annual ground temperature is ~8–9°C higher at 0.5 m depth in the depression compared to in the central parts, and higher maximum ground temperatures extend down to 1–1.5 m depth. Sjöberg et al.24 suggest that supra-taliks can be present above the permafrost table in small, relatively dry depressions. At this particular location (T4), the active layer currently (2007) refreezes all the way down to the permafrost in winter, but should a supra-talik develop more extensive vertical thaw can be expected.35 Snow can easily be redistributed by winds from elevated to low-lying landscape units in these open and treeless environments. The correlation between snow depth and ground temperature at 1 m depth reported in this study fits well with the results of earlier studies showing that snow depth is an important factor for the ground thermal regime in permafrost peatlands because of its insulating properties.19,22,26,27,36 A thicker snow cover also generates more meltwater in late spring, increasing the soil moisture in low-lying landscape units. Because saturated peat has nearly ten times higher thermal conductivity compared to dry peat, a high water content can warm the soil.23,37–39 If ground ice in the upper permafrost melts during the summer the ground surface is lowered as a result of volume loss, and over time depressions can become saturated with water trapped by the surrounding impermeable permafrost. A pilot study at the site in Tavvavuoma has shown that shallow soil volumetric water content (VWC) is higher in depressions compared to on the elevated peat plateaus even in late summer (mean values of 0.60 and 0.33 m³·m⁻³ respectively at 5 cm depth), and that there is a significant difference in VWC between the two landscape units.40 Small depressions in the peat plateau like the one described here can be the initial step in thermokarst formation. Where in the peat plateau depressions develop is probably controlled by a combination of factors such as peat depth, ground ice content and vegetation, but this needs further investigation.

In the other three landscape units – along the thermokarst lake shoreline, in the thermokarst lake and in the fen – permafrost is absent. Typically, permafrost-free settings in peat plateau complexes are characterized by a 20–80 cm thick snow cover in March.23 In the present study, the lake shoreline landscape unit has the thickest mean December–April snow depth (79–90 cm). MAGT at 1 m depth is 0.6°C higher where the shoreline is almost vertical and active erosion is taking place, compared to where the shoreline is stable.41 A possible explanation for the higher ground temperature at the actively eroding shoreline could be that deep, open cracks between the eroding peat blocks allow precipitation and warm air to penetrate the soil in summer.

On the thermokarst lake mean December–April snow depth is 41 cm. Similar snow depths can be expected for the fen, which is also located in a low-lying part of the landscape. Both in the lake and in the fen, soils are saturated, which increases the thermal conductivity of the peat. Winter freezing occurs down to ~0.3 m depth in the lake sediments and ~1 m depth in the fen (Figure 2c). Below these depths taliks are found. At the lake the talik is probably underlain by permafrost as the water level is higher compared to surrounding fens and lakes, whereas a through-talik is suggested beneath the fen based on geophysical methods (ground penetrating radar and electrical resistivity tomography).33,41 The rather high MAGT values in these landscape units (2.7°C in the lake sediments and 1.3°C in the fen at 1 m depth) can be explained by a combination of a relatively thick insulating snow cover, peat saturation and particularly for the lake also the presence of an overlying water column that slows cooling and freezing in autumn.

6 | CONCLUSIONS

This study provides insights into ground thermal patterns within peat plateau complexes that can be valuable for understanding and projecting future landscape development in these ecosystems. Permafrost is present in the elevated peat plateau and along the peat
plateau edge where mean December–April snow cover is thin (<20 cm). However, along the peat plateau edge a deeper late-season thaw depth suggests that the permafrost has started to degrade. Permafrost also occurs in a small and relatively dry depression in the peat plateau where mean snow cover is 60 cm, but a deeper late-season thaw depth (>100 cm) implies that vertical thaw is more extensive here compared to in the surrounding elevated plateau (thaw depth ~55 cm). Taliks are present along lake shorelines where mean snow cover is deep (~80–90 cm), and in other low-lying and saturated landscape units such as thermokarst lakes and fens. Because the small-scale landscape morphology affects both snow depth and soil moisture, it is a key parameter for the ground thermal regime in peat plateau complexes. To improve our understanding of future permafrost peatland thaw, more empirical data on landscape heterogeneity, snow cover variability and duration, soil moisture, thermokarst formation and expansion rates, and connections between local hydrology and permafrost are needed. Ideally, ground thermal variability and landscape dynamics within permafrost peatlands should be incorporated into process-based ecosystem models trying to forecast permafrost thaw and associated carbon emissions.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of this article.

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