**Vegetation succession, carbon accumulation dynamics and hydrological change in subarctic peatlands (Abisko, N. Sweden)**

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**Abstract** (up to 200 words)

Here we present the results of an investigation into the Late Holocene hydrological, ecological and carbon accumulation dynamics of two subarctic peatland sites in Abisko, Arctic Sweden. A high-resolution analysis of plant macrofossils, testate amoebae, pollen, mineral content, bulk density, and carbon and nitrogen content was carried out together with core chronologies using tephra, 14C and 210Pb. The local plant succession and hydrological changes in peatlands are synchronous with climatic shifts, although autogenous plant succession can not be excluded as a driver in peatlands development. The fen site, Marooned, experienced a shift ca. 2250 cal yr BP from rich to poor-fen as evidenced by the appearance of *Sphagnum fuscum* that remains as the main peat forming species of this peatland until present time. At the palsa mire, Stordalen, there is evidence of significant hydrological changes between 500 and 250 cal yr BP which we hypothesize may have been caused by drying during the Little Ice Age (LIA) period. Finally, during the last few decades we observe a decrease of water table levels and an increase of shrub communities that coincides with recent climate warming, which favours the expansion of shrubs in the arctic zone. Furthermore, we describe the paleoecology of *Sphagnum lindbergii*, a species typically found in high-latitude peatlands in wet habitats in transition zone between fen and bog. In palaeoecological reconstructions the presence of *S. lindbergii* can be indicative of wet phases in peatland development which most likely coincide with wet climatic conditions. Our work provides an important longer-term perspective for ongoing changes in permafrost peatlands driven by past and recent climate shifts.

**Introduction**

Northern peatlands located in the subarctic and arctic zones are important archives of environmental changes owing to their ecological sensitivity to climate and hydrological change (Sollid and Sřrbel, 1998; Turetsky et al., 2002, 2007; Lamarre et al., 2012, 2013; Swindles et al., 2015a). The recent rapid increase of global air temperatures at high latitude (IPCC, 2014) has led to partial or complete thawing of permafrost (Turetsky et al., 2002; Johansson et al., 2006; Callaghan et al., 2010). Numerous studies have been conducted in areas of permafrost degradation that focus on different aspects of ecosystem response, including changes in carbon accumulation rates (Loisel et al., 2014; Swindles et al., 2015a), organic matter decomposition rates (Scanlon and Moore, 2000), plant succession and peatland development pathways (Zoltai, 1993; Kuhry, 2008; Teltewskoi et al., 2016; Treat et al. 2016, Svensson et al., 1999; Christensen et al., 2004; Schuur et al., 2007), hydrology (Swindles et al., 2015a, b) and methane emissions (Lupascu et al., 2012, 2014).

Peatland carbon accumulation rates depend on soil temperature and moisture, peat composition and degree of decomposition at the time of permafrost aggradation (Kuhry and Vitt, 1996; Sannel and Kuhry, 2009; Treat et al., 2014; Vardy et al., 2000). The importance of the length of the growing season and incoming radiation has also been highlighted for northern peatland carbon accumulation (Charman et al., 2013).

Here we present a palaeoecolgical study from the Abisko region of northern Sweden, a region that has experienced rapid warming during the twentieth century (Callaghan *et al*. 2010; Swindles et al., 2015a) and documented degradation of permafrost peat and deepening of active layer in recent times (Zuidhoff and Kolstrup, 2000; Ĺkerman and Johansson, 2008; Kokfelt *et al.,* 2009). Furthermore, climate model projections suggest continued marked temperature increases in the near future in this region (Swindles *et al*., 2015a, b). Detailed long-term palaeoecological studies of these degrading permafrost peatlands are important for understanding future climate feedbacks including the relationships between vegetation, hydrology and carbon accumulation (Gao and Couwenberg, 2015).

Using palaeoecological reconstructions from two sites we aim to: i) to determine the drivers of vegetation change in the Late Holocene; ii) to reconstruct the late Holocene hydrological conditions of these peatlands to establish and possible links with climate and autogenic peat dynamics, iii) to assess the impact of climatic and ecological changes in carbon accumulation rates; iv) to improve of tephra dispersal maps in northern Scandinavia.

**Study sites**

The study sites are located in the Abisko area, of Northern Sweden in the subarctic zone (Fig. 1). Detailed site information is presented in Table 1. The Marooned and Stordalen peatlands were selected due to their location at a high latitude, near the tree-limit and at a sensitive climatic boundary that is controlled by alternating influences of air masses of Atlantic and Arctic origin (Shemesh et al., 2001). Because of this, we expect that these peatlands will be sensitive to small climatic changes. They are also contrasting in terms of permafrost – Marooned has no permafrost remaining, whereas Stordalen is in an advanced state of permafrost degradation.

Table 1. Description of study site

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Site name | Latitude (°N) | Longitude (°E) | Peatland type | Water table depth range (cm) | pH range | Permafrost conditions |
| Marooned | 67°57'24.0" | 19°59'11.4" | Fen and bog | -1 to 29 | 3.24 - 4.21 | No permafrost |
| Stordalen | 68°21'24.3" | 19°02'53.5" | Palsa and fen | -7 to 50 | 2.99 - 3.80 | Advanced degradation |

**Materials and Methods**

*Overview*

The palaeoecological reconstruction in this study is based on plant macrofossils, pollen, testate amoebae, sedimentological and geochemical analyses. Chronologies are based on 14C, 210Pb dating and the presence of microscopic tephra layers. The recent progress in tephrochronology (Lowe, 2011) allows for the detection of even tiny amounts of dispersed ash (cryptotephra) in distal and ultra-distal locations and has led to the improvement of tephra dispersal maps. Tephra layers can provide precise chronological control and synchronisation markers during paleoecological reconstructions (e.g. Brauer *et al*., 2014; Davies, 2015; Wulf *et al*., 2013).

The analysis of plant macrofossil remains reveals a record of local plant communities and hydrological conditions (Barber et al., 2004; Mauquoy et al., 2008), while pollen analysis provides information on vegetation composition and abundance at the wider regional context (Berglund et al., 1996). The testate amoebae record allows the reconstruction of changing hydrological conditions in the past (e.g. Swindles et al., 2015b). We used microscopic microcharcoal (particles smaller than 150 µm), quantified from pollen slides, as an indicator of fire occurrence (Mooney and Tinner, 2011). Finally we measure carbon accumulation rates as a way of assessing the effect of climatic and ecological changes on peat carbon accumulation (e.g. Charman et al., 2013).

Additionally, we compare our data with the palaeoecological evidence based on previous studies in the region, including plant macrofossils and pollen in lake and peat cores (Berglund et al., 1996; Bigler et al., 2002; Kokfelt et al., 2010).

*Coring and subsampling, chronology of the core*

Two short peat cores, Marooned (38 cm) and Stordalen (30 cm), were taken from each site using a Russian corer (De Vleeschouwer et al. 2010). To determine the age of the sediment samples, radiocarbon measurements were performed on handpicked terrestrial plant macrofossils at Direct AMS, Seattle, USA. High-resolution 210Pb-dating was applied to the uppermost part of the monolith samples at the Exeter laboratory (bulk peat). Samples were acid digested with concentrated HCl, HNO3, and H2O2, and a spike of 209Po added as a yield tracer. Material was plated onto silver disks and the activity measured by alpha spectrometry. The date of each sample was derived from the 210Pb inventory using a constant rate of supply model (Appleby, 2001). The calibrated dates are expressed as cal yr BP. Age models based on linear-interpolation were generated using Clam v 2.2 (Blaauw, 2010). Bayesian methods offered no advantage over simple linear interpolation for these peat profiles.

*Tephra*

Contiguous 5 cm samples were ashed at 550 ºC and treated with 10% HCl before mounting onto slides (Swindles et al., 2010). Where tephra shards were identified under 400 x magnification, cores were subsampled at 1 cm intervals. Extraction for geochemical analysis followed the density separation method (cleaning float 2.25 g cm-3, retaining float 2.50 g cm-3) (Blockley et al., 2005). Shards were mounted onto slides (Dugmore and Newton, 1992) and major element geochemistry was determined using an Electron Probe Micro Analyser (EPMA). Glass shards from Marooned peatland were analysed on the JEOL JXA8230 EPMA housed at the University of Leeds, samples from Stordalen peatland were analysed on the Cameca SX100 EPMA housed at the University of Edinburgh. Assignments to specific eruptions were based on stratigraphy and visual comparison of tephra geochemistry with the Tephrabase database (Newton et al., 2007) and published literature. The full analytical setup was as follows:

Stordalen

EPMA: Cameca SX100 EPMA housed at the University of Edinburgh

Geochemical analysis was conducted using a Cameca SX100 electron probe microanalyser at Tephra Analytical Unit (TAU), School of Geosciences, University of Edinburgh. All analyses were conducted with a beam diameter of 5 μm, 15kV and beam currents of 2 nA (Na, Mg, Al, Si, K, Ca, Fe) and 80 nA (P, Ti, Mn) (Hayward, 2012). Secondary glass standards (basalt (BCR-2G) and rhyolite (Lipari)), were analysed before and after unknown tephra samples.

Marooned

EPMA: JEOL JXA8230 EPMA housed at the University of Leeds

Geochemical analysis was conducted using a beam diameter to 10 μm, 15 kV and a beam current of and a beam current of 10 nA. Secondary glass standards (Lipari) were analysed before and after unknown tephra samples.

*Plant macrofossil analysis*

Plant macrofossil remains were analysed contiguously (sample volume of 5 cm3), at 1-cm intervals resulting in 68 samples. These were washed and sieved under a warm-water spray using a 0.20-mm mesh sieve. Initially, the entire sample was examined with a stereomicroscope to obtain volume percentage of individual subfossils of vascular plants and mosses. The subfossil carpological remains and vegetative fragments (leaves, rootlets, epidermis) were identified using identification keys (Smith, 2004; Mauquoy and van Geel, 2007). The volume percentages of the different vegetative remains and the *Sphagnum* sections were estimated to the nearest 5%. The number of seeds, fruits, needles, bud scales and leaves were counted separately. The relative proportions of taxonomic groups of *Sphagnum*, which are of key importance for interpretations, were estimated on the basis of the branch leaves, which were investigated under the microscope on two 22x22-mm cover glasses. The identification of *Sphagnum* remainsto the species level was performed separately on the basis of stem leaves and cross-sections, using specialist keys (Hölzer, 2010; Laine et al., 2011). We use the nomenclature of Mirek et al. (2002) for vascular plants and Smith (2004) for bryophytes.

*Palynological and charcoal analyses*

Samples of 1 cm3 were prepared using the standard procedure of Erdtman’s acetolysis (Berglund and Ralska-Jasiewiczowa, 1986). *Lycopodium* tablets were added to each sample to enable quantitative analysis of microfossil concentration (Stockmarr, 1971).

Analysis was carried out with an Olympus BX43 light microscope with a magnification of 600×; a higher magnification was used to identify problematic micro-remains. Approximately 500 terrestrial pollen grains per sample were counted. For taxonomical identification pollen keys (Beug, 2004) and a reference collection of modern pollen were used. Non-pollen palynomorphs (NPPs) were counted along with the pollen. NPPs were identiﬁed according to van Geel (1978, 2001), van Geel and Aptroot (2006), Jankovská and Komárek (2000) and Shumilovskikh et al. (2015). Microcharcoal particles were counted along with the pollen. The microcharcoal particles were grouped into four size classes: 10-30 µm, 30-70 µm, 70-100 µm and >100 µm (Rull, 2009). The aboreal pollen (AP) + non-aboreal pollen (NAP) sum was used for percentage calculations. The pollen diagram was stratigraphically ordered and zoned with Constrained Cluster Analysis (CONISS) and divided into local pollen assemblage zones.

*Testate amoebae*

Testate amoebae were extracted using a modified version of Booth et al. (2010). Peat samples were placed in boiling water for 15 minutes and shaken. Extracts were passed through a 300 µm sieve, back-sieved at 15 μm and allowed to settle before sub-samples were used to make slides for microscopy. 100 to 200 amoebae were counted and identified to species level or ‘type’ in each sample using high-power transmitted light microscopy at 200 to 400x magnification. For further detailed information on taxonomy and sources used see Swindles et al. (2015b).

*Geochemical analysis*

Bulk density was calculated by dividing sample mass after freeze-drying by volume (Chambers et al., 2011), with change in sample mass after drying determining the moisture content. C and N were measured on a Thermo Scientific Flash 2000 Series CHNS/O Analyser. Carbon density (g C cm-3) was calculated by multiplying bulk density with percentage carbon content, and carbon accumulation rates were calculated using the age depth model described above (Charman et al., 2013).

*Data presentation*

The results of plant macrofossils, pollen, testate amoebae records, and geochemical analysis (Fig. 4-8), were presented in the form of diagrams drawn with the C2 graphics program (Juggins 2003).

**Results**

*Lithology, chronology, and peat accumulation rate*

Despite the similar length of cores obtained in this study, the Marooned core has a much older basal date (38 cm = 2650 cal yr BP) when compared to the Stordalen core (25 cm = 800 cal yr BP) (radiocarbon and 210Pb data for both profiles are presented in Table 2). This means the mean peat sedimentation rate for the entire period at Marooned is slower (~0.14 mm/year) than that at Stordalen (~0.31 mm/year).

The bottom part of both the Marooned and Stordalen profiles consists mainly of herbaceous peat, formed by *Carex* sp. (Table 3). At Marooned, herbaceous-moss peat (including brown mosses) accumulated between 2650 and 2250 cal yr BP, between 2250 and 1500 cal yr BP the peat layer was mainly composed of *Sphagnum fuscum* and *Sphagnum magellanicum*. *S. fuscum* was a dominant peat-forming species after 1500 cal yr BP. In the case of Stordalen, herbaceaous peat accumulated between ca. 900 and 280 cal yr BP, while between ca. 280-150 cal yr BP the peat was composed mainly of *Drepanocladus* sp. and *Sphagnum lindbergii*. Peat accumulated since 150 cal yr BP consists of *Sphagnum balticum* and *Polytrichum commune* macrofossils in the latter site.

*Tephra (Fig. 3)*

The top 25 cm of peat at the Stordalen peatland contains one tephra layer (SD-1). SD-1 is at 23 cm depth and contains tephra shards matching the major element geochemistry of glass from the eruption of Hekla in AD 1158 (Pilcher *et al*., 2005; Thorarinsson, 1967) (Fig. 3). This tephra can be historically dated and provides a precise chronological tie point for the age of peat at the top of the Stordalen profile.

Two tephra layers (MR-1 = 70 cm, MR-2 = 85 cm) were identified in the top 1 m of peat at Marooned. MR-1 contains glass shards matching the geochemistry of glass from the Hekla-S/Kebister eruption (~3720 cal yr BP) (Wastegård et al., 2008). MR-2 contains glass shards matching the geochemistry of glass produced during the eruption of Hekla 4 (~4287 cal yr BP) (Pilcher *et al*., 1995).

*Plant macrofossils*

Four zones in the local vegetation development were visually delimited at Marooned peatland (Fig. 4A). In the first zone MA-ma-1 (2650-2250 cal yr BP) *Carex* sp. with brown mosses was dominant. The second zone MA-ma-2 (2250-600 cal yr BP) contained small amounts of *Betula nana*, *Empetrum nigrum* and *Andromeda polifolia*, but is characterised by the dominance of *Sphagnum fuscum* and *S. magellanicum*. The third zone (MA-ma-3,600- -5 cal yr BP) is dominated by *S. fuscum*. *Polytrichum strictum*, *Empetrum nigrum* and *Andromeda polifolia* were also present in this zone. In the fourth zone MA-ma-4 (-5- -62 cal yr BP) *S. fuscum* was the dominant species. For the first time ca. -10 cal yr BP *Dicranum elongatum* appears. A shrub layer is represented by the presence of *Betula nana* and *Empetrum nigrum.*

Three phases in the local vegetation development were visually delimited at the Stordalen peatland (Fig. 4B). The first zone ST-ma-1 (ca. 900-280 cal yr BP) is characterised by the continuous presence of vegetative Cyperaceae macrofossils and *Carex* sp. fruits. Ca. 600 and 300 cal yr BP *Andromeda polifolia* seeds were found. In the bottom part of the second stage ST-ma-2 (280-150 cal yr BP) *Drepanocladus* sp. was the dominant species. *Sphagnum lindbergii* played a major role at ca. 220 cal yr BP. In the third zone ST-ma-3 (150-62 cal yr BP) *Sphagnum balticum* was dominant. Since ca. 100 cal yr BP *Polytrichum commune* appeared. In the most upper part of the sequence *Andromeda polifolia* macrofossils re-appeared.

*Pollen*

Four phases in the regional and local vegetation development were statistically delimited at Marooned peatland (Fig. 5). The first phase MA-po-1 (2650-2300 cal yr BP) is characterised by the highest presence of Cyperaceae pollen (up to 10%) and by the occurrence of *Menyanthes trifoliata* and *Aster* type, which were present only in this zone. Among non-pollen palynomorphs *Botryococcus, Rhabdocoela* and copepod spermatophores were present. In the second phase (2300-1000 cal yr BP) there is a peak in *Salix* (up to 15%) and *Rubus chameomorus* (up to 10%). *Empetrum/Ledum*, Asteraceae, and *Arctostaphylos* appeared. In the third zone MA-po-3 (1000-25 cal yr BP) there is a peak of Ericaceae (up to 30%) ca. 450 cal. BP, and ca. 5 cal yr BP *Picea* increased (up to 2%), and *Rubus chamaemorus* (up to 5%). *Thalictrum, Calluna, Equisetum*, and palynomorphs such as the shells of *Habrotrocha angusticollis* and ascospores of Xylariaceae were present. Numerous fruit bodies of microthyriaceous fungi were also noted in this zone. The middle part of this zone also contains abundant microcharcoal. In the fourth zone MA-po-4 (-25- -62 cal yr BP) *Picea* inceased up to 3%, and *Pinus* up to 87% together with an increase in the role of Filicales monoletae, Ericaceae, and *Arctostaphylos*.

*Testate amoebae*

Two phases in the testate amoebae sequence were visually delimited at Marooned (Fig. 6A). In first zone MA-ta-1 (2650-30 cal yr BP) *Diffulugia pristis* type (up to 30%), *Diffulugia pulex* (up to 40%) and *Nebela militaris* (up to 25%) were the dominant taxa. Reconstructed water table depth ranged between 22 and 28 cm below the peatland surface. During the second zone MA-ta-2 (30-62 cal yr BP) *Nebela militaris* increased to 40%. The upper part of this zone is characterised by increases in the abundance of *Hyalosphenia elegans* and *H. papilio.* At ca. 5 cal yr BP there are peaks of *Archerella flavum* (up to 17%), and at ca. -40 cal yr BP *Euglypha tuberculata* (up to 12%). Reconstructed water table depth in this zone ranged between 21 and 28 cm below the peatland surface. Overall, the water table reconstruction suggests relatively dry conditions throughout the profile.

Three phases in the testate amoebae succession were visually delimited at Stordalen (Fig. 6B). The first phase ST-ta-1 (ca. 900-480 cal yr BP) is characterised by *Trigonopyxis acrula* type (up 65%) and deep, stable reconstructed water table ca. 35 cm. In the next phase ST-ta-2 (480-320 cal yr BP) there in an increase in the abundance of *Archerella flavum, Ansulina scandinavica, Hyalosphenia papilio*, and *Placocista spinosa* type. In the upper part of phase ST-ta-2 (480-320 cal yr BP) *Nebela griseola* appears for the first time (up 20%) and reconstructed water table indicates a fluctuating water table. It gets wetter from ca. 34 to 15 cm, then dryer to 25 cm and again towards wetter up to 8 cm in the most upper part. In the third phase St-ta-3 (320-62 cal yr BP) *Archerella flavum* increases up to 65% and *P. spinosa* type up to 27%. Reconstructed water table ranged between 8 and 18 cm. Overall, the water table reconstruction suggests a shift from dry to wet conditions (a wet shift) in this peat profile.

*Geochemical analysis (Fig. 7 and Fig. 8)*

The bulk density values for Marooned and Stordalen are typical of northern peatlands (Loisel et al., 2014) but vary noticeably during the different phases of peatland development. In general, values are higher for the fen phase when peat is mainly composed of *Cyperaceae*, while the values decrease for the more ombrotrophic phase, when the main peat forming plants are mosses, which tend to form a less dense peat. This pattern may also be due partly to compaction. The values of C:N show the opposite pattern, with low values in the deeper peat, during the more minerotrophic phase and higher values during the ombrotrophic phase.

*Carbon accumulation rates*

*Average carbon accumulation rates are very different between the two peatlands, Stordalen has a lower average rate of carbon accumulation (8.3 ± 5.9 gC m-2 yr-1) while Marooned has a much higher mean carbon accumulation rate (61.5 ± 35.8 gC m-2 yr-1). This trend is contrary to the sedimentation rate trend which was higher for Stordalen. Both sites have high variability of carbon accumulation rates during the studied time periods, Marooned rates range from 0 to 128 gC m-2 yr-1 and are lowest at zone B (ca. 500 yr BP – 2250 yr BP) and highest in the boundary between D and C zones (ca. 50 yrs BP). The rates at Stordalen vary from 0 to 27 gC m-2 yr-1 and are generally much slower than at Marooned. The carbon accumulatino rate at Stordalen is highest in the boundary between zones B and C (ca. 300 BP) and lowest at the boundary between A and B (ca. 500 BP).*

**Discussion**

***Drivers of development of the subarctic peatland communities in Abisko region***

The accumulation of organic sediments in Marooned took place at the coring point but in our reconstructions we focus on the last 2650 cal yr BP. While in Stordalen peat accumulation commenced ca. 4,700 cal BP as a result of terrestrialisation (Kokfelt et al., 2010), our reconstructions cover ca. 900 cal yr BP. In the bottom part of both peat sequences the main peat-forming plants included Cyperaceae (Fig. 7, phase A, Fig. 8, phase A and B). The presence of *Carex* fruits and rootlets, as well brown mosses in both sites indicate that during this period the peatlands were operating as fens, a widespread wetland type in the permafrost area of the northern hemisphere (Vardy et al., 1998; Kuhry, 2008; Teltewskoi et al., 2016, Treat et al., 2016) and both sites present high carbon accumulation rates during this period, especially Marooned. Pollen data indicate that between 2650 and 2300 cal yr BP the non-peatland community at Marooned was dominated by *Betula*. Previous research indicates that the role of *Betula* in regional plant communities gradually increased since ca. 4100 cal yr BP (Bigler et al., 2002), as a result of climate cooling in northern Fennoscandia (Berglung et al., 1996; Korhola et al., 2000).

Around 2250 cal yr BP, a new plant community dominated by *Sphagnum fuscum* and *S. magellanicum* developed at Marooned, these species indicate a transition from groundwater fed fen to rainwater fed bog (Hughes, 2000), due to autogenic plant succession toward hummock development (Malmer, 2014). *Sphagnum fuscum,* is a typical ombrotrophic species and usually occurs on dry areas of the bog (Hölzer 2010; Laine et al. 2011), but can also build high hummocks in fens (Laine et al., 2011; Hajkova et al., 2012). Autogenic plant community changes from fen to dry bog may be supported by appearance of *Rubus chamaemorus* and *Ledum/Empetrum* pollen. These plants usually grow on the top of hummocks in ombrotrophic peatlands in subarctic zone in Scandinavia (Zuidhoff and Kolstrup, 2005). Further evidence of drying is provided by testate amoebae communities which indicate dry hydrological conditions with a reconstructed water table depth of between 24 and 30 cm below the peat surface in the first ombrotrophic stage (Fig. 7, zone B). In terms of carbon balance in this new system, the period is characterized by a hiatus in the carbon accumulation, this means rates of decomposition were similar l to the photosynthetic rates and the system stopped being a carbon sink. The development of poor fen and then bog communities ca. 2250 cal yr BP may also be caused by permafrost aggradation and physical separation of this part of peatland from the groundwater (Vardy et al., 1998). According to Kokfelt et al. (2010) one period of the permafrost phases have occurred ca. 2,650–2,100 cal BP in the Abisko region.

Stable hydrological conditions, DWT ca. 23 cm in Marooned were inferred between ca. 2000 and 50 cal yr BP (Fig. 7, zone B and C). In this period *S. fuscum, S. magellanicum* were dominant species, but also *Dicranum undulatum* (formerly *Dicranum bergeri*) and then ca. 500 cal yr BP *Polytrichum strictum* appeared, with a brief high peak in carbon accumulation rates. The last both species usually occur in dry places in bogs, often on hummocks (Hájková and Hájek, 2004; Hedenäs and Bisang, 2004).

A different hydrological pattern was apparent at Stordalen, where there was trend toward wetter conditions, from ca. 450 to 400 cal yr BP (WTD from 35 to 16 cm), before a shift to dryer condictions from ca. 400 to 330 cal yr BP and reverting to wet conditions from 330 cal yr BP to present day (Fig. 8, zone B). In this time period of unstable hydrological conditions (Zone B) plant assemblages dominated by *Carex* sp. are observed, indicative of poor-fen conditions. From the start to the finish of this time period (500-300 BP, Zone B), carbon accumulation rates increase. Hydrological changes between 500 and 300 cal yr BP in Stordalen may coincide with hydrological shifts caused by regional scale climatic changes during Little Ice Age (LIA) which have been documented in various part of Europe (Mauquoy et al., 2002, 2004, 2008; Swindles et al., 2007; De Vleeschouwer et al., 2011; Gałka and Lamentowicz, 2014; Gałka et al., 2014; Feurdean et al., 2015). During the LIA moisture patterns differed between NE Europe and CE Europe. NW Europe and Scandinavia incurred shifts toward wetter climate (Barber et al., 2003; Charman et al., 2006; Mauquoy et al., 2004, 2008; Väliranta et al., 2007; Swindles et al., 2007, 2010; Knapp et al. 2011) whilst CE Europe tended toward dryer conditions (Gałka et al., 2014; Feurdean et al., 2015).

Hydrological shifts for the duration of LIA have been not observed in Marooned. Differences in the hydrological pattern in Marooned and Stordalen may partly result from autogenic drivers of peatland development. Plant autogenic succession is also an important factor, that should be considered during peatland development (Swindles et al., 2012, Loisel and Yu, 2013; Gałka et al., 2016). The lack of a clear hydrological signal at Marooned peatland during LIA might be explained by the dominance of *Sphagnum fuscum* which has a wide ecological range in hydrological conditions (Rydin and McDonald, 1985) and therefore may not be sensitive to changes in climate and hydrological conditions, such as those during the LIA. Another reason for the lack of visible hydrological changes during LIA may be associated with a very low rate of peat accumulation in Marooned.

Between 500 and -10 cal yr BP we noted changes in local plant communities, mainly shrubs, that coincide to microcharcoal increase in Marooned (Fig. 7). The appareance of *Polytrichum strictum*, and increasing role of *Ericaceae, Calluna vulgaris*, and since ca. 40 cal yr BP, *Rubus chamaemorus* and *Empetrum/Ledum* pollen may indicate the lowering of water table which favoured shrub community development (Zuidhoff and Kolstrup, 2005).

The reconstructed water table between ca. 500 and 50 cal yr BP is low and stable at ca. 22 cm below the surface. Further lowering to 28 cm below the peatland surface took place after ca. 50 cal yr BP (Fig. 7). On the one hand, the lack of macrocharcoal (eg. burned branches of shrubs or *Sphagnum* leaves) in the *Sphagnum fuscum* peat layer indicates that fire was most likely not present at the site, but possibly in the surrounding environment. Furthermore, it has been suggested that fires are generally not an important driver in modifying *Sphagnum* communities (Kuhry, 1994; Magnan et al., 2012; Sillasoo et al., 2011; Gałka et al., 2015). Fire may be favored by low water table llevels in some peatlands which may lead to widespread thaw subsidence of permafrost terrain (Jones et al., 2015). Additionally, ﬁre is known to lower water reserves in adjacent unburned wetland areas (Watts et al., 2015).

The hydrological similarity between the two sites is clear for the last few decades. In both sites there is a trend toward dryer conditions (lowering water table) (Fig. 7, upper part of zone E and Fig. 8, upper part of zone D). In Marooned the deepening of water table coincides with the development of shrub communities including *Betula nana* and *Calluna vulgaris,* and in the case of Stordalen, this drying corresponds with the presence of *Polytrichum commune* and a significant increase of *Andromeda polifolia*. The trend to dry hydrological conditions marked by the appearance of *Polytrichum strictum* and *Dicranum elongatum* has been documented in previous studies at Stordalen (Kokfelt et al., 2010). The increasing role of shrub communities in the Abisko region may be also have been caused by modern climate warming, which favours the expansion of shrubs in the arctic zone (Myers-Smith et al., 2011; Loranty and Goetz 2012; Ropars and Boudreau, 2012).

Palaeoecology of *Sphagnum lindbergii*

*Sphagnum lindbergii* is a circumpolar species, that occurs in peatlands or boggy depressions located in arctic, subarctic and boreal zones (Daniels and Eddy, 1990; Laine et al., 2011) and in high altitude peatlands further south eg. Sudety Mountains, Poland (Wojtuń et al., 2013), Black Forest Mountains, Germany (Hölzer 2010), Rocky Mountains, Wyoming, USA (Lemly et al., 2007). *S. lindbergii* occurs in oligotrophic to mesotrophic habitats from pools to lawns in bogs and poor-fens, often bordering nutrient-poor flushes and lakes (Foster 1984; Laine et al., 2011; Wojtuń et al., 2013). It grows together with *S. riparium, S. balticum, S. flexuosus,* and *S. majus* (Laine et al., 2011; Hölzer, 2010). Although *S. lindbergii* is very common in arctic and subarctic zone, it is one of the rarest *Sphagnum* species noted in its fossilised state. In Stordalen *S. lindbergii* grew together with *Drepanoclaus* sp., *Andromeda polifolia* and *Carex* ssp. for ca. 50 years and disappeared with the appearance and spread of *Sphagnum balticum.* The depth of the water table during the presence of *S. lindbergii* was ca. 10 cm (Fig. 8), indicative of a wet poor-fen. In the *S. lindbergii* population dominant species of testate amoebae were *Archerella flavum, Placocista spinosa* type, *Hyalosphenia papilio,* and *Nebela tincta*. These testate amoebae species usually occur in wet habitats, where the pH ranges…… (?????, reference). What is interesting, is that the disappearance of *Cyclopyctris arceloides,* and *Difflugia pristice* type coincided with appearance and increase of *S. lindbergii*. It may be proved, that…….. In previous palaeoecological studies conducted in Stordalen peatland (Kokfelt et al., 2010), *S. lindbergii* was accumulated on *Drepanocladus exannulatus* and sedge peat layer and from ca. 700 to 120 cal yr BP it was dominant species in plant assemblage. Presently, at this point *S. lindbergii* builds communities with *Polytrichum strictum* and *Dicranum elongatum* (Kokfelt et al., 2010). In the Hudson Bay Lowlands, Canada, *S. lindbergii* was found in two peat profiles (Kuhry, 2008). In first site *S. lindbergii* remains were identified in a 20 cm thin peat layer accumulated between ca. 500 cal yr BP to 1960 AD during a wet poor-fen stage (Kuhry 2008). It appeared after a phase dominated by *Drepanocladus* sp. and *Scorpidium* sp. *S. lindbergii* occured there together with *S. jensseni/balticum, S. magellanicum,* *S. riparium* and disappeared after spreading of *S. cf. fuscum* and *Polytrichum* sp. While in second Canadian site *S. lindbergii* macrofossils with *S. jensseni/balticum*, *S. riparium* and *Drepanocladus* sp. between 2250-800 cal yr BP in peat layer 43 cm thick was found and re-appeared ca. 350 cal yr BP (Kuhry 2008). The mountain peatland in Sudety Mts. located in subalpine belt is the next site where *S. lindbergii* remains have been documented (Gałka and Fiałkiewicz–Kozieł, unpubl. data). In first coring point *S. lindbergii* remains occured in 15 cm thick peat layer accumulated after ca. 50 cal yr BP. *S. lindbergii* appeared after *S. russowii* and *S. majus* presence and occurred together with *S. balticum, S. russowii, Eriophorum angustifolium, Polytrichum strictum,* then disappeared after *S. russowii* increase. At the second coring point in Sudety Mts. *S. lindbergii* remains in 17 cm thick peat layer after ca. 50 cal yr BP were accumulated. It appeared at the same time as *S. russowii*, and disappeared with the appearance of *S. fuscum/rubellum* and increased role of *S. russowii.* Then reappeared and disappeared by presence of *P. strictum, S. balticum* and increase of *S. russowii.* Based on above presented fossil data of *S. lindbergii,* may be concluded, that fossil habitat of this species was not different from the habitat identified in present data. *S. lindbergii’s* ecological requirements and accompanying plants was the same as today in the northern hemisphere. What’s more the presence of *S. lindbergii* macrofossils in a rather thin peat layer prove that this species is not very competitive and mainly plays role as a transitional species during fen to bog transition. Furthermore, analysis of fossil sites with *S. lindbergii* shows that it is sensitive to changes in water table depth and disappeared with the appearance of *S. fuscum, S. russowii* or *Polytrichum strictum.* These last three species usually grow in drier places in peatlands, like hummocks (Smith 2004; Hölzer, 2010, Laine et al. 2011). Therefore, in palaeoecological reconstructions the presence of *S. lindbergii* can be indicative of wet phases in peatland development which most likely coincide with wet climatic conditions. However, the autogenic role during *Sphagnum* succession with presence of *S. lindbergii* should also be considered during reconstructions, especially when it appeared in transition zone between fen and bog.

***Implications of tephra layers for improvement of tephra dispersal maps in Scandinavia***

The peatlands included in this study contain a total of three tephra layers, all tephra are of Icelandic origin, produced by different eruptions of the same volcano (Hekla) and have been previously detected in northern Europe. The only tephra layer identified in the top 25 cm of peat at Stordalen was SD-1, correlated to the eruption of Hekla 1158. Until recently, Hekla 1158 had been reported at only one site in northern Europe (Pilcher et al., 2005). However, this discovery and recent identifications of the Hekla 1158 tephra at two other sites in northern Sweden (Watson et al., In Press) indicate that the Hekla 1158 tephra could provide an important dating isochron in northern Scandinavia.

Despite the close proximity of the Marooned and Stordalen peatlands, tephra shards from the eruption of Hekla 1158 were not detected in the Marooned peatland. However, two tephra layers correlated to the eruptions of Hekla-S (=MR-1) and Hekla 4 (=MR-2) were identified. The identification of MR-1 represents the most northerly occurrence of the Hekla-S tephra which has been identified at ~20 sites in northern Europe (Lawson et al., 2012). MR-2 contains glass shards matching the geochemistry of glass from the most widespread tephra deposit in northern Europe, Hekla 4 (4287 cal yr BP).

**Summary**

Multi-proxy palaeoecological investigations provide important data for understanding ecological effects of climate changes. Long term ecological studies provide valuable proxy to insight into peatland ecosystem response to past environmental changes.

Climate model projections suggest continued marked temperature increases that can lead to further environmental changes in permafrost area. It requires understanding of hydrological and ecological processes to predict response this ecosystem to climatic changes.

THIS DOES NOT REALLY SUMMARISE THE WHOLE PAPER.

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**References**

Appleby PG. 2001. Chronostratigraphic techniques in recent sediments in *Tracking environmental change using lake sediments Vol. 2: Physical and geochemical methods* (eds Last, W. M. and Smol, J. P.) 171–203 (Springer, 2001).

Barber KE, Chambers FM, Maddy D 2003. Holocene palaeoclimates from peat

stratigraphy: macrofossil proxy climate records from three oceanic raised bogs in England and Ireland. *Quaternary Science Reviews* **22**: 521–539.

Barber KE, Chambers FM, Maddy D. 2004. Late Holocene climatic history of

northern Germany and Denmark: peat macrofossil investigations at Dosenmoor,

Schleswig-Holstein, and Svanemose, Jutland. *Boreas* **33**: 132-144.

Berglund BE, Barnekow L, Rammarlund D, Sandgren P, Snowball IF. 1996. Holocene forest

dynamics and climate changes in the Abisko area, northern Sweden - the Sonesson model of vegetation history reconsidered and confirmed. *Ecological Bulletins* **45**: 15-30.

Berglund BE, Ralska-Jasiewiczowa M. 1986. Pollen analyses and pollen diagrams. In: *Handbook of Holocene palaeoecology and palaeohydrology*, Berglund BE (ed). John Wiley: Chichester; 455-484.

Beug HJ. 2004. *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. Pfeil: München.

Blaauw, M., 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. Quaternary Geochronology **5**: [512-518](http://dx.doi.org/10.1016/j.quageo.2010.01.002)

Blockley SPE, Pyne-O’Donnell SDF, Lowe JJ, Matthews IP, Stone A, Pollard AM, Turney CSM, Molyneux EG. 2005. A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. *Quaternary Science Reviews* **24**: 1952-1960.

Booth, R.K., Lamentowicz, M., Charman, D.J., 2010. Preparation and analysis of testate amoebae in peatland paleoenvironmental studies. Mires and Peat 7, Article 2, 1-7.

Callaghan TV, Bergholm F, Christensen TR, Jonasson C, Kokfelt U, Johansson M., 2010. A

new climate era in the sub-Arctic: Accelerating climate changes and multiple impacts. Geophysical Research Letters 37: L14705. DOI: 10.1029/2009GL042064

Carcaillet C, Richard PJH. 2000. Holocene changes in seasonal precipitation highlighted by ﬁre incidence in eastern Canada. *Climate Dynamics* **16**: 549–559.

Carcaillet C, Bergman I, Delorme S, Hornberg G, Zackrisson O. 2007. Long-term fire frequency not linked to prehistoric occupations in northern Swedish boreal forest. *Ecology* **88**(2): 465–477.

Chambers FM, Beilman DW, Yu Z. 2011. Methods for determining peat humification

and for quantifying peat bulk density , organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics. *Mires and Peat* **7**: 1-10.

Charman, D. J. et al. 2013. Climate-related changes in peatland carbon accumulation during the last millennium. *Biogeosciences* **10**: 929–944.

Charman DJ, Blundell A, Chiverrell RC et al. 2006. Compilation of non-annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table reconstructions from northern Britain. *Quaternary Science Reviews* 25: 336–350.

Daniels RE, Eddy A. 1990. Handbook of European Sphagna. Institute of Terrestrial

Ecology. Natural Environment Research Council, London.

De Vleeschouwer F, Chambers FM, Swindles GT. 2010. Coring and sub-sampling of

peatlands for palaeoenvironmental research. *Mires and Peat* **7:** 1–10.

Dugmore AJ, Newton AJ. 1992. Thin tephra layers in peat revealed by X-Radiography. *Journal of Archaeological Science* **19**: 163-170.

Feurdean A, Gałka M, Kuske E et al. (2015) Last millennium hydroclimate variability in the

Northern Carpathians (Romania) based on multi-proxy approach. *The Holocene* 25: 1179–1192.

Gałka M, Tobolski K, Górska A et al. (2014) Disentangling the drivers for the development of a Baltic bog during the ‘Little Ice Age’ in northern Poland. *Quaternary International* 328–329: 323–337.

Gałka M, Tantau I, Ersek V, Feurdean A. 2016. A 9000 year record of cyclic vegetation changes identified in a montane peatland deposit located in the Eastern Carpathians (Central-eastern Europe): Autogenic succession or regional climatic influences? *Palaeogeography, Palaeoclimatology, Palaeoecology* 449: 52–61.

Gao Y, Couwenberg J. 2015. Carbon accumulation in a permafrost polygon peatland:

steady long-term rates in spite of shifts between dry and wet conditions. *Global*

*Change Biology* **21**: 803–815. DOI:10. 1111/gcb.12742.

Hájková P, HájekM. 2004. Bryophyte and vascular plant responses to base-richness and

water level gradients in western Carpathian *Sphagnum*-rich mires. Folia Geobotanica **39**: 335–351.

Hájková P, **Grootjans AB, Lamentowicz M, Rybníčková E, Madaras M, Opravilová V,**

**Michaelis D,** Hájek M, **Joosten H, Wołejko L. 2012.** How a *Sphagnum fuscum*-dominated bog changed into a calcareous fen: the unique Holocene history of a Slovak spring-fed mire. Journal of Quaternary Science **27**: 233-243.

Hayward C. 2012. High spatial resolution electron probe microanalysis of tephras and melt inclusions without beam-induced chemical modification. *Holocene,* 22: 119-125.

Hedenäs L, Bisang I. 2004. Key to European *Dicranum* species. *Herzogia* **17**: 179–197.

Hölzer, A., 2010. Die Torfmoose Südwestdeutschlands und der Nachbargebiete. Weissdorn

Verlag Jena, Jena.

Hughes PDM. 2000. A reappraisal of the mechanisms leading to ombrotrophy in British

raised mires. *Ecology Letters* **3**:7–9.

Jankovská V, Komárek J. 2000. Indicative value of *Pediastrum* and other coccal green algae in palaeoecology. *Folia Geobotanica* **35**: 59–82.

Jones BM, Grosse G, Arp CD, Miller E, Liu L, Hayes DJ, Larsen CF. 2015. Recent Arctic

tundra fire initiates widespread thermokarst development. *Scientific Reports* 5:15865. DOI: 10.1038/srep15865.

Johansson M, Christensen TR, Akerman HJ, Callaghan TV. 2006. What determines the

current presence or absence of permafrost in the Torneträsk region, a sub-arctic landscape in northern Sweden? *Ambio* **35:** 190–197.

Juggins, S., 2003. C2 User Guide. Software for Ecological and Palaeoecological Data

Analysis and Visualisation. University of Newcastle, Newcastle Upon Tyne, UK, 69 pp.

Kokfelt, U. *et al.* 2009. Ecosystem responses to increased precipitation and permafrost decay

in subarctic Sweden inferred from peat and lake sediments. *Global*

*Change Biology* **15:** 1652–1663.

Korhola A, Weckstrlm J, Holnstrim L, Eristl P. 2000. A quantitative climatic record from

diatoms in northern Fennoscandia. *Quaternary Research* **54**: 284-94.

Kuhry P. 1994. The role of fire in the development of *Sphagnum* dominated peatlands in

western boreal Canada. *Journal of Ecology* **82**: 899–910.

Kuhry P. 2008. Palsa and peat plateau development in the Hudson Bay Lowlands, Canada:

Timing, pathways and causes. *Boreas* **37**: 316–327, doi:10.1111/j.1502-3885.2007.00022.x.

Kuhry P, Grosse G, et al. 2013. Characterisation of the permafrost carbon pool. *Permafrost*

*and Periglacial Processes* **24**: 146–155.

Laine J, Harju P, Timonen T, Laine A, Tuittila E.-S, Minkkinen K, Vasander H.

2011. The Intricate Beauty of *Sphagnum* Mosses – A Finnish Guide to Identification. 2. University of Helsinki Department of Forest Sciences Publications, pp. 1–191.

Lamarre, A., Garneau, M., Asnong, H., 2012. Holocene paleohydrological reconstruction

and carbon accumulation of a permafrost peatland using testate amoeba and macrofossil analyses, Kuujjuarapik, subarctic Quebec, Canada. *Review Palaeobotany and Palynology* **186**: 131–141.

Lamarre A, Magnan G, Garneau M, Boucher E. 2013. A testate amoeba-based transfer

function for paleohydrological reconstruction from boreal and subarctic peatlands in

northeastern Canada. *Quaternary International* **306**: 88–96.

Lawson IT, Swindles GT, Plunkett G, Greenberg D. 2012. The spatial distribution of Holocene cryptotephras in north-west Europe since 7 ka: implications for understanding ash fall events from Icelandic eruptions. *Quaternary Science Reviews,* **41**: 57-66.

Lemly JM, Andrus RE, Cooper DJ. 2007. *Sphagnum lindbergii* Schimp. in Lindb.

and other new records of *Sphagnum* in geothermal fens, Yellowstone National Park, Wyoming, USA. *Evansia* **24**: 31-33.

Ĺkerman H J, Johansson M. 2008. Thawing permafrost and thicker active layers in sub-arctic

Sweden. *Permafrost and Periglacial Processes* **19:** 279–292.

Loisel J, Yu Z. 2013. Surface vegetation patterning controls carbon accumulation in

peatlands. *Geophysical Research Letters* **40**: 1–6. http://dx.doi.org/10.1002/grl.50744.

Loisel, J., Z. Yu, D. Beilman, P. Camill, J. Alm, M.J. Amesbury, D. Anderson, S. Andersson, C. Bochicchio, K. Barber, L.R. Belyea, J. Bunbury, F.M. Chambers, D.J. Charman, F. De Vleeschouwer, B. Fiałkiewicz-Kozieł, S.A. Finkelstein, M. Gałka, M. Garneau, D. Hammarlund, W. Hinchcliffe, J. Holmquist, P. Hughes, M.C. Jones, E.S. Klein, U. Kokfelt, A. Korhola, P. Kuhry, A. Lamarre, M. Lamentowicz, D. Large, M. Lavoie, G. MacDonald, G. Magnan, M. Mäkilä, G. Mallon, P. Mathijssen, D. Mauquoy, J. McCarroll, T.R. Moore, J. Nichols, B. O’Reilly, P. Oksanen, M. Packalen, D. Peteet, P.J.H. Richard, S. Robinson, T. Ronkainen, M. Rundgren, A.B.K. Sannel, C. Tarnocai, T. Thom, E.-S. Tuittila, M. Turetsky, M. Väliranta, M. van der Linden, B. van Geel, S. van Bellen, D. Vitt, Y. Zhao, and W. Zhou, 2014: A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. Holocene **24:** 9: 1028-1042, doi:10.1177/0959683614538073.

Loranty M M, Goetz S J. 2012. Shrub expansion and climate feedbacks in Arctic tundra. Environmental Research Letters **7**: 011005. doi:10.1088/1748-9326/7/1/011005.

**Lupascu, M**., Wadham, J.L., Hornibrook, E., Pancost, R.D. 2012. Temperature sensitivity of

methane production in the permafrost active layer at Stordalen, Sweden: A comparison with non-permafrost northern wetlands. *Arctic, Antarctic and Alpine Research* **44**: 469-482.

**Lupascu M,** Wadham JL, Hornibrook E, Pancost RD. 2014. Methanogens Biomarkers

variations in active permafrost layers during a single melting season. *Permafrost and Periglacial Processes* **25**: 1823-1832.

Magnan GM, Lavoie M, Payette S. 2012. Impact of fire on long-term vegetation

dynamics of ombrotrophic peatlands in northwestern Quebec, Canada. *Quaternary Research* 77: 110–121.

Malmer N. 2014. On the relations between water regime, mass accretion and formation of

ombrotrophic conditions in *Sphagnum* mires *Mires and Peat* **14**: 1–23. http://www.mires-and-peat.net/

Mauquoy D, van Geel B, Blaauw M et al. (2002. Evidence from northwest European bogs shows ‘Little Ice Age’ climatic changes driven by variation in solar activity. *Holocene* 12: 1-6.

Mauquoy D, van Geel B, Blaauw M et al. (2004) Changes in solar activity and Holocene climatic shifts derived from 14C wiggle-match dated peat deposits. *Holocene* 14: 45-52.

Mauquoy D, van Geel B. 2007. Mire and peat macros. In: Elias SA (ed.) *Encyclopedia of*

*Quaternary Science*. Amsterdam: Elsevier, pp. 2315–2336.

Mauquoy D, Yeloff D, van Geel B, Charman D, Blundell A. 2008. Two decadally resolved records from north-west European peat bogs show rapid climate changes associated with solar variability during the mid-late Holocene. *Journal of Quaternary Science* **23**: 745-763.

Mirek, Z., Piękoś-Mirkowa, H., Zając, A., Zając, M., 2002. Flowering Plants and

Pteridophytes of Poland. A Checklist. IB PAN, Kraków.

Mooney, S.D., Tinner W., 2011. The analysis of charcoal in peat and organic sediments.

Mires and Peat 7: Art. 9. (Online: http://www.mires-and-peat.net/pages/volumes/map07/map0709.php)

Myers-Smith IH, Forbes BC, et al. 2011. Shrub expansion in tundra ecosystems: dynamics,

impacts and research priorities. Environmental Research Letters **6**: 045509, doi:10.1088/1748-9326/6/4/045509.

Newton AJ, Dugmore AJ, Gittings BM. 2007. Tephrabase: tephrochronology and the development of a centralised European database. *Journal of Quaternary Science* **22**: 737-743.

Pilcher, J.R., Hall, V.A., McCormac, F.G., 1995. Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats. Holocene 5, 103-110

Pilcher J, Bradley RS, Francus P, Anderson L. 2005. A Holocene tephra record from the Lofoten Islands, Arctic Norway. *Boreas,* **34**: 136-156.

Rydin H, McDonald AJS. 1985. Tolerance of *Sphagnum* to water level. *Journal of*

*Bryology* **13**: 571–578.

Ropars P, Boudreau S. 2012. Shrub expansion at the forest–tundra ecotone: spatial

heterogeneity linked to local topography. Environmental Research Letters **7**: 015501, doi:10.1088/1748-9326/7/1/015501.

Rull V. 2009. New paleoecological evidence for the potential role of ﬁre in the Gran Sabana, Venezuelan Guayana, and implications for early human occupation. *Vegetation History and Archaeobotany* 18: 219-224.

Shemesh A, Rosqvist G, Rietti-Shati M, Rubensdotter L, Bigler C, Yam R, Karlen,

W. 2001. Holocene climatic change in Swedish Lapland inferred from an oxygen-isotope record of lacustrine biogenic silica. *The Holocene* **11**: 447-54.

Shumilovskikh LS, Schlütz F, Achterberg I, Kvitkina A, Bauerochse A, Leuschner HH. 2015. Pollen as nutrient source in Holocene ombrotrophic bogs. *Review of Palaeobotany and Palynology* **221**: 171–178.

Sillasoo U, Valiranta M, Tuittila E-S. 2011. Fire history and vegetation recovery in two raised

bogs at the Baltic Sea. *Journal of Vegetation Science* **22**: 1084–1093.

Smith, A.J.E., 2004. The Moss Flora of Britain and Ireland. Cambridge University

Press, Cambridge, 1113 p.

Sollid JL, Sřrbel L. 1998. Palsa bogs as a climate indicator: examples from Dovrefjell,

southern Norway. *Ambio* **27:** 287–291.

Stevens FL, Ryan MH. 1939. *The Microthyriaceae*. The University of Illinois Press: Urbana.

Stockmarr J. 1971. Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13:

615-621.

Swindles GT, Plunkett G, Roe HM. 2007. A multiproxy climate record from a raised bog in County Fermanagh, Northern Ireland: a critical examination of the link between bog surface wetness and solar variability. *Journal of Quaternary Science* **22**: 667-679.

Swindles GT, Blundell A, Roe HM et al. (2010) A 4500-year proxy climate record from peatlands in the North of Ireland: the identification of widespread summer `drought phases'? *Quaternary Science Reviews* **29**: 1577-1589.

Swindles GT, Morris PJ, Baird AJ, Blaauw M, Plunkett G. 2012. Ecohydrological feedbacks

confound peat-based climate reconstructions, *Geophysical Research Letters* **39**: L11401, doi:10.1029/2012GL051500.

Swindles, G.T., Morris, P.J., Mullan, D., Watson, E.J., Turner, T.E., Roland, T., Amesbury, M.J., Kokfelt, U., Schoning, K., Pratte, S., Gallego-Sala, A., Charman, D.J., Sanderson, N., Garneau, M., Carrivick, J.L., Woulds, C., Holden, J., Parry, L. and Galloway, J.M. 2015a. The long-term fate of permafrost peatlands under rapid climate warming. Scientific Reports 5, 17951.

Swindles, G. T. *et al.* 2015b.Evaluating the use of testate amoebae for palaeohydrological

reconstruction in permafrost peatlands. *Palaeogeography, Palaeoclimatology, Palaeoecology* **424**:111–122 (2015).

Swindles GT, De Vleeschouver F, Plunkett G. 2010. Dating peat profiles using tephra: stratigraphy, geochemistry and chronology *Mires and Peat,* **7**: 1-9.

Teltewskoi A, Beermann F, Beil I, Bobrov A, de Klerk P, Lorenz S, Lüder A,

Michaelis D, Joosten H. 2016. [4000 years of changing wetness in a permafrost polygon peatland (Kytalyk, NE Siberia): a comparative high-resolution multi-proxy study](http://onlinelibrary.wiley.com/doi/10.1002/ppp.1869/abstract). *Permafrost and Periglacial Processes* **27**: 76-95.

Thorarinsson, S., 1967. The eruptions of Hekla in historical times: A tephrochronological

study, The Eruption of Hekla 1947-48 I. *Societas Scientiarum Islandica*, p. 170

Turetsky MR, Wieder RK, Vitt DH. 2002. Boreal peatland C fluxes under varying

permafrost regimes. *Soil Biology and Biochemistry* **34**: 907–912.

Turetsky MR, Wieder RK, Vitt DH, Evans RJ, Scott KD. 2007. The disappearance

of relict permafrost in boreal North America: effects on peatland carbon storage

and fluxes. *Global Change Biology* **13**: 1922–1934.

Väliranta M, Korhola A, Seppä H et al. (2007) High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: a quantitative approach. *The Holocene* **17**: 1093-1107.

Van Geel B. 1978. A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands. *Review of Palaeobotany and Palynology* **25**: 1–120.

Van Geel B. 2001. Non-pollen palynomorphs. In *Tracking environmental change using lake sediments (terrestrial, algal and silicaceous indicators).* Smol JP, Birks HJB, Last WM (eds). Kluwer: Dordrecht; Vol. 3: 99–119.

Van Geel B, Aptroot A. 2006. Fossil ascomycetes in Quaternary deposits. *Nova Hedwigia* **82**: 313–329.

Van der Knaap WO, Lamentowicz M, van Leeuwen JFN, Hangartner S,

Leuenberger M, Mauquoy D, Goslar T, Mitchell EAD, Lamentowicz Ł,

Kamenik C. 2011. A multi-proxy, high-resolution record of peatland development

and its drivers during the last millennium from the subalpine Swiss Alps.

*Quaternary Science Reviews* **30**: 3467-3480.

Vardy SR, Warner BG, Aravena R. 1998. Holocene climate and the development of a

subarctic peatland near Inuvik, Northwest Territories, Canada. *Climate Change* **40**: 285–313.

Wastegård, S., Rundgren, M., Schoning, K., Andersson, S., Bjorck, S., Borgmark, A.,

Possnert, G., 2008. Age, geochemistry and distribution of the mid-Holocene Hekla-S/Kebister tephra. *Holocene* **18**, 539-549.

Watson EJ, Swindles GT, Lawson IT, Savov IP. In Press. Do peatlands or lakes provide the most comprehensive distal tephra records? *Quaternary Science Reviews*.

Wojtuń B, Sendyk A, Martyniak A. 2013. *Sphagnum* species along environmental

gradients in mires of the Sudety Mountains (SW Poland). *Boreal Environmental Research* **18**: 74–88.

Watts AC, Schmidt CA, McLaughlin DL, Kaplan DA. 2015. Hydrologic implications of smoldering fires in wetland landscapes. *Freshwater Science* **34**(4): 1394–1405.

Yu ZC. 2012. Northern peatland carbon stocks and dynamics: a review. *Biogeosciences* **9**:

4071– 4085.

Zoltai SC 1993. Cyclic development of permafrost in the peatlands of Northwestern Alberta,

Canada. *Arctic, Antarctic, and Alpine Research* **25**: 240–246.

Zuidhoff FS, Kolstrup E. 2000. Changes in palsa distribution in relation to climate change in

Laivadalen, northern Sweden, especially 1960–1997. *Permafrost and Periglacial Processes* **11**: 55–59.

Zuidhoff FS, Kolstrup E. 2005. Palsa Development and Associated Vegetation in Northern

Sweden. *Arctic, Antarctic, and Alpine Research* **37**:49–60.

Malmer, N. & Wallén, B. Peat Formation and Mass Balance in Subarctic Ombrotrophic Peatland around Abisko, Northern Scandinavia. *Ecol. Bull.* **45,** 79–92 (1996).

Figure caption

Figure 1. Setting of the study site.

Figure 2. Age-depth model of the peat profile in Marooned and Stordalen peatlands.

Figure 3. Geochemical bi-plots of major elements of tephra shards (glass) from Stordalen and Marooned plotted against envelopes for the glass geochemistry of known tephras based on type data from the Tephrabase database. All data have been normalised.

Figure 4. Percentage plant macrofossils diagram presenting local vegetation development in Marooned and Stordalen peatlands.

Figure 5. Percentage pollen diagram presenting local and regional vegetation changes in Marooned peatland

Figure 6. Percentage testate amoebae diagram presenting changes in testate amoebae communities and water table changes in Marooned and Stordalen peatlands.

Figure 7. Comparison of chosen taxa from three: plant macrofossils, pollen, and testate amoebae with the quantitative reconstruction of depth water table (DWT) and results of geochemical analysis in Marooned peatland.

Figure 8. Comparison of chosen taxa from two data set: plant macrofossils and testate amoebae with the quantitative reconstruction of depth water table (DWT) and results of geochemical analysis in Stordalen peatland.