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Vegetation succession, carbon accumulation and hydrological change in sub-Arctic peatlands (Abisko, N. Sweden)

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Keywords

Climate change; permafrost; tephra; testate amoebae; carbon accumulation; *Sphagnum lindbergii.*

Abstract

We present a multiproxy study of the hydrological, ecological and carbon accumulation dynamics of two sub-Arctic peatlands in Abisko, Sweden. High-resolution analyses of plant macrofossils, testate amoebae, pollen, mineral content, bulk density, and carbon and nitrogen were undertaken. The peat records were dated using tephrochronology, ^{14}C and ^{210}Pb. 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 500-250 cal yr BP, which is most probably associated with climate change during the Little Ice Age. During the last few decades we observe a deepening of water table and an increase in shrub pollen, coinciding with recent climate warming and the associated expansion of shrub communities across the Arctic zone. Rates of carbon accumulation vary greatly between the sites, illustrating the importance of local vegetation communities, hydrology and permafrost dynamics. We also use multiproxy data to elucidate the palaeoecology of *Sphagnum lindbergii* and find it is indicative of wet conditions in peatlands.

Introduction

Peatlands located in the sub-Arctic and Arctic zones 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 global air temperatures at high latitude (IPCC, 2013) has led to partial or complete thawing of permafrost in many regions (Turetsky *et al*., 2002; Johansson *et al*., 2006; Callaghan *et al*., 2010). Numerous peatland 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; Lemus-Lauzon *et al*., 2016; Teltewskoi *et al*., 2016; Treat *et al*., 2016) and hydrology (Swindles *et al*., 2015a,b). 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; Treat *et al*., 2014). The importance of the length of the growing season and incoming 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 long term dynamics of permafrost peatlands. The Abisko region 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 during recent decades (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 relationships between climate, vegetation, hydrology and carbon accumulation, which has implications for understanding the response of high latitude peatlands to climate warming (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, 2004; Kokfelt *et al*., 2009), this study represents the first multiproxy late Holocene data from peatlands in this region.

The aims of this study are to: i) determine the drivers of vegetation change over the late Holocene (last 2250 years); ii) reconstruct the late Holocene hydrological conditions of two peatlands to evaluate possible links with climate and autogenic peatland processes; and iii) assess the impact of climatic and ecological changes on carbon accumulation rates; and iv) elucidate the palaeoecology of *Sphagnum lindbergii*. We also 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 northern Sweden's sub-Arctic zone (Fig. 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*., 2015a), (Swindles *et al*., 2015b). It has been suggested that the Marooned site thawed in the mid-late twentieth 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 characterized by *Sphagnum fuscum*, *Rubus chamaemorus, Eriophorum vaginatum*, *Eriophorum angustifolium* and *Betula nana*. *Sphagnum balticum*, *Drepanocladus* sp. and *Carex rostrata* are also present in each site. Peat depth was highly variable in both sites and varied from <1m to >3m in places. 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. The Marooned peatland no longer contains permafrost.

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 in Stordalen peat accumulation commenced ca. 4700 cal BP as a result of terrestrialisation (Kokfelt *et al*., 2010), 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 not 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 lead-210 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).

Coring and subsampling, chronology of the core

Two short peat monoliths, Marooned (38 cm) 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 to allow this detailed multiproxy study, and the accurate determination of bulk density for carbon accumulation estimates.

A narrow-chamber core of 1m was also taken from Marooned using a Russian corer immediately adjacent to the monolith 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 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 ^{210}Pb inventory using a constant rate of supply model (Appleby, 2001). The calibrated dates are expressed as cal yr 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 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). Refer to Gałka et al. (2016) for detailed information on 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 cm^3 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 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) and Shumilovskikh *et al*. (2015). Microcharcoal particles were counted along with the pollen and were grouped into four size classes: 10-30 μm, 30-70 μm, 70-100 μm 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 (2cm^3) 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). The Abisko transfer function (Swindles *et al.,* 2015b) was applied to the data to generate water-table depth reconstructions.

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 cm^3) 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). We note that these are apparent accumulation rates and must be treated with some degree of caution as they are from uppermost peats that not have undergone full decomposition.

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 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 date (38 cm = ca. 2650 cal yr BP) when compared with the Stordalen profile (25 cm = ca. 900 cal yr BP), resulting in a slower mean peat accumulation rate at Marooned (~0.14 mm/year) compared with Stordalen (~0.31 mm/year) over the respective periods. Full radiocarbon and ^{210}Pb data for both profiles are presented in Appendix 2 and age-depth model on Fig. 2. Detailed lithostratigraphic information is presented in Table 1 and Fig. 3.

Plant macrofossils

Four zones in the local vegetation development were visually delimited at the Marooned peatland (Fig. 3A). In the first zone MA-ma-1 (2650 to 2250 cal yr BP) *Carex* sp. with brown mosses is dominant. The second zone MA-ma-2 (2250 to 600 cal yr BP) contains small amounts of *Betula nana*, *Empetrum nigrum* and *Andromeda polifolia*, but is primarily 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 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 (Fig. 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) *Sphagnum 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 (Fig. 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 chameomorus* (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%) 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 were present. The middle part of this zone also contains abundant microcharcoal. In the fourth zone MA-po-4 (ca. -25- -62 cal yr BP) *Picea* increased 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 identified at Marooned (Fig. 5A). In first zone MA-ta-1 (ca. 2650-30 cal yr BP) *Difflugia pristis* type (up to 30%), *Difflugia 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%. 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 (Fig. 5B). The first phase ST-ta-1 (ca. 900-480 cal yr BP) is characterised by *Trigonopyxis arcula* type (up to 65%) and deep, stable WTD ca. 35 cm. In the phase ST-ta-2 (ca. 480-320 cal yr BP) there in 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 fluctuating water table from 34 to 8 cm. In the third phase St-ta-3 (ca. 320-62 cal yr BP) *Archerella flavum* increases up to 65% and *P. spinosa* type up to 27%. The WTD ranged between 8 and 18 cm. The Stordalen profile, in contrast to Marooned, contains a clear 'wet-shift' in hydrology.

Geochemical analysis

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 (Fig. 6 and Fig. 7). This pattern may also be due partly to compaction. C/N ratio increases in both sites through time and is higher in the later ombrotrophic phases before decreasing in the near-surface zone.

Carbon accumulation rates

Our study sites have high variability of carbon accumulation (CA) rates during the studied time periods. In Marooned the CA rates range from ~0 to 128 gC m^{-2} yr^{-1} and are lowest in zone B (ca. 500 yr BP – 2250 yr BP) and highest in the boundary between zones C and D (ca. 50 yrs BP) (Fig. 6). The CA rates at Stordalen vary from ~0 to 27 gC m^{-2} yr^{-1} and are generally much slower than at Marooned. The CA 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) (Fig. 7).

Tephra

All tephra data are displayed in Appendix 3. Two tephra layers (MR-1 = 70 cm, MR-2 = 85 cm) were identified in the 1 m core 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).

The 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). This tephra layer is historically dated and with a peak within a one-centimeter horizon provides a precise chronological marker for the Stordalen profile.

Discussion

1. Ecohydrological development

In the bottom part of both peat sequences the main peat-forming plants included Cyperaceae (Fig. 6, phase A, Fig. 7, 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). 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 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 2,250 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 most likely to autogenic plant succession toward 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 appearance of *Rubus chamaemorus* and *Ledum/Empetrum* pollen. These plants usually grow on the top of hummocks in ombrotrophic peatlands in the sub-Arctic zone of 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 (Fig. 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 peatland from the groundwater (Vardy *et* *al*., 1998). According to Kokfelt *et al*. (2010) a period of notable permafrost aggradation occurred ca. 2650–2100 cal yr BP in the Abisko region.

2. Little Ice Age (LIA) conditions

Stable hydrological conditions with DWT at ca. 23 cm were inferred between ca. 500 and 50 cal yr BP at Marooned (Fig. 6, zone 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 areas of peatlands, often on hummocks (Hedenäs and Bisang, 2004; Smith, 2004).

During the LIA we noted changes in local plant communities in Marooned, mainly shrubs that coincide with the increase in micro-charcoal (Figs. 4 and 6). The appearance of *P. strictum*, and increasing abundances of *Ericaceae, Calluna vulgaris* pollen in Marooned peatland may indicate the deepening of 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 most likely not present 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 and subsidence of permafrost (Jones *et al*., 2015). Additionally, fire is known to lower water reserves in adjacent unburned wetland areas (Watts *et al*., 2015).

A very different hydrological pattern is apparent at Stordalen, where a marked shift toward 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 reverting to wet conditions from ca. 330 cal yr BP to present day (Fig. 7, zone B). In this time period of variable hydrological conditions (Zone B) plant assemblages dominated by *Carex* sp. are observed, indicative of 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 Little Ice Age (LIA) which have been documented in various parts of Europe (Mauquoy *et al*., 2008; Swindles *et al*., 2007; Gałka *et al*., 2014; Feurdean *et al*., 2015). During the LIA moisture patterns differed between North-East Europe and Central-East Europe. North-West Europe and Scandinavia incurred shifts toward wetter climate (Charman *et al*., 2006; Väliranta *et al*., 2007; Swindles *et al*., 2007, 2010; Mauquoy *et al*., 2008) whilst Central-East Europe tended toward drier conditions (Gałka *et al*., 2014, 2017; Feurdean *et al*., 2015). The different palaeohydrological pathways in peatland development in North-West Europe, Scandinavia and Central-East Europe could be connected with the fluctuations in largescale 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 most 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 LIA may be the very low rates of peat accumulation at this time in Marooned.

3. Recent warming

The hydrological similarity between the two sites is clear in the context of the last few decades. At both sites there is a trend toward drier conditions (lowering water table) (Fig. 6, upper part of zone E and Fig. 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 in the case of Stordalen, this drying corresponds with 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 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 has facilitated the expansion of shrubs in the Arctic zone (Myers-Smith *et al*., 2011; Loranty and Goetz, 2012).

4. Carbon accumulation and C/N ratio

The CA rates here need to be interpreted with some 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, Fig. 7). CA accumulation rate increased from ca. 500-300 cal yr BP in Stordalen (Zone B). In 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 (Fig. 6). In contrast, Stordalen has been closer to steady state despite marked vegetation changes over time (Fig. 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 peat profile in Marooned and Stordalen C/N ratios are low (Fig. 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 upper part of both sites correlated with the spread of *Sphagnum* species. The range of values are considered typical for ombrotrophic peatlands (Kuhry and Vitt, 1996; Malmer and Wallén, 2004) and indicate relatively low levels of decomposition. In Marooned a decrease of C/N ratio in the last two decades took place (Fig. 6), what is associated with increase of peat decomposition and loss of C over N during microbial decomposition (e.g. Krüger *et al*., 2015).

5. Palaeoecology of *Sphagnum lindbergii*

Sphagnum lindbergii is a circumpolar species which occurs in oligotrophic to mesotrophic habitats from pools to lawns in bogs and poor fens, often bordering nutrient-poor flushes and lakes located in Arctic, sub-Arctic 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). In 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 during the presence of *S. lindbergii* was ca. 10 cm (Fig. 7), indicative of a wet poor fen environment. In the *S. lindbergii* population dominant species of testate amoebae were *Archerella flavum, Placocista spinosa* type, *Hyalosphenia papilio,* and *Nebela tincta,* what indicates mostly usually wet habitats and a relatively wide range of pH (e.g. 3.0-6.5 in Swindles *et al*., 2015b).

In previous palaeoecological studies conducted in the Stordalen peatland (Kokfelt et al., 2010), *S. lindbergii* was found alongside *Drepanocladus exannulatus* and sedges and from ca. 700 to 120 cal yr BP it was the dominant species in the plant assemblage. In others sites in northern hemisphere, e.g. the Hudson Bay Lowlands, Alaska, and in the Sudety Mts. *S. lindbergii macrofossils* during a wet poor-fen stage with *S. jensseni/balticum, S.*

magellanicum, S. riparium, S. balticum, S. russowii, Eriophorum angustifolium, and *P. strictum* was found (Kuhry, 2008; Jones *et al*., 2013; Lemus-Lauzon *et al*., 2016; Gałka and Fiałkiewicz–Kozieł, unpubl. data).

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

6. Improvement of tephra dispersal maps in Scandinavia

The peatlands included in this study contain a total of three tephra layers, all of Icelandic origin and produced by different eruptions of the same volcano (Hekla). They have all 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 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

We present a multi-proxy palaeoecological dataset from two peat profiles from Abisko, Arctic Sweden and conclude the following:

1. Local plant succession and hydrological changes in peatlands were synchronous with climatic shifts, although autogeneous plant succession during peatland development towards ombrotrophic status were also influential.
2. We observe 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 zone.
3. Rates of carbon accumulation vary greatly between the sites and in 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 finding in various part of world prove that *S. lindbergii* can be indicative of wet conditions at the peatland's 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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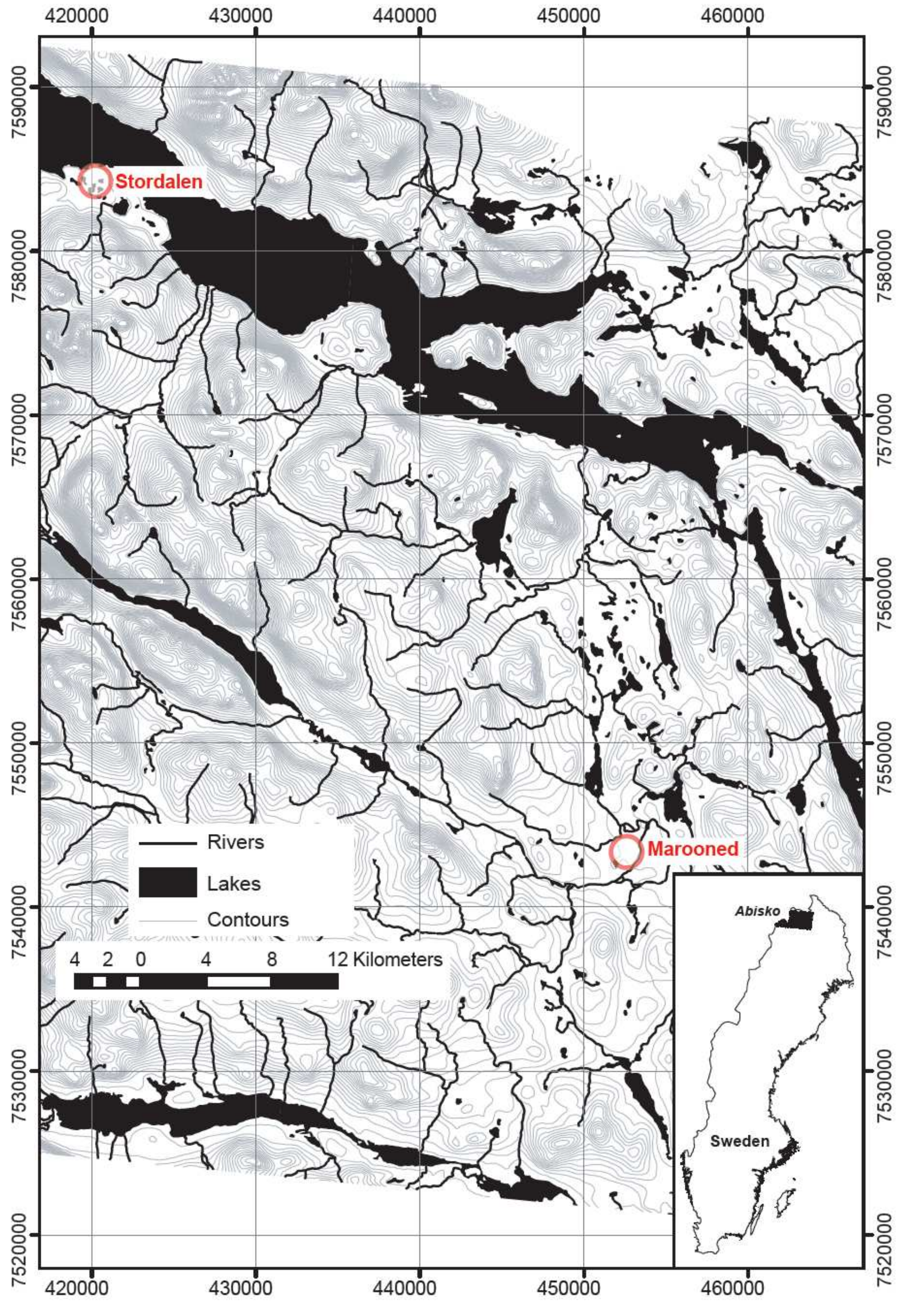
Figure caption



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744 Figure 1. Study site.

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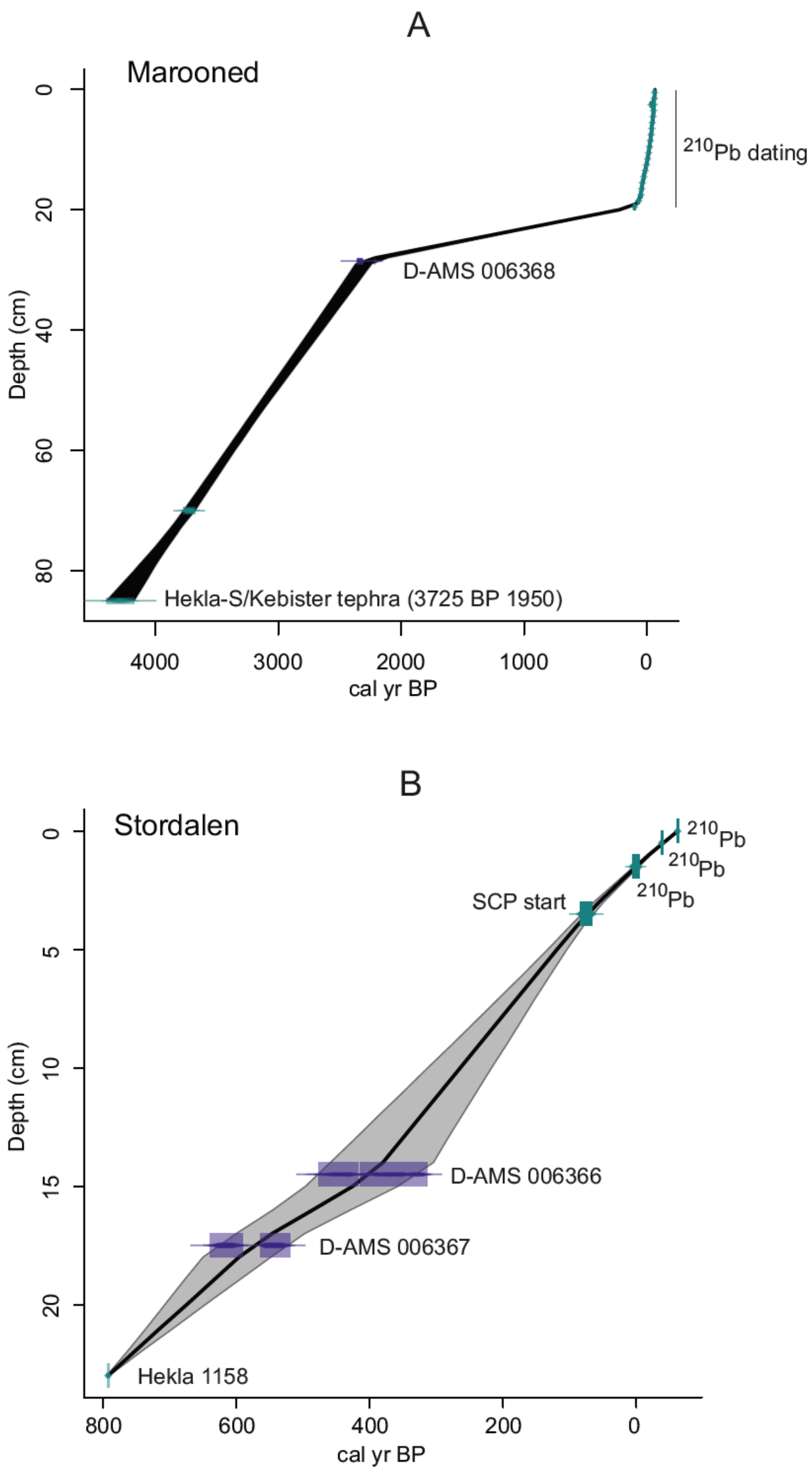


Figure 2. Age-depth model of the peat profile from Marooned and Stordalen peatlands.

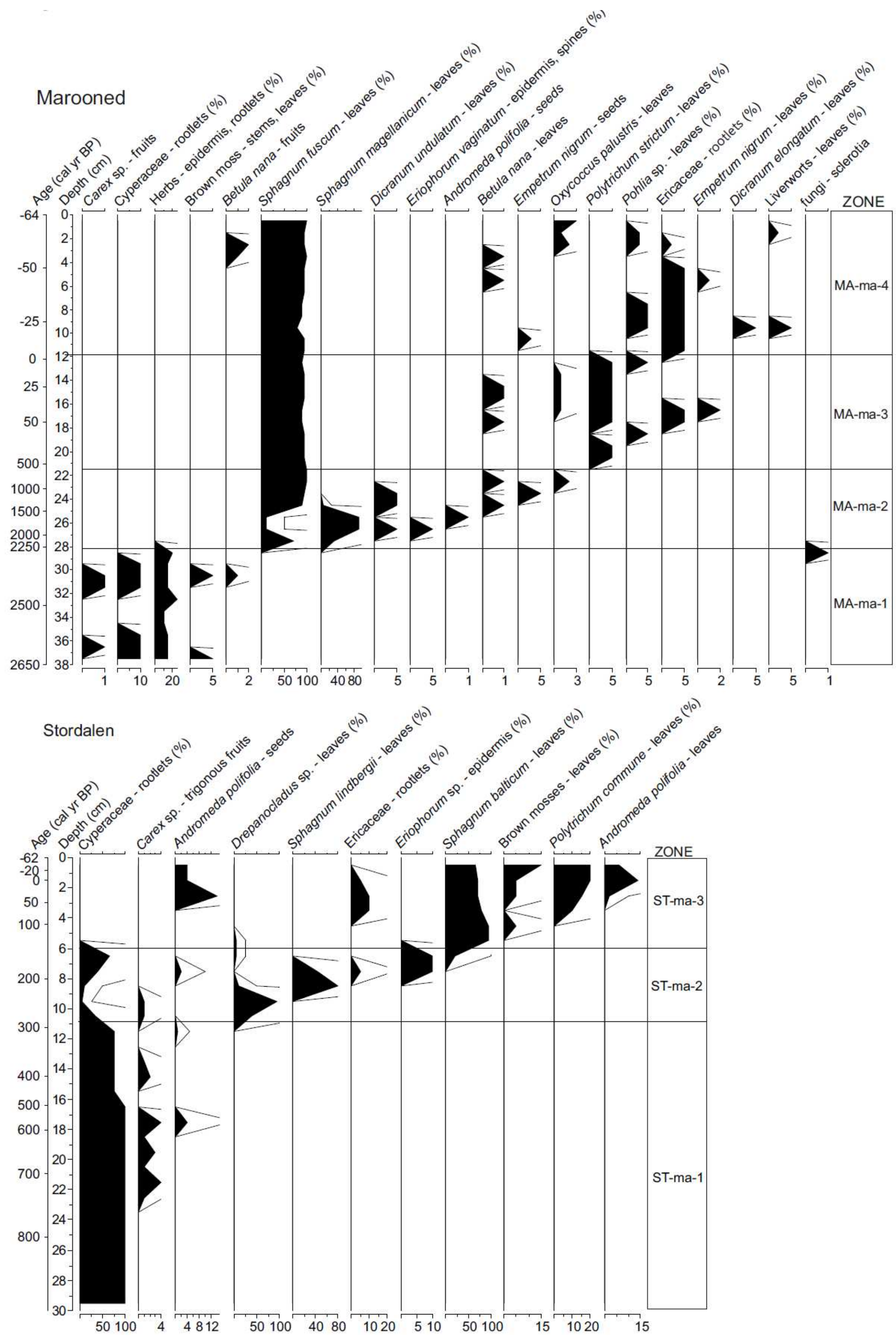


Figure 3. Percentage plant macrofossils diagram presenting local vegetation development in Marooned and Stordalen peatlands.

Figure 4

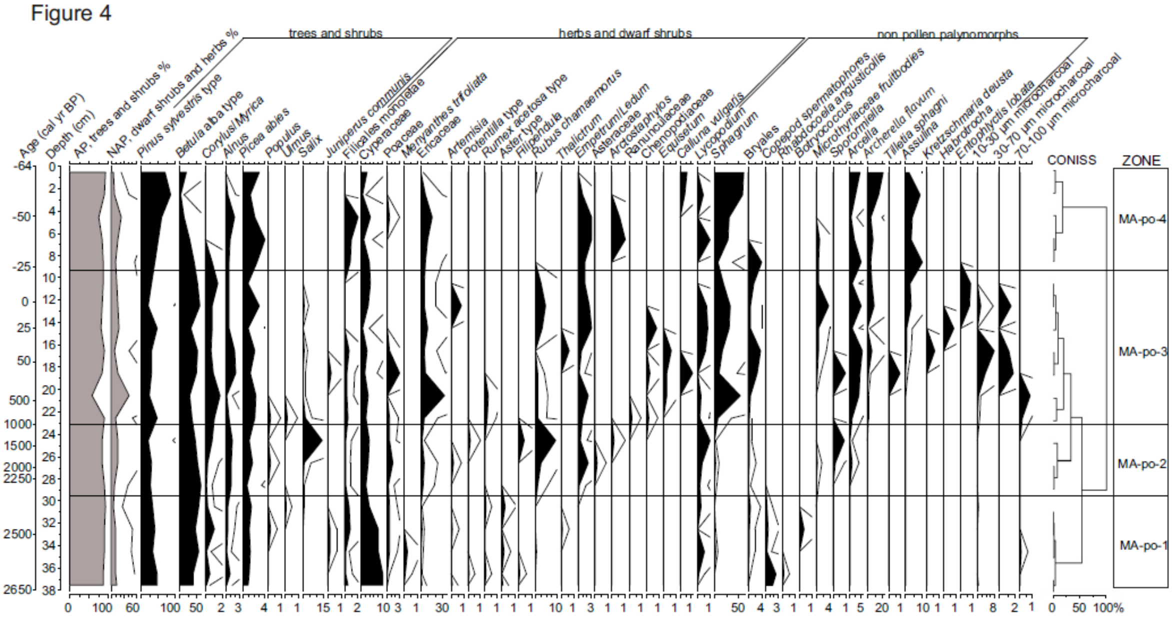


Figure 4. Percentage pollen diagram presenting local and regional vegetation changes in the Marooned peatland.

Figure 5

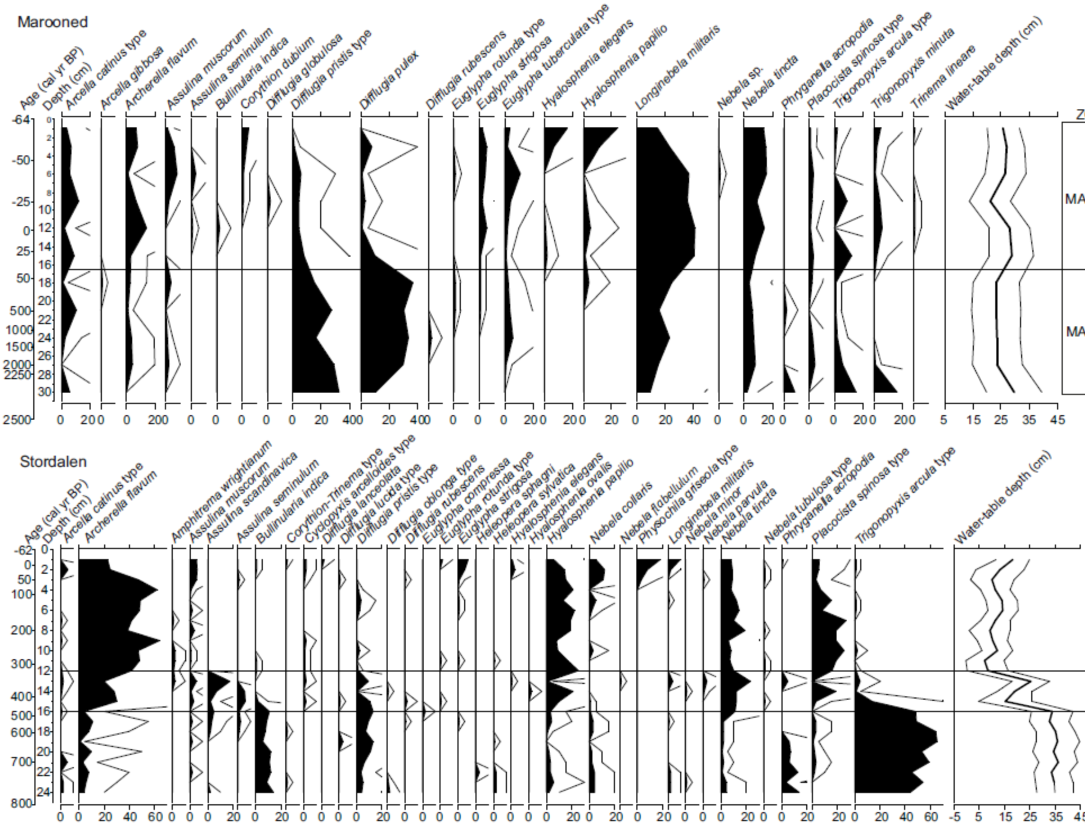


Figure 5. Percentage testate amoebae diagram presenting changes in testate amoebae communities and water table changes in Marooned and Stordalen peatlands.

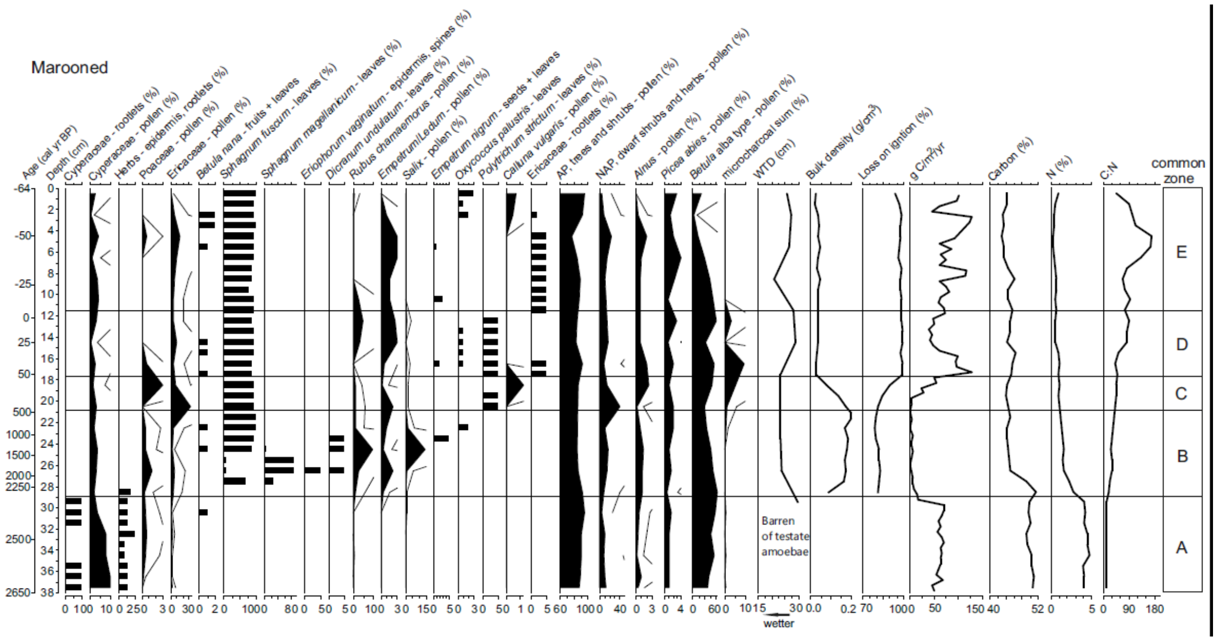


Figure 6. Comparison of chosen taxa from three: plant macrofossils, pollen, and testate amoebae with the quantitative reconstruction of water-table depth (DWT) and results of geochemical analysis in Marooned peatland.

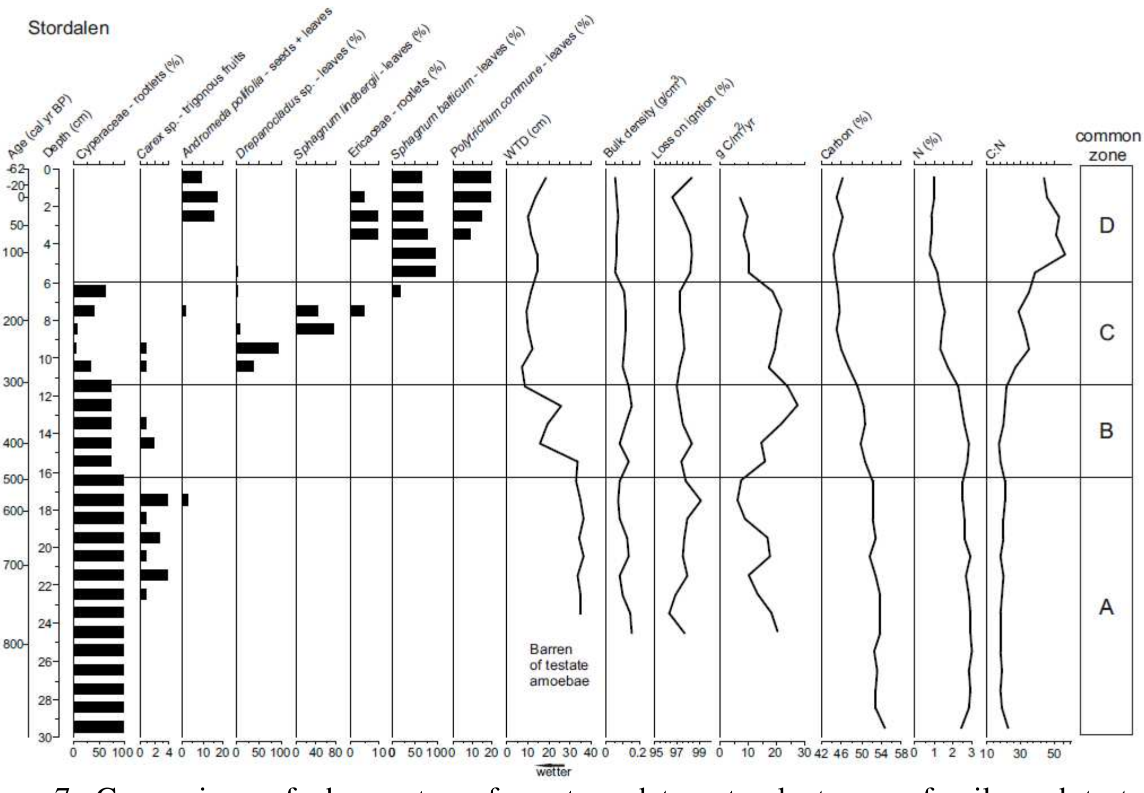


Figure 7. Comparison of chosen taxa from two data set: plant macrofossils and testate amoebae with the quantitative reconstruction of water-table depth (DWT) and results of geochemical analysis in Stordalen peatland.

Table

Table 1. Lithostratigraphic description of the sediment sequence

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

Appendix caption

1. Analytical setup of tephra EPMA analysis.

Appendix 1

Analytical setup of tephra geochemical analysis.

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

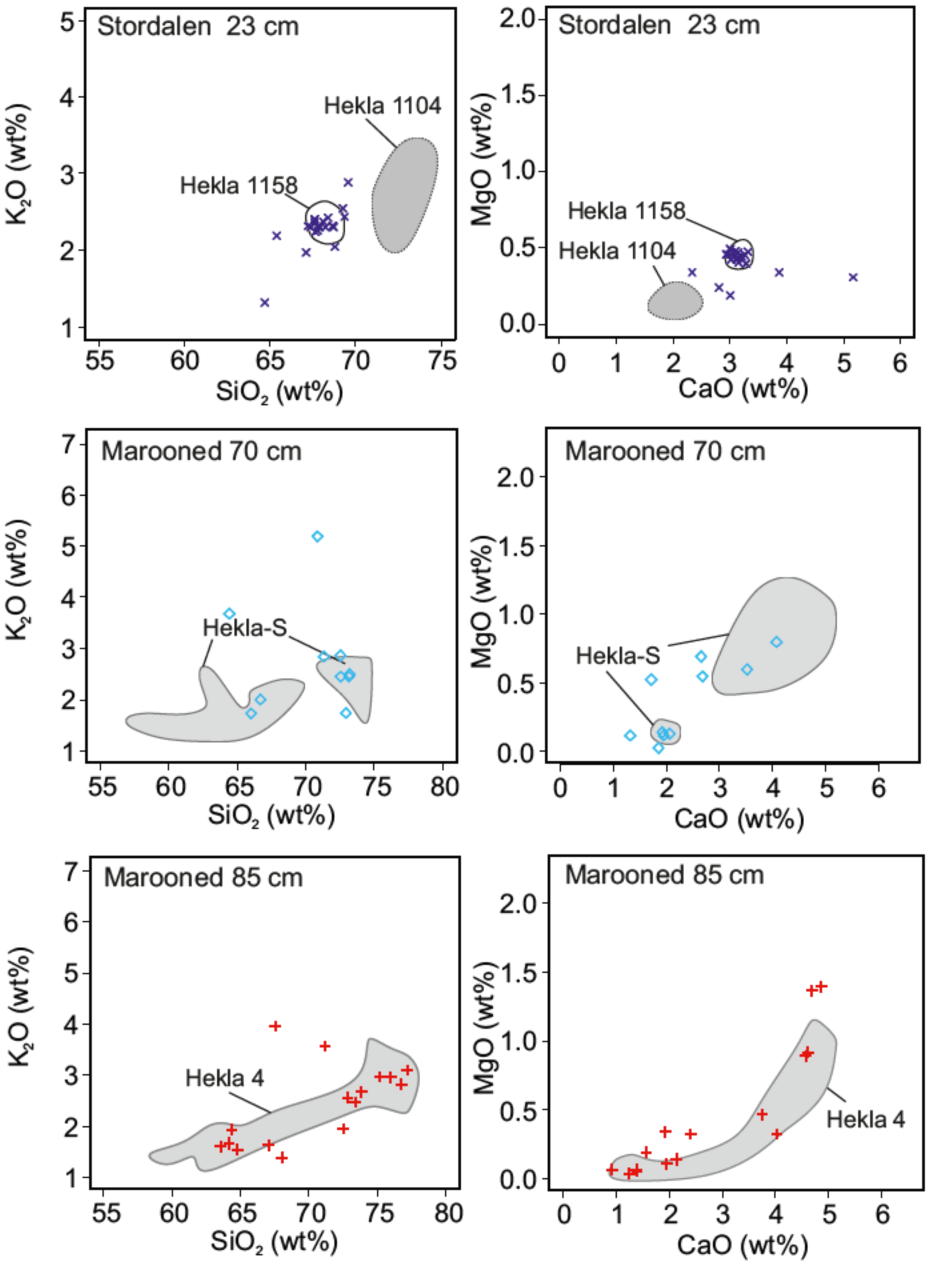
EPMA: JEOL JXA8230 EPMA housed at the University of Leeds

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.

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

Appendix 2. Radiocarbon dates and ^{210}Pb measurements: S – Stordalen, M - Marooned

Site/Depth (cm)	Lab. No.	Age ^{14}C date	Calibrated range 95.4%	Dated material
S14-15	D-AMS 006366	340±24	477-314	*Sphagnum*
S17-18	D-AMS 006367	553±31	640-518	*Sphagnum*
M28-29	D-AMS 006368	2317±26	2360-2211	*Sphagnum,* herb epidermis
		210Pb 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 tephras based on type data from the Tephrabase database. All data have been normalised.