

Vegetation Succession, Carbon Accumulation and Hydrological Change in Subarctic Peatlands, Abisko, Northern Sweden

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ABSTRACT

High-resolution analyses of plant macrofossils, testate amoebae, pollen, mineral content, bulk density, and carbon and nitrogen were undertaken to examine the late Holocene dynamics of two permafrost peatlands in Abisko, Subarctic Sweden. The peat records were dated using tephrochronology, ¹⁴C and ²¹⁰Pb. Local plant succession and hydrological changes in peatlands were synchronous with climatic shifts, although autogenous plant succession towards ombrotrophic status during peatland development was also apparent. The Marooned peatland experienced a shift ca. 2250 cal yr BP from rich to poor fen, as indicated by the appearance of *Sphagnum fuscum*. At Stordalen, a major shift to wetter conditions occurred between 500 and 250 cal yr BP, probably associated with climate change during the Little Ice Age. During the last few decades, the testate amoeba data suggest a deepening of the water table and an increase in shrub pollen, coinciding with recent climate warming and the associated expansion of shrub communities across the Arctic. Rates of carbon accumulation vary greatly between the sites, illustrating the importance of local vegetation communities, hydrology and permafrost dynamics. Multiproxy data elucidate the palaeoecology of *S. lindbergii* and show that it indicates wet conditions in peatlands. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: climate change; permafrost; tephra; testate amoebae; carbon accumulation; *Sphagnum lindbergii*

INTRODUCTION

Peatlands in the Subarctic and Arctic are important archives for palaeoenvironmental reconstruction owing to their sensitivity to climate and hydrological change (Turetsky *et al.*, 2002; Lamarre *et al.*, 2012; Swindles *et al.*, 2015a). The recent rapid increase of air temperatures at high latitudes (IPCC, 2013) has led to partial or complete thawing of permafrost in many regions (Johansson *et al.*, 2006; Callaghan *et al.*, 2010). Numerous peatland studies in areas of permafrost degradation have focused on different aspects of ecosystem response, including changes in carbon accumulation rates (Yu, 2012; 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). Peatland carbon accumulation rates depend on complex relationships between soil temperature and moisture, litter composition and production, and degree of decomposition (Vardy *et al.*, 1998; Malmer and Wallén, 2004; Sannel and Kuhry, 2009; Kuhry *et al.*, 2013; Treat *et al.*, 2016). The importance of the length of the growing season and photosynthetically active radiation has also been highlighted for carbon accumulation in northern peatlands (Charman *et al.*, 2013).

Here we present a palaeoecological study from the Abisko region of northern Sweden to examine the late Holocene dynamics of permafrost peatlands. This region has experienced rapid climate warming during the 20th century (Callaghan *et al.*, 2010; Swindles *et al.*, 2015a), and degradation of permafrost peat and deepening of the

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active layer in recent decades (Zuidhoff and Kolstrup, 2000; Åkerman and Johansson, 2008; Kokfelt *et al.*, 2009). Furthermore, climate models project 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 relationships between climate, vegetation, hydrology and carbon accumulation (Gao and Couwenberg, 2015). We focus on the late Holocene, because this period contains several phases of climate change (e.g. Roman Warm Period, cold Migration Period, Medieval Warm Period, Little Ice Age). Although several palaeoecological studies have been conducted in Abisko (e.g. Zuidhoff and Kolstrup, 2000; Malmer and Wallén, 1996; Kokfelt *et al.*, 2009), this study represents the first multiproxy late Holocene data from peatlands there.

The aims of this study are to: (i) determine the drivers of vegetation change over the late Holocene (last 2650 years); (ii) reconstruct the late Holocene hydrological conditions of two peatlands to evaluate possible links with climate and autogenic peatland processes; (iii) assess the impact of climatic and ecological changes on carbon accumulation rates; (iv) elucidate the palaeoecology of *Sphagnum lindbergii*; and (v) present new tephra data from our study sites in northern Scandinavia, extending the current northern European tephrostratigraphy.

STUDY SITES

The study sites are located in the Abisko region of Subarctic northern Sweden (Figure 1). The Marooned (7°57'24.0"N, 19°59'11.4"E) and Stordalen (68°21'24.3"N, 19°02'53.5"E) peatlands were selected due to their high-latitude location near the tree line and at a sensitive climatic boundary subject to alternating influences of air masses of Atlantic and Arctic origin (Shemesh *et al.*, 2001). Because of this, we expect these peatlands to be sensitive to relatively small changes in climate. They also contrast in terms of permafrost; Stordalen is in an advanced state of permafrost degradation, whereas Marooned has no remaining permafrost (Swindles *et al.*, 2015b) because, it has been suggested, of thaw in the mid- to late 20th century (Swindles *et al.*, 2015a). Both peatlands are part of large peat complexes in this area, and typical of the peatlands of northern Scandinavia in terms of microform characteristics and vegetation communities. The vegetation communities of both peatlands are characterised by *Sphagnum fuscum*, *Rubus chamaemorus*, *Eriophorum vaginatum*, *E. angustifolium* and *Betula nana*. *S. balticum*, *Drepanocladus* sp. and *Carex rostrata* are also present in each site. Peat depth was highly variable in both sites, from <1 m to >3 m. However, peat probing proved difficult in places owing to the presence of permafrost. The Stordalen monolith was extracted from the top of a palsa-peat plateau complex containing permafrost, whereas the monolith at Marooned was in a wet hollow at the edge of a thaw lake.

Peat initiation in Marooned took place (as determined from the core) before deposition of the Hekla 4 tephra (~4287 cal yr BP), but our reconstructions here focus on the last 2650 cal yr BP (i.e. the large-capacity monolith required for our detailed multiproxy analysis). While peat accumulation in Stordalen commenced ca. 4700 cal years BP because of terrestrialisation (Kokfelt *et al.*, 2009), our reconstructions cover ca. 900 cal yr BP. It has been reported that the ombrotrophic *Sphagnum* peat (depth < 1 m) above the fen peat in Stordalen began accumulating no later than 800 cal yr BP (Malmer and Wallén, 2004). However, both monoliths captured the marked transition from Cyperaceae- to *Sphagnum*-dominated peat and the vegetation succession, which is our primary interest in this study.

MATERIALS AND METHODS

Overview

Our palaeoecological investigation employs plant macrofossils, pollen, testate amoebae, as well as analysis of the physical and geochemical properties of peat. Chronologies are based on radiocarbon and 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) and provides precise chronological control and synchronisation markers for paleoecological reconstructions (e.g. Wulf *et al.*, 2013; Davies, 2015).

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 a wider regional scale (Berglund *et al.*, 1996). The testate amoebae record is used to reconstruct past changes in hydrological conditions; in this study we used the transfer function of Swindles *et al.* (2015b) to reconstruct palaeo water table depths. We used micro-charcoal as an indicator of fire occurrence and frequency (Mooney and Tinner, 2011). Finally, we determined carbon accumulation rates to assess the effect of climatic and ecological changes on peatland carbon sequestration (e.g. Charman *et al.*, 2013). The palaeoecological results were presented in the form of diagrams drawn with the C2 graphics program (Juggins, 2003).

Coring and Subsampling, Chronology of the Core

Two short peat monoliths, Marooned (38 cm long) and Stordalen (30 cm), were taken from each site following excavation of a small trench following De Vleeschouwer *et al.* (2010). The monoliths were large in volume (10 × 10 cm) to allow detailed multiproxy analysis and accurate determination of bulk density for carbon accumulation estimates.

Immediately adjacent to the monolith at Marooned, a 5-cm-diameter Russian D-section corer (1 m long) was

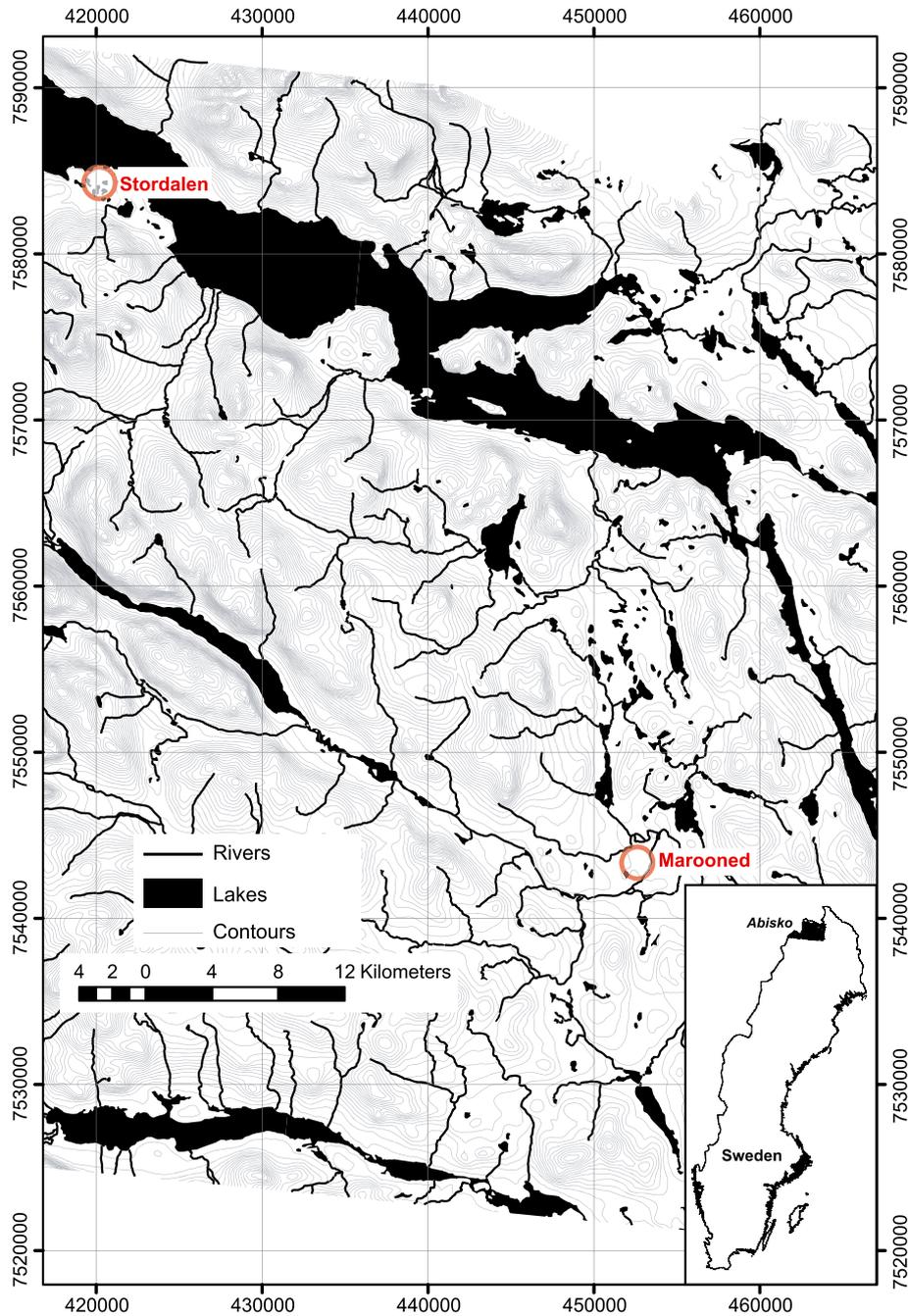


Figure 1 Location map of the two study sites in the Abisko region. [Colour figure can be viewed at wileyonlinelibrary.com]

taken using a Russian corer for analysis of tephra. Not enough material was available in the core for a detailed multiproxy study. To determine the age of the peat samples, radiocarbon measurements were performed on handpicked terrestrial plant macrofossils at Direct AMS, Seattle, USA. High-resolution ^{210}Pb dating was applied to the uppermost part of the monolith samples. Samples were acid digested with concentrated HCl , HNO_3 and H_2O_2 , and a spike of ^{209}Po was added as a yield tracer. Material was plated onto silver discs and the activity measured by alpha

spectrometry. The age of each sample was derived from the ^{210}Pb inventory using a constant rate of supply model (Appleby, 2001). The calibrated ages are expressed as cal years BP. Simple age models based on linear interpolation were generated using Clam v 2.2 (Blaauw, 2010).

Plant Macrofossil Analysis

Plant macrofossil remains were analysed contiguously at 1-cm intervals, resulting in 68 samples. Samples of 5 cm^3

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 percentages of individual microfossils of vascular plants and mosses. The microfossil carpological remains and vegetative fragments (leaves, rootlets, epidermis) were identified using identification keys (Smith, 2004; Mauquoy and van Geel, 2007). Gałka *et al.* (2016) detailed the methods used for plant macrofossil analysis of peats. We use the nomenclature of Mirek *et al.* (2002) for vascular plants and of 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. Approximately 500 terrestrial pollen grains per sample were counted. For taxonomic 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) and Shumilovskikh *et al.* (2015). Microcharcoal particles were counted along with the pollen and were grouped into four size classes: 10–30, 30–70, 70–100 and >100 µm (Rull, 2009). The arboreal pollen (AP) + non-arboreal 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 (2 cm³) were placed in boiling water for 15 min 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. In total, 100–200 amoebae were counted and identified to species level or 'type' in each sample using high-power transmitted light microscopy at 200–400× magnification. Further details on taxonomy and sources used are given by Swindles *et al.* (2015b). The Abisko transfer function (Swindles *et al.*, 2015b) was applied to the data to reconstruct water-table depths.

Physical Properties and Geochemical Analysis

The difference in sample mass before and after freeze drying was used to calculate moisture content, with bulk density calculated by dividing dry sample mass by volume (Chambers *et al.*, 2011). A volume of 0.5 × 2.5 × 2.5 cm (3.125 cm³) was used for bulk density determination. C and N content was 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). These are apparent accumulation rates and must be treated with caution as they are from uppermost peats that have not fully decomposed.

Tephra

Contiguous 5-cm-long samples were ashed at 550°C and treated with 10 per cent HCl before mounting onto slides (Swindles *et al.*, 2010a,b). Where tephra shards were identified under magnification of 400×, 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 microanalyser (EPMA). Glass shards from Marooned peatland were analysed on the JEOL JXA8230 EPMA (University of Leeds) and samples from Stordalen peatland were analysed on the Cameca SX100 EPMA (Tephra Analytical Unit, 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 other published literature. The full analytical setup is presented in Appendix 1.

RESULTS

Chronology, Peat Accumulation Rate and Lithology

The Marooned core has a much older basal age (38 cm = ca. 2650 cal yr BP) than the Stordalen profile (25 cm = ca. 900 cal yr BP), resulting in a slower mean peat accumulation rate at Marooned (~0.14 mm yr⁻¹) than at Stordalen (~0.31 mm yr⁻¹) over the respective periods. Full radiocarbon and ²¹⁰Pb data for both profiles are presented in Appendix 2 and an age–depth model in Figure 2. Detailed lithostratigraphic information is presented in Table 1 and Figure 3.

Plant Macrofossils

Four zones in the local vegetation development were visually delimited at the Marooned peatland (Figure 3A). In the first zone, MA-ma-1 (2650–2250 cal yr BP), *Carex* sp. with brown mosses is dominant. The second zone, MA-ma-2 (2250–600 cal yr BP), contains 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 to –5 cal yr BP), and the fourth zone, MA-ma-4 (–5 to –62 cal yr BP), are dominated by *S. fuscum*. *Dicranum elongatum* appears for the first time at

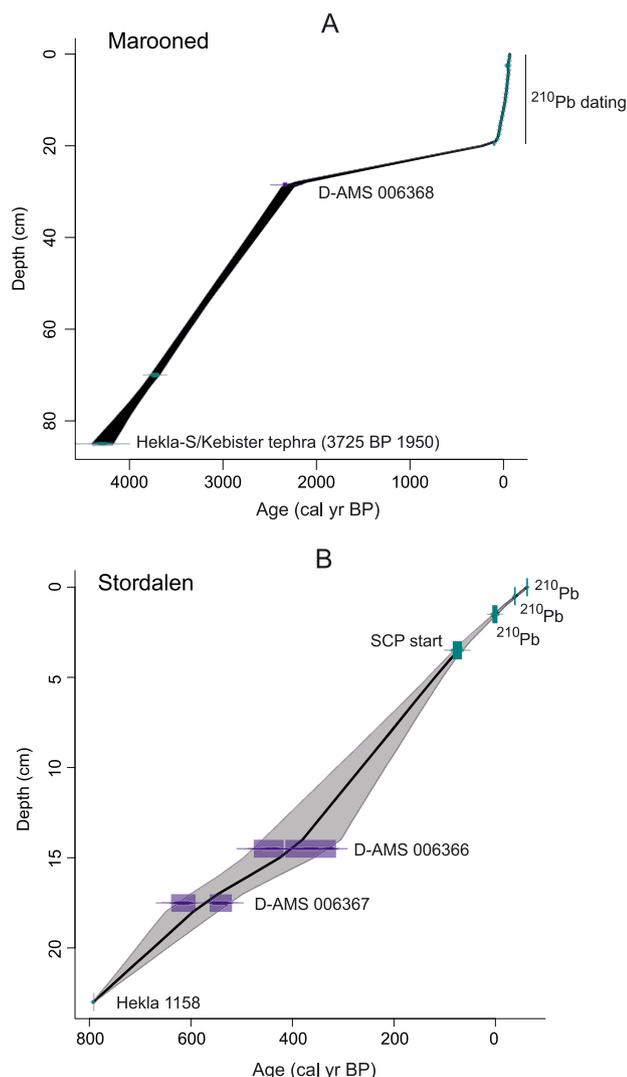


Figure 2 Age–depth model of the peat profile from the Marooned and Stordalen peatlands. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1 Lithostratigraphic description of the peat sequences.

Site	Description of peats
Marooned	38–28 cm herbaceous-moss peat 28–0 cm <i>Sphagnum</i> – brown moss peat
Stordalen	30–11 cm herbaceous-moss peat 11–6 cm <i>Sphagnum</i> – brown moss-herbaceous peat 6–0 cm fresh <i>Sphagnum</i> peat

ca. –10 cal yr BP. An expansion of shrubs is represented by the presence of *B. nana* and *E. nigrum*.

Three phases in the local vegetation development were delimited at Stordalen (Figure 3B). 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. In the bottom part of the second stage,

ST-ma-2 (ca. 280–150 cal yr BP), *Drepanocladus* sp. was the dominant species. *Sphagnum lindbergii* played a dominant role at ca. 220 cal yr BP. In the third zone, ST-ma-3 (ca. 150–62 cal yr BP), *S. balticum* was dominant. Since ca. 100 cal yr BP, *Polytrichum commune* appeared and *A. polifolia* macrofossils re-appeared.

Pollen

Four phases in the regional and local vegetation development were statistically delimited at Marooned peatland (Figure 4). The first phase, MA-po-1 (ca. 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. Among non-pollen palynomorphs, *Botryococcus* and copepod spermatophores were present. In the second phase (ca. 2300–1000 cal yr BP), there is a peak in *Salix* (up to 15%) and *Rubus chamaemorus* (up to 10%). In the third zone, MA-po-3 (ca. 1000–25 cal yr BP), there is a peak of Ericaceae (up to 30%) at ca. 450 cal. BP, and at ca. 5 cal yr BP *Picea* (up to 2%) and *R. chamaemorus* (up to 5%) increased. *Thalictrum*, *Calluna*, *Equisetum*, and palynomorphs such as the shells of *Habrotrocha angusticollis* and ascospores of Xylariaceae are present. The middle part of this zone also contains abundant microcharcoal. In the fourth zone, MA-po-4 (ca. –25 to –62 cal yr BP), *Picea* increased up to 3 per cent, and *Pinus* up to 87 per cent together with an increase in the role of Filicales monoletae, Ericaceae, and *Arctostaphylos*.

Testate Amoebae

Two phases in the testate amoebae sequence were identified at Marooned (Figure 5A). In first zone, MA-ta-1 (ca. 2650–30 cal yr BP), *Diffugia pristis* type (up to 30%), *Diffugia pulex* (up to 40%) and *Nebela militaris* (up to 25%) were the dominant taxa. The reconstructed water table depth (WTD) ranged between 22 and 28 cm below the peatland surface. During the second zone, MA-ta-2 (30–62 cal yr BP), *Longinebla militaris* increased to 40 per cent. 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%). The WTD in this zone ranged between 21 and 28 cm below the peatland surface. Overall, the WTD reconstruction suggests relatively dry conditions throughout.

Three phases in the testate amoebae succession were delimited at Stordalen (Figure 5B). The first phase, ST-ta-1 (ca. 900–480 cal yr BP), is characterised by *Trigonopyxis arcuata* type (up to 65%) and a deep, stable WTD of ca. 35 cm. In the second phase, ST-ta-2 (ca. 480–320 cal yr BP), there is an increase in the abundance of *Archerella flavum*, *Assulina scandinavica*, *Hyalosphenia papilio* and *Placocista spinosa* type. In the upper part of phase ST-ta-2 (ca. 480–320 cal yr BP), *Physochila griseola* appears for the first time (up 20%) and reconstructed WTD indicates a

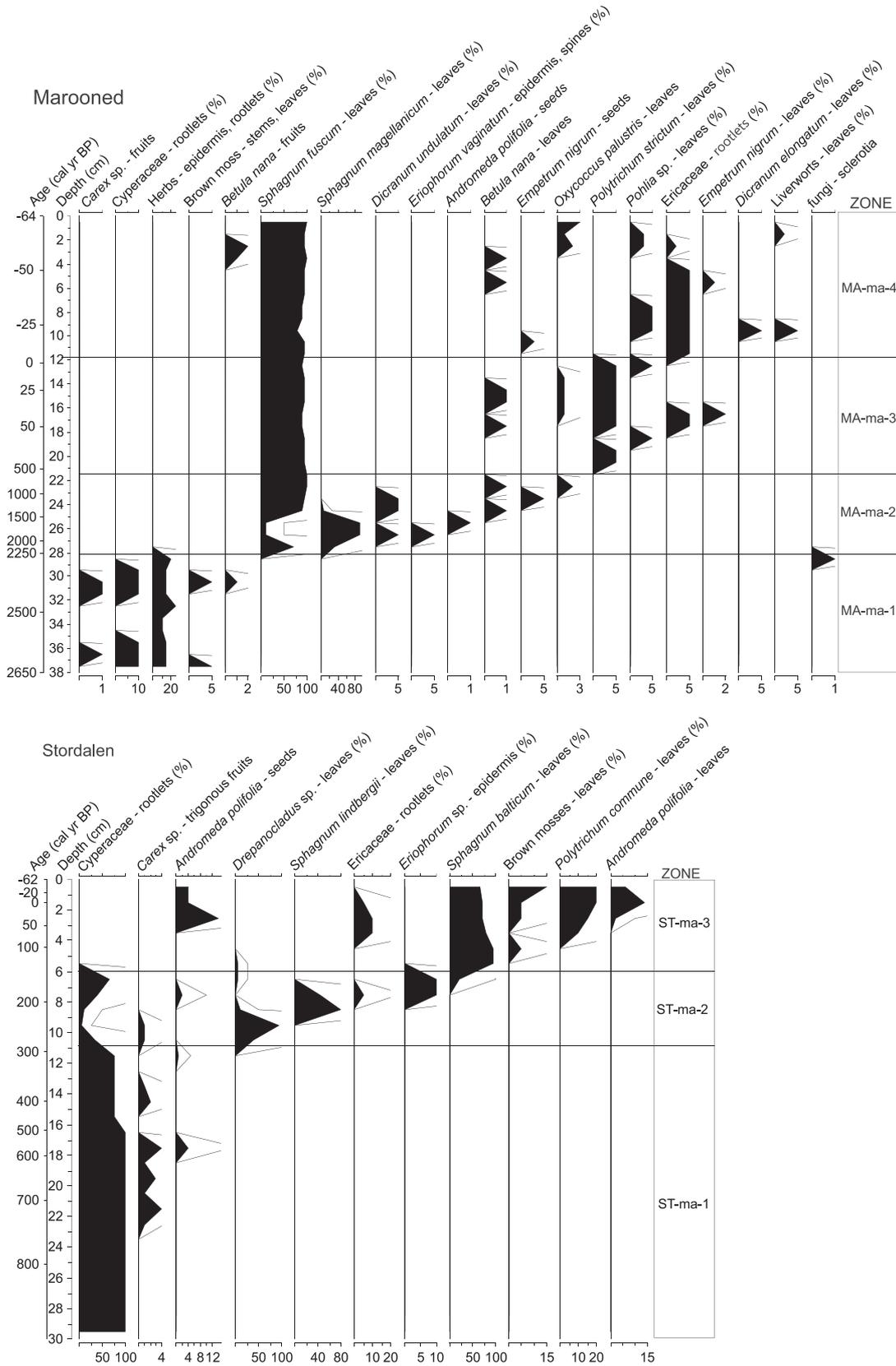


Figure 3 Percentage plant macrofossils diagram presenting local vegetation development in the Marooned and Stordalen peatlands.

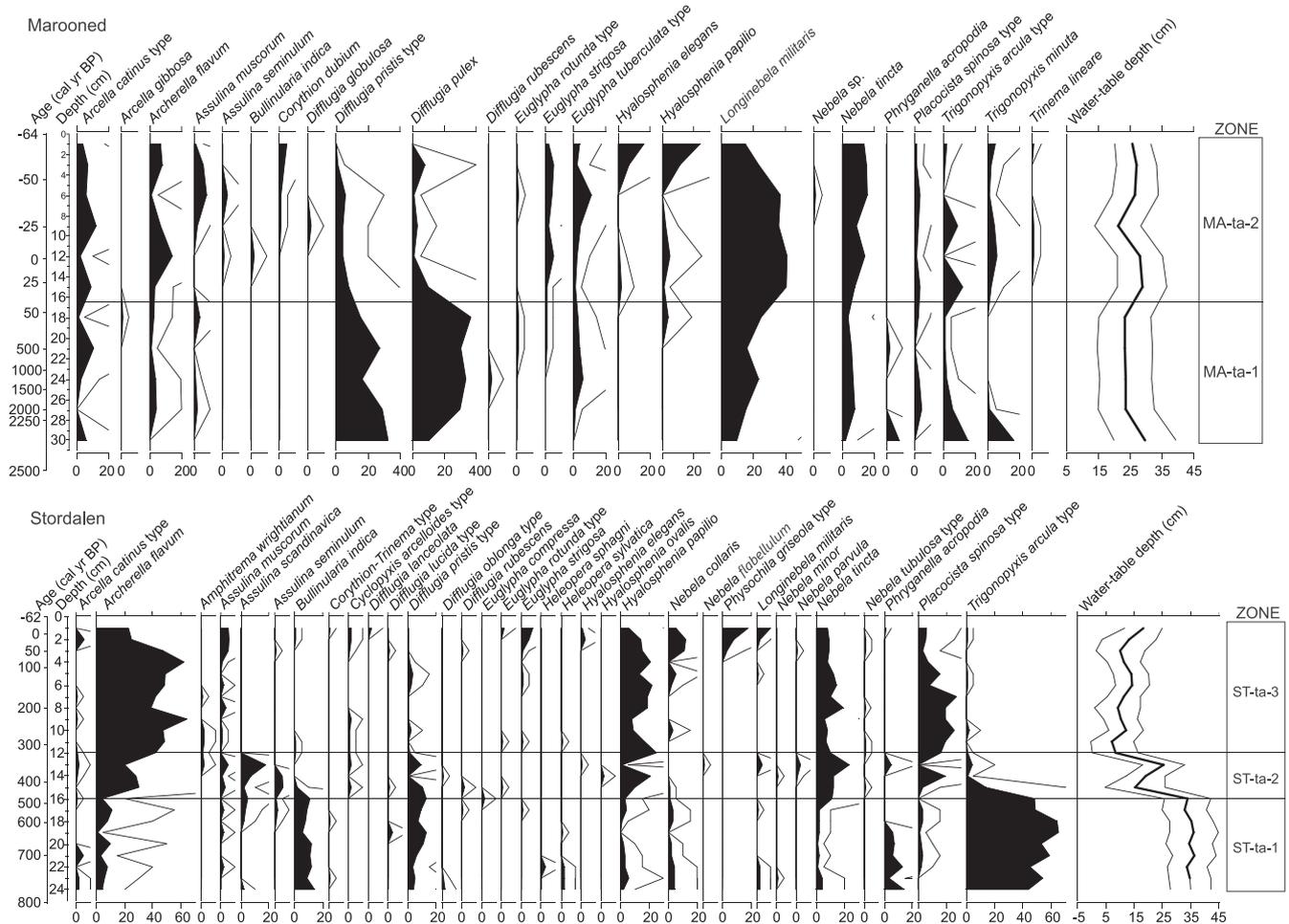


Figure 5 Percentage testate amoebae diagram presenting changes in testate amoebae communities and water table changes in the Marooned and Stordalen peatlands.

northern hemisphere (Vardy *et al.*, 1998; Kuhry, 2008; Teltewskoi *et al.*, 2016; Treat *et al.*, 2016). 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 proportion of *Betula* in regional plant communities gradually increased after ca. 4100 cal yr BP (Bigler *et al.*, 2002), because of climate cooling in northern Fennoscandia (Berglund *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), probably due to autogenic plant succession towards hummock development (Malmer, 2014). *S. 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). Autogenic plant community changes from fen to dry bog may be supported by the appearance of *Rubus chamaemorus* and *Ledum/Empetrum* pollen. These plants usually grow on the

top of hummocks in ombrotrophic peatlands in Subarctic Scandinavia (Zuidhoff and Kolstrup, 2005). Further evidence of drying is provided by testate amoebae communities, which indicate dry hydrological conditions with a reconstructed WTD of between 24 and 30 cm below the peat surface in the first ombrotrophic stage (Figure 6, zone B). 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 the peatland from the groundwater (Vardy *et al.*, 1998). According to Kokfelt *et al.* (2009) a period of notable permafrost aggradation occurred ca. 2650–2100 cal yr BP in the Abisko region.

Little Ice Age Conditions

Stable hydrological conditions with a WTD at ca. 23 cm were inferred between ca. 500 and 50 cal yr BP at Marooned (Figure 6, zones B and C). In this period, *S. fuscum* and *Polytrichum strictum* were the dominant species, with a persistent presence of *Dicranum undulatum*. *D. undulatum* and *P. strictum*, which usually occur in dry

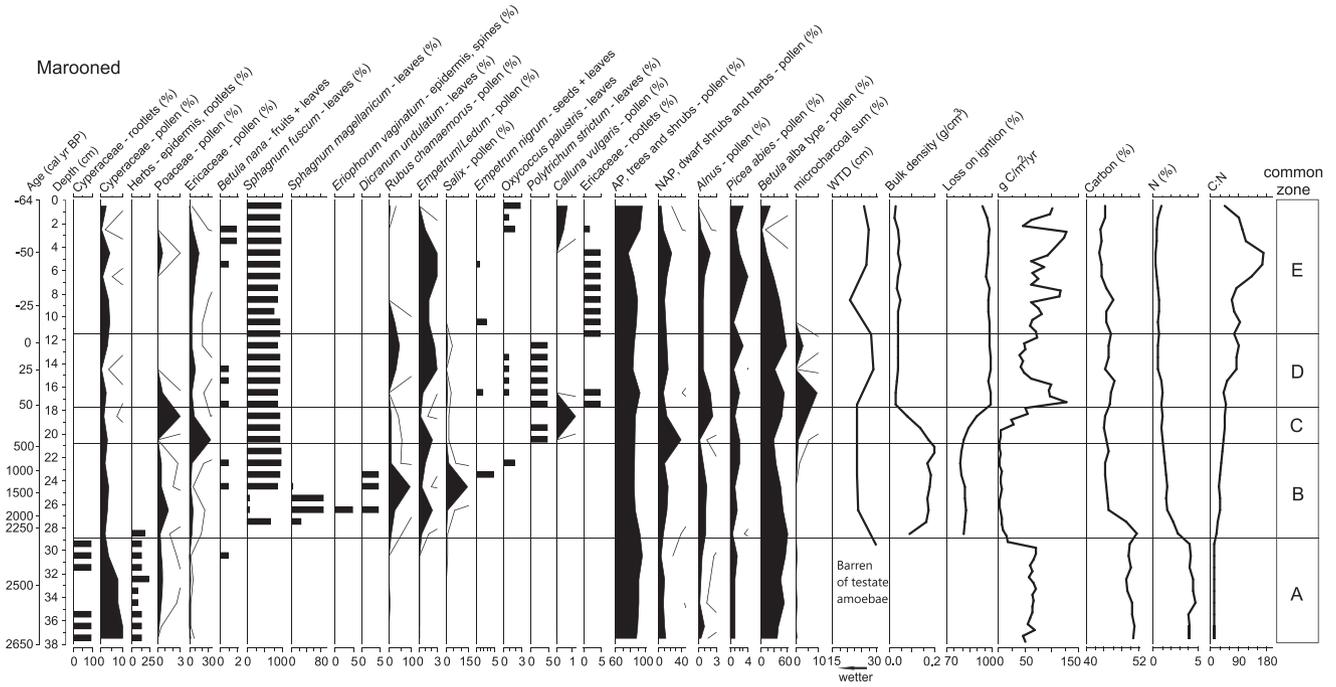


Figure 6 Comparison of chosen taxa from plant macrofossils pollen, and testate amoebae with the quantitative reconstruction of water table depth (WTD) and results of geochemical analysis in the Marooned peatland.

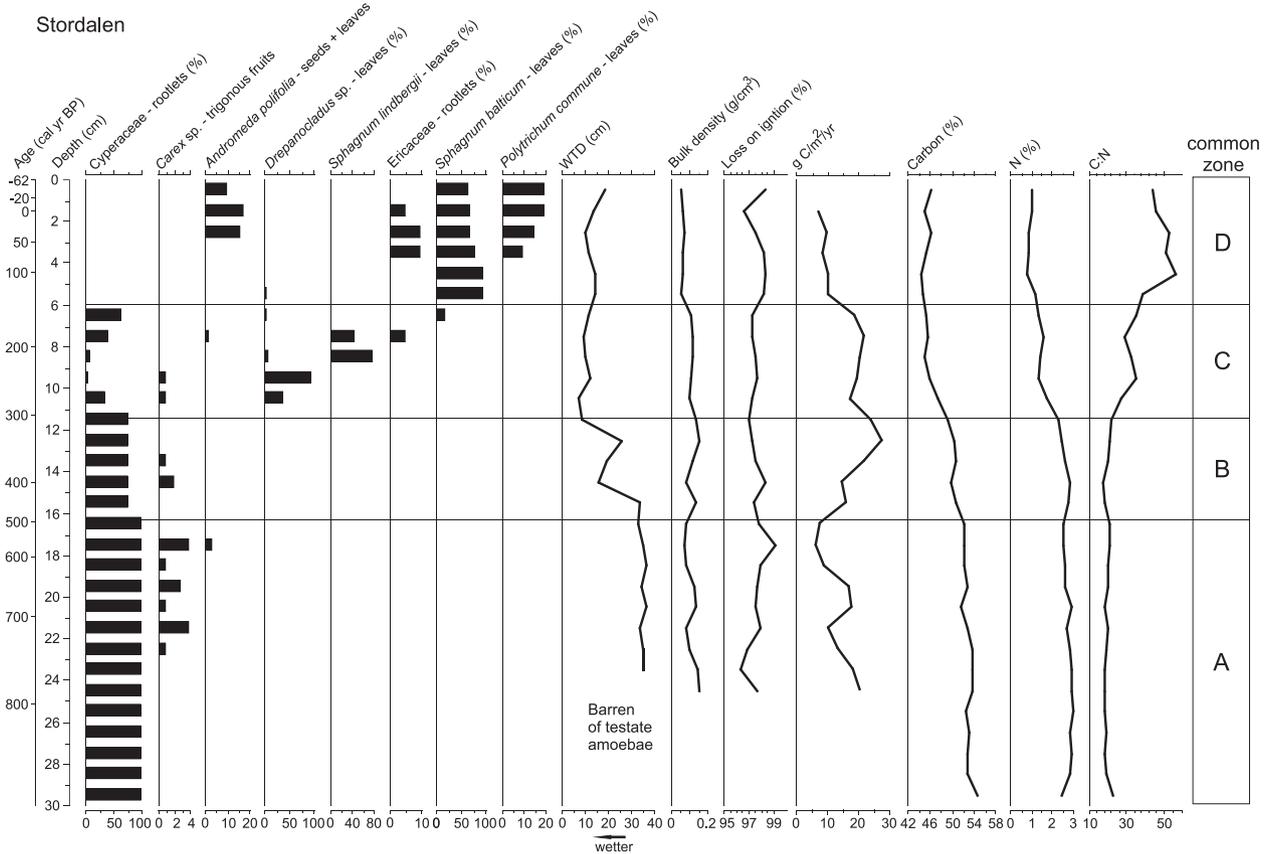


Figure 7 Comparison of chosen taxa from plant macrofossils and testate amoebae with the quantitative reconstruction of water table depth (WTD) and results of geochemical analysis in the Stordalen peatland.

areas of peatlands, often on hummocks (Hedenäs and Bisang, 2004; Smith, 2004).

The local plant communities in Marooned changed during the Little Ice Age (LIA), inferred mainly from shrubs that coincide with an increase in micro-charcoal (Figures 4 and 6). The appearance of *P. strictum*, and increasing abundances of *Ericaceae* and *Calluna vulgaris* pollen in Marooned peatland may indicate deepening of the water table, which favoured the development of shrub communities (Zuidhoff and Kolstrup, 2005). The lack of macro-charcoal (e.g. burned branches of shrubs or *Sphagnum* leaves) in the *S. fuscum* peat layer indicates that fire was probably absent at the site, but possible elsewhere 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). Fire may be favoured by deep water tables in some peatlands, which may lead to widespread thaw of permafrost and subsidence of the ground surface (Jones *et al.*, 2015). Additionally, fire is known to lower water reserves in adjacent unburned wetlands (Watts *et al.*, 2015).

A very different hydrological pattern is apparent at Stordalen. There, a marked shift towards wetter conditions occurred from ca. 450 to 400 cal yr BP (WTD from 35 to 16 cm), before a shift to drier conditions from ca. 400 to 330 cal yr BP and reversion to wet conditions from ca. 330 cal yr BP to the present day (Figure 7, zone B). During this period of variable hydrological conditions (zone B) plant assemblages were dominated by *Carex* sp., indicating poor fen conditions. Hydrological changes between ca. 500 and 300 cal yr BP in Stordalen may coincide with hydrological shifts caused by regional-scale climatic changes during the LIA, which have been documented in various parts of Europe (Swindles *et al.*, 2007; Mauquoy *et al.*, 2008; Gałka *et al.*, 2014; Feurdean *et al.*, 2015). During the LIA moisture patterns differed between northeast and central-east Europe. Northwest Europe and Scandinavia incurred shifts towards wetter climate (Charman *et al.*, 2006; Swindles *et al.*, 2007, 2010a,b; Valiranta *et al.*, 2007; Mauquoy *et al.*, 2008), while central-east Europe tended towards drier conditions (Gałka *et al.*, 2014, 2017; Feurdean *et al.*, 2015). The different palaeohydrological pathways in peatland development in northwest Europe, Scandinavia and central-east Europe could be connected to the fluctuations in large-scale atmospheric circulation (Feurdean *et al.*, 2015; Gałka *et al.*, 2017). However, hydrological shifts associated with the LIA were not observed at 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 to be considered when examining 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 the LIA could be explained by the dominance of *S. fuscum*, which has a wide ecological tolerance across a range of hydrological conditions (Rydin and McDonald, 1985). Furthermore, plant assemblages with dominant *S. fuscum* are usually

characterised by testate amoebae indicative of dry habitats, especially when hummocks have developed. Therefore, the peatland may have been climatically insensitive at this time owing to the dominance of *S. fuscum*. Another reason for the lack of visible hydrological changes during the LIA may be the very low rates of peat accumulation at this time in Marooned.

Recent Warming

The hydrological similarity between the two sites is clear in the context of the last few decades. Both sites show a trend towards drier conditions (lowering water table) (Figure 6, upper part of zone E and Figure 7, upper part of zone D). At Marooned this deepening of the water table coincides with the development of shrub communities, including *Betula nana* and *C. vulgaris*, and at Stordalen, this drying corresponds to the presence of *Polytrichum commune* and a significant increase of *A. polifolia*. The trend to dry hydrological conditions marked by the appearance of *P. strictum* and *D. elongatum* has been documented previously at Stordalen (Kokfelt *et al.*, 2009). The increasing role of shrub communities in the Abisko region may be also have been caused by modern climate warming, which has facilitated shrub expansion in the Arctic (Myers-Smith *et al.*, 2011; Loranty and Goetz, 2012).

Carbon Accumulation and C/N Ratio

The CA rates here need to be interpreted with caution, as no correction for incomplete decomposition was applied. However, the data suggest that Stordalen has the highest rates of apparent CA in zones B and C (500–150 cal yr BP, Figure 7). The CA rate increased from ca. 500 to 300 cal yr BP in Stordalen (zone B). At Marooned, CA is lowest in zones B and C (2300–100 cal yr BP) and higher in the other parts of the peat profile. The Marooned site switched from a period of very slow CA at 200 cal yr BP, which also mirrors an increase in organic content (Figure 6). In contrast, Stordalen has been closer to steady-state conditions despite marked vegetation changes over time (Figure 7). However, the shift from a sedge- to *Sphagnum*-dominated system at ~140 cal yr BP led to a moderate decline in CA.

In deeper layers of the peat profile at Marooned and Stordalen the C/N ratios are low (Figures 6 and 7), indicating strong microbial transformation of the herbaceous peat (Kuhry and Vitt, 1996; Krüger *et al.*, 2015). An increase of C/N ratios in the upper part of both sites is correlated with the spread of *Sphagnum* species. The range of values is considered typical for ombrotrophic peatlands (Kuhry and Vitt, 1996; Malmer and Wallén, 2004) and indicates relatively low levels of decomposition. At Marooned, the C/N ratio decreased in the last two decades (Figure 6), which is associated with an increase of peat decomposition and loss of C over N during microbial decomposition (e.g. Krüger *et al.*, 2015).

Palaeoecology of *Sphagnum lindbergii*

Sphagnum lindbergii is a circumpolar species that occurs in oligotrophic to mesotrophic habitats from pools to lawns in bogs and poor fens, often bordering nutrient-poor flushes and lakes in Arctic, Subarctic and boreal zones (Laine *et al.*, 2011) and in high-altitude peatlands further south in mountain areas (Lemly *et al.*, 2007; Hölzer, 2010; Wojtuń *et al.*, 2013). It grows together with *S. riparium*, *S. balticum*, *S. flexuosus* and *S. majus* (Hölzer, 2010; Laine *et al.*, 2011). At Stordalen, *S. lindbergii* grew together with *Drepanocladus* sp., *Andromeda polifolia* and *Carex* ssp. for ca. 50 years and disappeared with the appearance and spread of *S. balticum*. The depth of the water table contemporaneous with the presence of *S. lindbergii* was ca. 10 cm (Figure 7), indicating a wet, poor-fen environment. In the *S. lindbergii* population, the dominant species of testate amoebae were *Archerella flavum*, *Placocista spinosa* type, *Hyalosphenia papilio* and *Nebela tinctoria*, which usually indicate wet habitats and a wide range of pH values (e.g. 3.0–6.5 in Swindles *et al.*, 2015b).

Previous palaeoecological studies of the Stordalen peatland (Kokfelt *et al.*, 2009) found *S. lindbergii* alongside *Drepanocladus exannulatus* and sedges, and from ca. 700 to 120 cal yr BP it was the dominant plant species. At other sites in the northern hemisphere, e.g. the Hudson Bay Lowlands, interior Alaska and in the Sudety Mountains, *S. lindbergii* macrofossils are found during a wet poor-fen stage with *S. jenssenii/balticum*, *S. magellanicum*, *S. riparium*, *S. balticum*, *S. russowii*, *Eriophorum angustifolium* and *P. strictum* (Kuhry, 2008; Jones *et al.*, 2013; Lemus-Lauzon *et al.*, 2016; M. Gałka and B. Fiałkiewicz-Kozieł, unpubl. data).

Based on the fossil data outlined here, we conclude that the ecological requirements and accompanying plants associated with *S. lindbergii* have not changed significantly over time compared with the habitat identified from the present data. The presence of *S. lindbergii* macrofossils in a relatively thin (usually, several centimetres thick) peat layer suggests that this species is not very competitive and functions mainly as a transitional species during fen-to-bog transition. Therefore, the presence of *S. lindbergii* in palaeoecological reconstructions is likely to indicate wet phases in peatland development, which probably coincide with wet climatic conditions. However, the role of autogenic processes during *Sphagnum* succession should also be considered during reconstructions, with *S. lindbergii* present in the transition between fen and bog.

Improvement of Tephra Dispersal Maps in Scandinavia

The peatlands in this study contain three tephra layers, all of Icelandic origin and produced by different eruptions from the same volcano (Hekla). All three 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.*, 2016) indicate that this 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).

CONCLUSIONS

We draw the following conclusions from multi-proxy palaeoecological data from two peat profiles near Abisko, Subarctic Sweden:

1. Local plant succession and hydrological changes in both peatlands were synchronous with climatic shifts, although autogenous plant succession during peatland development towards ombrotrophic status was also influential.
2. We infer a fall in water tables and an increase in shrub pollen during the last few decades, coinciding with recent climate warming and associated with expansion of shrub communities noted in various parts of the Arctic.
3. Rates of carbon accumulation vary greatly between the sites and through time, illustrating the importance of local vegetation communities, hydrology and permafrost dynamics.
4. Our paleoecological data of *Sphagnum lindbergii* supported by its recent ecological requirements and its other fossils findings elsewhere prove that *S. lindbergii* can indicate wet conditions at the peatland surface.
5. Three tephra layers (Hekla 1158, Hekla-S and Hekla-4), of Icelandic origin, produced by different eruptions of Hekla were recorded.

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APPENDIX 1

Analytical set-up of tephra geochemical analysis

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 , 15 kV, 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 of 10 μm , 15 kV and a beam current of 10 nA. Secondary glass standards (Lipari) were analysed before and after unknown tephra samples.

APPENDIX 2

Radiocarbon dates and ^{210}Pb measurements: S, Stordalen; M, Marooned.

Site/depth (cm)	Lab. No.	Age (^{14}C years BP)	Calibrated age range (95.4%)	Dated material
S14–15	D-AMS 006366	340 \pm 24	477–314	<i>Sphagnum</i>
S17–18	D-AMS 006367	553 \pm 31	640–518	<i>Sphagnum</i>
M28–29	D-AMS 006368	2317 \pm 26	2360–2211	<i>Sphagnum</i> , herb epidermis
^{210}Pb measurements				
S,1	^{210}Pb	1988	1	Bulk peat
S,3	^{210}Pb	1949	3	Bulk peat
S,5	SCP start	1875	5	Bulk peat
M0,5	^{210}Pb	2012.61	0.01	Bulk peat
M1,5	^{210}Pb	2011.12	0.06	Bulk peat
M2,5	^{210}Pb	2008.60	0.09	Bulk peat
M3,5	^{210}Pb	2005.03	0.18	Bulk peat
M4,5	^{210}Pb	2000.70	0.28	Bulk peat
M5,5	^{210}Pb	1994.52	0.41	Bulk peat
M6,5	^{210}Pb	1989.59	0.69	Bulk peat
M7,5	^{210}Pb	1985.03	0.48	Bulk peat
M8,5	^{210}Pb	1978.01	0.53	Bulk peat
M9,5	^{210}Pb	1971.48	0.67	Bulk peat
M10,5	^{210}Pb	1964.21	0.69	Bulk peat
M11,5	^{210}Pb	1956.38	0.90	Bulk peat
M12,5	^{210}Pb	1946.70	0.96	Bulk peat
M13,5	^{210}Pb	1936.20	0.87	Bulk peat
M14,5	^{210}Pb	1925.00	0.90	Bulk peat
M15,5	^{210}Pb	1913.56	0.97	Bulk peat
M16,5	^{210}Pb	1907.17	0.81	Bulk peat
M17,5	^{210}Pb	1901.37	0.99	Bulk peat
M18,5	^{210}Pb	1883.16	0.70	Bulk peat
M19,5	^{210}Pb	1849.26	0.73	Bulk peat

APPENDIX 3

Geochemical bi-plots of major elements of tephra shards (glass) from Stordalen and Marooned plotted against

envelopes for the glass geochemistry of known tephtras based on type data from the TephraBase database. All data have been normalised.

