Peat stratigraphical study of hydrological conditions at Stass Mosse, southern Sweden, and the relation to Holocene bog-pine growth

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Cover Picture: Subfossil pine stump, Stass Mosse (Photo:Linda Adamsson)

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Abstract: Peat horizons with numerous subfossil stumps and roots of Scots pine (*Pinus sylvestris*), frequently occurring in northern European peat bogs, are reveling periods with considerable pine growth on the bogs during the Holocene. It is assumed that periods with relatively low bog surface wetness (BSW) have enhanced establishment of bog-pines in the past and that hydrological changes have influenced the growth and degeneration of these pines. The hydrological conditions during a Holocene bog-pine period at the raised bog Stass Mosse in southern Sweden were investigated using peat stratigraphy, macrofossil analysis, humification analysis, organic bulk density and loss on ignition. The aim was to connect Scots pine (*Pinus sylvestris*) establishment, growth and degeneration to changes in bog surface wetness (BSW). Peat stratigraphical data show that Stass Mosse initially was a lake that first developed by terrestrialisation to a forested fen and later became an ombrotrophic *Sphagnum* dominated bog sometime between 6000 and 5000 cal BP. Pine remains (periderm and mycorrhizal roots) were identified during the macrofossil analysis of a selected focus interval radiocarbon dated to 6000-3300 cal BP, with increased occurrence between 5000 and 3900 cal BP. These findings are consistent with existing information showing that the subfossil pine stumps lived during the period 4215-3779 ± 105 cal BP. The humification records and stratigraphies reflect three distinct shifts to wetter conditions at 5200 cal BP, around 4600 cal BP and 4100 cal BP, followed by rapid fluctuations in BSW beginning after 3900 cal BP. These unstable hydrological conditions are thought to have affected the bog-pine population negatively in form of reduced growth and eventual die off. The timing of the wet-shifts around 4600 cal BP and 4100 cal BP is comparable to similar shifts found in several other palaeohydrological studies in the region, which implies regional climatic influence. The investigated bog-pine period coincides with the onset of a transition to a wetter and colder climate in the North Atlantic region termed the Neoglacial around 5000-4000 cal BP, believed to be caused by changes in oceanic and atmospheric circulation patterns.

Keywords: Climate change, bog, pines, macrofossil analysis, palaeoecology.

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Torvstratigrafisk studie av hydrologiska förhållanden på Stass Mosse, centrala Skåne, och förhållandet till tallväxt under Holocen

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Sammanfattning: Torvhorisonter med stora mängder subfossila stubbar och rötter av tall (*Pinus sylvestris*) förekommer ofta i nordeuropeiska torvmossar. De visar att mossarna varit tallbevuxna under delar av Holocen. Det antas att perioder med relativt låg mossefuktighet har förstärkt etableringen av dessa mossetallar och att hydrologiska förändringar har påverkat tillväxt och degeneration hos tallarna. De hydrologiska förhållandena på Stass Mosse, centrala Skåne, under en period av tallväxt undersöktes med hjälp av torvstratigrafi, makrofossilanalys, humifieringsanalys, organisk bulkdensitet och glödförlust. Syftet var att koppla tallarnas etablering, tillväxt och degeneration till fuktighetsförändringar vid mosseytan. Torvstratigrafin visar att den nuvarande mossen ursprungligen var en sjö som först utvecklades till ett beskogat kärr och senare till en ombrotrof och *Sphagnum*-dominerad mosse någon gång mellan 6000 och 5000 cal BP. Subfossila rester av tall (periderm och mykorrhizarötter) identifierades under makrofossilanalys av ett valt intervall som C14-daterats till 6000-3300 cal BP och de visade ökad förekomst mellan 5000 och 3900 cal BP. Dessa fynd överensstämmer med de subfossila tallstubbarna som daterats till att ha levt under perioden 4215-3779 ± 105 cal BP. Humifieringsgraden visade tre distinkta förändringar till ökad fuktighet på mossen vid 5200 cal BP, runt 4600 cal BP och 4100 cal BP och snabba svängningar i fuktighet från och med 3900 cal BP. De instabila hydrologiska förhållandena tros ha påverkat tallpopulationen negativt i form av reducerad tillväxt och så småningom utdöende. Tidpunkterna för ökad fuktighet runt 4600 cal BP och 4100 cal BP är jämförbara med liknande förändringar i flera andra paleohydrologiska studier i regionen, vilket antyder en regional klimatpåverkan. Den undersökta tallperioden sammanfaller med en övergång till ett fuktigare och kallare klimat i den nordatlantiska regionen omkring 5000-4000 cal BP, kallad Neoglaciationen, som tros ha orsakats av förändringar i oceaniska- och atmosfäriska cirkulationsmönster.

Nyckelord: Klimatförändringar, mosse, tall, makrofossilanalys, paleoekologi

Ämnesinriktning: Kvartärgeologi

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1. Introduction

The on-going man-induced climate change has already started to have global consequences and is expected to have far-reaching impacts on the earth's ecosystems in the future (IPCC, 2007). It is a key concern for modern society. Knowledge of the forcing mechanisms of and ecosystem responses to climate change is fundamental to understand the on-going changes and foresee future effects. The study of past climate change can help to gain this knowledge.

Climatic conditions on earth are never constant, but are continuously changing at different scales and rates. Natural causes of large-scale climate change include variations in the Earth's orbit around the sun, in solar activity and in oceanic and atmospheric circulation patterns. The Quaternary time period (2.6 million years ago to present) is characterized by multi-millennial glacial-interglacial cycles. The cycles are most likely caused by orbital changes reinforced by internal feedback mechanisms of the earth system such as fluctuating sea level, surface albedo effects (light surfaces, for example ice, reflect more sunlight than dark surfaces, such as forests) and greenhouse gas concentrations (Roberts, 1998).

The present interglacial, the Holocene, which started about 11 700 years ago, offers the best opportunity to study past climate change in detail since there are plenty of well-preserved natural archives available from this time period (Roberts, 1998). Peat bogs, built up of accumulated subfossil plant remains, are one such archive, offering highly valuable information especially of hydrological changes (de Jong *et al*., 2009). Since raised peat bogs are ombrotrophic, which means that they are entirely dependent on rainfall for their water and nutrient balance, effective precipitation (precipitation minus evapotranspiration) has a great effect on the development of a peat ecosystem. Moreover, information of these changes in the past is preserved in the peat stratigraphy itself (Charman, 2002). They can often be seen with the naked eye as changes in the degree of decomposition of the peat, or they can be defined by other proxy methods such as plant macrofossil analysis (the study of macroscopic plant remains), laboratory methods measuring decomposition (humification analysis and bulk density) or testate amoebae analysis (study of microscopic tests from unicellular organisms preserved in the peat).

Hydrological changes related to variations in precipitation and evapotranspiration, although equally important components of climate change as direct temperature changes, have been in less focus of palaeoclimatic research in the past (Hammarlund *et al*., 2003). Since development of peatlands are directly linked to hydrological conditions, and peatlands have acted as an increasingly large carbon sink during the Holocene through continuous accumulation and storage of organic material as peat, it is of great importance to study the effects of hydrological changes in peatland ecosystems (Rundgren, 2008). Large scale hydrological changes influence decomposition in peatlands, and if they are regional over large areas they might affect both atmospheric CO^2 and methane concentrations and become thus a potential feedback mechanism further enhancing climate change (Rundgren, 2008).

Dendrochronology (the study of tree-ring width providing records of annual growth with the purpose of dating living and fossil trees or wooden objects) conducted on subfossil tree trunks and stumps found in peat bogs offers an excellent indicator of past hydrological changes (Edvardsson *et al*., 2012a). When dendrochronology can be used, it offers a higher resolution (annual to decadal) than proxies of hydrological change applied to the peat itself (humification analysis, peat stratigraphy, macrofossil analysis, testate amoebae analysis) since the tree ring width reflects the annual growth of a tree. A combination with stratigraphical analysis and other hydrological proxies is, however, necessary to put the tree samples in a palaeohydrological context (Edvardsson *et al*., 2012a). To be able to draw correct conclusions from dendrochronological studies, it is important to study the environmental conditions of the time period in the peatland's development when the bog-trees occurred with focus on the questions of when and why the trees established and died.

1.1 Aim of the study

The aim of this study is to document and date the Holocene occurrence of Scots pine (*Pinus sylvestris*) on the raised bog Stass Mosse (central Scania, southern Sweden) and how it is related to local hydrological conditions and bog development. The intention is to test if the establishment, growth and degeneration of bog-pines are connected to changes in bog surface wetness (BSW). Already existing evidence of pine occurrence, consisting of subfossil pine stumps dendrochronologically investigated by Edvardsson (2013a), are supplemented with macrofossil analysis focusing on pine remains. The bog-pines are placed in a local palaeohydrological context using visual peat stratigraphical analysis, macrofossil analysis and peat humification (level of decomposition) measurements. The results are compared with similar studies of past hydrological conditions in the region to analyze possible connections between bog-tree occurrence and hydrological and climatic conditions on a regional scale.

1.2 Background

1.2.1 Peatland development

Peat initiation can only take place if a critical threshold is crossed, i.e. that production of plant organic matter exceeds decay (Charman, 2002). Many factors can play a part to make an ecosystem cross this threshold.

The most important are climatic factors, mainly effective precipitation. Other factors include topography which affects water collection, geology, the presence of certain plant taxa (for example *Sphagnum* mosses) and in some cases human activities.

There are two ways in which peatlands can form, from a shallow lake (terrestrialisation) or directly on mineral soil (paludification) (Charman, 2002). The process of terrestrialisation, also called hydroseral succession, is natural and requires no environmental change (Charman, 2002). A shallow water body is infilled with accumulated debris so that the water table is at or below the surface. At that point gyttja formation is replaced by fen peat formation that may later be replaced by bog peat formation.

Once a peatland is formed, peat accumulation continues to be determined by a balance of production and decay rates, where decay rate is the more important of the two (Charman, 2002). Both production and decay of a peatland largely takes place in the surface layer of peat, called the acrotelm. The acrotelm is aerated and active, with both more growth and decay taking place than further down in the peat, called the catotelm. The catotelm is always waterlogged slowing down the rate of decay due to anoxic conditions and supports no production except for deep penetrating roots of certain higher plants. Also, when the organic material reaches the catotelm, much of the produced material is already lost due to the fast decay in the acrotelm. The decay taking place in the catotelm, though slow, becomes relevant at the millennial time scale. Therefore it is somewhat simplified to calculate peat accumulation rates for old peat based on only age and depth, because the peat has constantly been slowly degrading since it entered the catotelm.

Water table depth and in consequence bog surface wetness (BSW) are very important factors for both production and decay in a peatland (Charman, 2002). BSW is closely linked to effective precipitation (precipitation minus evapotranspiration), which in turn is driven by both precipitation and temperature (Charman *et al*., 2009). In the case of production, different plants respond differently to changes in BSW (Charman, 2002). The production of *Sphagnum* has been shown to increase with increased wetness in northern oligotrophic (nutrient poor) mires. Decay is affected by water table changes because bacterial communities change relatively to aerobic and anaerobic conditions and aerobic decay is faster than anaerobic decay. In a forested peatlands there is often a greater depth of the aerobic zone, due to thick roots penetrating the peat supporting oxygen and therefore forested peatlands often show faster decay rates than non-forested. Additionally, *Sphagnum* dominated peatlands in general have slower decay rates than peatlands dominated by other peat forming plants, because *Sphagnum* withstands decay by release of phenolic compounds and carbohydrates (uronic acids) which acidifies the environment. *Sphagnum* slows down the decay in the catotelm even more by the release of tannins (Charman, 2002).

BSW is not uniform over a peat bog, but is affected by microtopography, where hummocks are drier than hollows (Wallén *et al*., 1988). Mire plant species are often specialized to grow on either hummocks or hollows.

1.2.2 Fens and bogs

The difference between a fen and a bog is that fens receive water and nutrients from surface water and groundwater inflow, while bogs only input of water and nutrients comes from rainfall (Charman, 2002). This makes fens in general eutrophic (nutrient rich) and bogs in general oligotrophic (nutrient poor). The special characteristic of a raised bog's nutrient supply coming entirely from rainfall is termed ombrotrophy. This characteristic makes bogs much more sensitive archives of past climate change, than fens (Langdon *et al*., 2003; de Jong *et al*., 2009). Most bogs have been fens in the past and the fen-bog transition (FBT) is a well known characteristic seen in raised bog peat stratigraphies (Hughes & Barber, 2003).

The FBT has often been viewed as an autogenic process and part of the hydroseral succession (through acidification from rainfall and establishment of *Sphagnum* mosses), but Hughes & Barber (2003) showed several ways in which the FBT could be speeded up or even caused by climatic factors, mainly through changes in effective precipitation. They showed two opposite hydrological changes by which a first transition from eutrohpy to oligotrophy begins in a fen ecosystem. One route to oligotrophy is caused by a period of wet climate (high effective precipitation). This benefits *Sphagnum* establishment and growth at the same time as humification (level of decomposition) is low. The water table remains at or close to the mire surface and the separation from surrounding surface and groundwater is entirely caused by rapid peat accumulation by increased production of *Sphagnum* and decreased decomposition. The opposite route begins with lowering or fluctuations of the groundwater table during dry or unstable climatic conditions, separating the mire surface from groundwater influence. This leads to decreased BSW and in turn increased aerobic conditions and increased decomposition. The highly humified peat formed under those conditions may be constituted either by drought-tolerant *Sphagnum* species, *Eriophorum vaginatum* or *Calluna vulgaris* (Hughes and Barber, 2003). The mire water table then stabilizes at or near the bog surface, species composition changes (increases in *Sphagnum*, *Rynchospora alba, Erica tetralix*) and with time a *Sphagnum* dominated ombrotrophic raised bog begins to develop.

1.2.3 Bog-trees

The presence of buried tree trunks and stumps in peat bogs is a phenomenon that has been known for a long time and the focus of scientific interest since the early 19th century. In Denmark it was in fact bog-tree horizons that brought the idea that preserved plant remains in peat could be connected to different past climatic conditions (Birks & Seppä, 2010). Bog-tree horizons, especially of Scots pine, have been found to be a common feature in Scandinavian peat bogs, often with repeated establishment phases during the Holocene (Edvardsson *et al*., 2013a). The horizons often cover a large part of the bog surface, making up a woodland phase in the bog's development history (Eckstein *et al*., 2011). The establishment phases are thought to have occurred during periods of low BSW, since trees need a certain distance to the water table beneath their root system. A high groundwater table would stress the trees and inhibit root development by lack of oxygen, CO^2 accumulation, Fe reduction, toxic compound formation and lack of nutrients by thinning of the unsaturated zone where decomposition takes place (Boggie, 1972; Mighall *et al*., 2004; Eckstein *et al*., 2011; Edvardsson *et al*., 2012b). Because of these unfavourable conditions, stemming from a high groundwater table, bog trees generally grow close to their physiological distribution limit. On the other hand, a lowering of the groundwater table might enable increased tree growth and germination and in turn spread of trees to new parts of the bog. Lower BSW enabling widespread establishment of trees that are characteristic of a woodland phase might be related to either drier climatic conditions or local hydrological changes, for example the FBT (Eckstein *et al*., 2011). Leuschner *et al*. (2002) dated and investigated tree-ring series on subfossil bog-oaks from Germany, the Netherlands and Ireland and found synchronous regional changes in establishment phases and annual growth related to water table fluctuations. This indicates that regional hydrological change impacted the establishment and growth of the bog-oaks.

Edvardsson *et al*. (2012a) conducted dry bulk density measurements, that can be used as a proxy for BSW, on peat accumulated during a bog-pine phase at Viss Mosse, central Scania, Sweden. The results showed that BSW decreased during the pine-period at the bog, indicating a dry period. This is consistent with the fact that the pines grew during the warm and dry period during mid-Holocene usually termed the Holocene Thermal Maximum (HTM), beginning ca 8000 cal BP and ending sometime between 5000 and 4000 cal BP (Jessen *et al*., 2005; Seppä *et al*., 2009). Establishment and degeneration phases also reflect the BSW changes recorded by Edvardsson *et al*. (2012a). During this period, bog-pine ring-width chronologies from Southern Sweden analyzed by Edvardsson *et al*. (2012b) significantly matched similar ring-width chronologies from North-western Germany, indicating that the bog-pines growth were influenced by large scale climatic variations. Modern bog-pine populations were, however, to a lesser degree influenced by regional large scale climatic changes than the HTM bog-pines. (Edvardsson *et al*., 2012b).

1.2.4 Peat-stratigraphical and palaeoecological research in Scandinavia, a historical overview

Studies of Holocene hydrological changes preserved in peatland archives have a long history in Scandinavia (Birks & Seppä, 2010). Heinrich Dau, a Danish researcher who dug and cored in mires during the 19th century, noticed that the peat consisted of lighter and darker layers, where the lighter layers were constituted by poorly decomposed peat and the darker ones by highly decomposed peat. The Norwegian Alex Blytt and the Swede Rutger Sernander were two later pioneers in late Quaternary palaeoclimatic research (Birks & Seppä, 2010). They took the peat-stratigraphical research further by connecting the variations in decomposition and floristic composition, through macrofossil analysis, with varying climatic conditions. Light, less decomposed peat layers had been formed during humid conditions and dark, higher decomposed layers often containing wood remains had been formed during dryer periods. The model for past climate change that Sernander created based on his own and Blytt's research became known as the Blytt-Sernander scheme and was quickly established in the Scandinavian countries and spread to other parts of Europe. The scheme divided the Holocene interglacial into four different climatic periods, the Boreal (continental climate), the Atlantic (oceanic climate), the sub-Boreal (continental climate) and the sub-Atlantic (oceanic climate). The Blytt-Sernander scheme has been extensively used as a model for past climate change or simply as a timeframe in late-Quaternary research. It has been questioned, however, that regional climate change and not local changes in BSW caused the observed decomposition changes. In recent decades, the scheme has been abandoned because it is not entirely consistent with the current knowledge of Holocene climate change, as the large-scale regional climatic periods implicated by the scheme have not been confirmed by modern palaeoclimatic studies supported by radiocarbon dating (Birks & Seppä, 2010).

Granlund (1932) found several abrupt changes from high to low decomposed peat in late Holocene peat stratigraphies from central Sweden that he connected to changes in effective precipitation and humidity. He termed the sharp stratigraphic boundaries "recurrence surfaces" (Swedish: rekurrensyta). The initial idea by Granlund (1932) that the rapid changes in decomposition were caused by climatic factors, making the recurrence regionally synchronous, is today considered to be too simplified, since different peatland systems have different thresholds for change and responses may be non-linear (Rundgren, 2008). Therefore changes in decomposition caused by the same climatic change may differ more or less in time and magnitude between different peatlands. Today these kind of abrupt changes to more humid conditions

Fig. 1. Map of Scandinavia with the province of Scania zoomed in, with the location of the study site Stass Mosse marked with a black dot. Marked with small black dots are the Swedish sites of the studies used for the regional comparison in the discussion section. They are: 1: Lake Igelsjön (Hammarlund *et al.*, 2003; Jessen *et al.*, 2005) 2: Store Mosse, Halland, 3: Undarsmosse (de Jong *et al.*, 2009), 4: Store Mosse, Småland (Kylander *et al.*, 2013), 5: Fågelmossen, 6: Kortlandamossen and 7: Strömyren (Borgmark & Wastegård, 2008). Maps modified from Google Maps (2013).

clearly visible in peat-stratigraphies are usually called "wet-shifts" (Rundgren, 2008).

2. Study site

Stass Mosse (55°54'N, 13°45'E) is a peat bog approximately 0.3 km^2, situated on the Linderödsåsen Ridge in central Scania (Fig. 1). Since the bog has been used for peat mining in the past, which continued until the 1960s, only a small area of the undisturbed bog surface remains (Liljegren & Björkman, 2012). This area is today covered with a coniferous forest dominated by Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). Downy birch (*Betula pubescens*) is also present. Understory vegetation is dominated by *Calluna vulgaris, Erica tetralix, Vaccinium spp*. and brown mosses. The bog was also drained in connection with the exploitation and numerous drainage ditches can be seen south of the bog. Remains of rail tracks that were used for peat transport during the peat cutting period still run across the bog and a shed with old train wagons was found to the southeast of the bog. Information of how much peat has been removed was not found during this project, but the excavated area covers more than 0.1

Fig. 2. Part of the excavated peat surface on Stass Mosse, with exposed subfossil stumps and roots of Scots pine. (Photograph: Linda Adamsson, 2012)

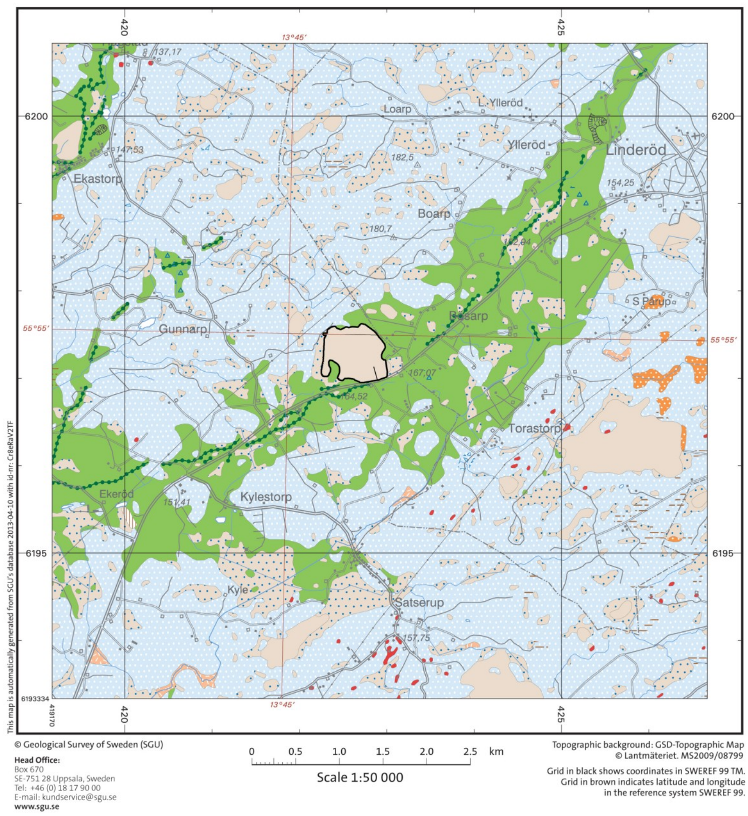
km². On the mined surface a large amount of Scots pine stumps and roots have been exposed, giving an impression of a once relatively densely forested peat bog (Fig. 2). Vegetation on the mined peat surface is scarce, but includes scattered occurrence of *Eriophorum vaginatum, Carex spp. and Calluna vulgaris.*

2.1 Bedrock

Linderödsåsen Ridge is a bedrock horst formed by movements in the Tornquist deformation zone, which is running NW-SE across Scania (Erlström *et al.*, 1997). The deformation of the Tornquist zone started when the continents Avalonia and Baltica collided during the early Silurian (440-420 million years ago). The bedrock at the locality consists of Precambrian gneiss (Ringberg, 1986). It probably derives from granite. Permian-Carbonian diabase dykes, part of the Tornquist deformation zone, are running in a NW-SE direction through the area.

2.2 Quaternary deposits

Stass Mosse is situated on an almost 20 km² large glaciofluvial deposit running in a NE-SW direction (Fig. 3). An esker with a ridge crest 3-10 m above the surroundings runs just south of the bog and continues to the northeast and southwest. Surrounding the esker occur thinner deposits of glaciofluvial gravel and sand, which are, in the lower parts of the terrain, overlain by organic deposits (bog or fen peat). The glaciofluvial deposit is characterized by broken-up and forked eskers containing course material from boulders to gravel with layers of sand and sometimes silt (Ringberg, 1986). These more defined eskers are gradually transcending into thinner glaciofluvial deposits forming low hills, ridges and plateaus containing gravel or sand. The last ice-movement in the area was from the northeast as shown by striae. Today's landscape was shaped as the ice melted away on a relatively flat terrain and sedimentation took place on top and in between dead-ice bodies separated from the active ice sheet, probably in shallow water. Ice retreat took place sometime between 15,000 and



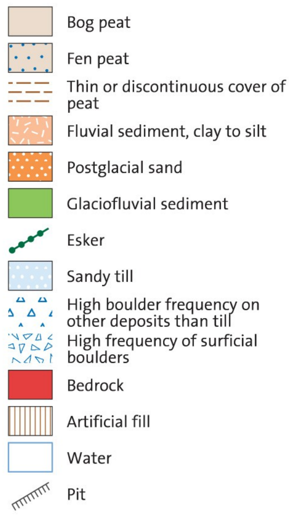


Fig. 3. Map of Quaternary deposits in the vicinity of the study area. The Stass Mosse peat bog (area shown with a black line) is situated just north of an esker ridge on top of glaciofluvial deposits. Fen peat deposits border the bog peat to the west and southeast. Sandy till emerges to the northwest. Map modified from SGU (2013).

14,000 years ago (Lundquist & Wohlfarth, 2001). During the deglaciation there was likely a large dead-ice body left behind where Stass Mosse now is situated, preventing sedimentation and leaving a depression in the landscape when the ice later melted away. At the northern edge of the bog the sandy till underlying the glaciofluvial deposit emerges at the surface.

2.3 Current climate

Meteorological data from Linderöd village, situated about 4.5 km NE of Stass Mosse, from the latest 30-year standard period (1961-1990) show that the mean annual temperature was 6.8°C and mean annual precipitation 793 mm/year (SMHI, 2013).

3. Material and Methods

3.1 Field work

The field work was conducted during the autumn of 2012. An initial survey of the study site was performed on 4 September 2012, during which two peat sequences were retrieved with a Russian sampler and described in the field (but not used for further analyses).

The main field work took place 11-12 September 2012. During these days peat cores were collected with a Russian sampler (1 m length, 7.5 cm diameter) at three different locations on the peat bog (Fig. 4). One location, where the uncut peat surface was preserved, was selected to obtain a complete peat sequence until today (Complete Sequence, CS). Another location immediately next to an exposed pine-tree stump on the excavated part of the bog (Tree Sequence, TS) was cored for correlation of the pine-horizon to the complete sequence with help of the stratigraphy, bulk density and humification analysis. A third location midway between the two mentioned locations was also sampled (Mid Sequence, MS), to facilitate in the correlation of the two other sequences. An overlap of 50 cm between 1 m segments was used while coring. The cores were described and photographed in the field and then wrapped in plastic and brought to Lund to be stored in a cold room at Geocentrum, Lund University, awaiting further analysis.

Levelling of the surface of the bog in relation to an arbitrary reference point (ground surface at the CS location) was conducted with a levelling instrument between the cored locations and also along two perpendicular transects across the bog. During the levelling the distance between coring locations and among points along the transects were also measured. GPS points were taken for the coring locations and some transect points. Depth to underlying minerogenic sediments was measured with a probe at some points along the transects to make a depth profile of the bog. Photographs were taken to document the bog environment and some additional wood samples were collected (by Johannes Edvardsson).

An additional day of field work took place 31 October 2012. Levelling data were verified and modern vascular plants and mosses were sampled to be used as a reference collection during the macrofossil analysis. The plants and mosses selected were vascular plants commonly growing on peat bogs and fens (for example *Carex spp., Eriophorum vaginatum, Juncus spp.* and several species of the *Ericaceae* family), *Sphagnum* mosses and brown mosses, as well as bark, roots and other parts of trees (*Pinus sylvestris, Betula pubescens, Picea abies, Alnus glutinosa*).

3.2 Laboratory work

3.2.1 Description, correlation and initial sampling

A well developed description and correlation of the stratigraphy gives an understanding of the major changes in time and space that have taken place in the bog (Charman, 2002). It also provides information for the next steps of laboratory analysis and provides a basis for decision of a focus interval.

The peat cores were opened in the laboratory and the field depths and descriptions were verified or changed accordingly. The cores were photographed again in the lab. The cores from each sequence (CS, MS and TS) were correlated internally by choosing corresponding correlation points between overlapping cores. These points were carefully selected using boundaries of changing humification or peat composition. The cores were shifted in relation to each other so that each corresponding correlation point was in line with each other. New depths were measured according to the new correlated overlaps. Master stratigraphies were then developed by removing overlaps. The internal correlation of the sequences resulted in three master stratigraphies with description of depth, peat type, colour, estimated humification level and additional details for each peat sequence. The field description of peat type and humification estimation was revised after verification with a low power microscope. The stratigraphies were then divided into larger units for a better overview of the main peat characteristics and changes during peat development.

After the internal correlation of the three sequences they were also correlated externally to each other. The external correlation was particularly important in this study since the bog has been cut for peat and the goal was to get an idea where the pine-tree horizon might have been situated in depth (and time) in relation to the uncut bog surface. To do this the TS had to be correlated to the CS. The MS was used as a help in the correlation since it was reaching stratigraphically higher than the TS. The procedure of the correlation was the same as for the internal correlation. Correlation points were selected using clear shifts in humification and/or peat (or gyttja) type.

Unfortunately, since it was the most important core to correlate, the highest of the core segments within the TS differed from the assumed corresponding intervals in the CS and MS. The difference was due to a rich occurrence of *E. vaginatum* and wood/root remains in the highest core segment within the TS. Therefore it could not be exactly correlated to the CS at this stage, but rather three possible correlation alternatives were retained. Depending on the uncertain correlation, a wider focus interval in the CS, taking into account all three alternatives was selected for further analysis. The analyses were expected to solve both the question of when the pines found at the excavated bog surface where present in the CS and the correlation problem between the CS and the TS. Radiocarbon dating was also expected to help solving these problems. The focus interval chosen for the CS was between 230 and 390 cm depth.

Subsampling of the focus interval for further analyses was done by cutting the cores in halves, saving one half as reference and for future analyses. The other half was cut in contiguous samples of 1 cm thickness.

Determination of the sample volume was made by drawing shapes (cross sections) of samples on a piece of paper. The drawn shapes were cut out and weighed. Uncut A4 papers were also weighed to calculate average paperweight. The area of an A4 paper then gave weight per area paper. The area of the cut shapes and the thickness of the samples (1 cm) were then used to calculate sample volume. Determination of the weight of wet samples was made by weighing a plastic bag, weighing the sample in the plastic bag and then subtracting the weight of the plastic bag.

3.2.2 Radiocarbon dating and age-depth modelling

Radiocarbon (^{14}C) dating together with age-depth

Fig. 4. Stass Mosse from above, showing coring locations where the CS, MS and TS were obtained (white dots), transects (red lines) with leveling points marked (yellow dots) and the initial survey coring locations (white dots). Picture modified from Google Earth (2013).

modelling is necessary to provide time-scales for and timing of events shown in the peat cores (Bronk Ramsey, 2008). Seven samples for radiocarbon dating were taken from cores in the relevant interval. Both the CS and the TS were sampled. *Sphagnum* macrofossil samples were used for dating when possible. In the samples where bulk peat material had to be used, major roots were removed from the samples to increase dating precision.

The seven dates acquired from radiocarbon dating were calibrated individually but also in a stratigraphically constrained sequence to create an age-depth model for the dated intervals within the two peat sequences. The age-depth model was created in the OxCal online software version 4.2 applying the INTCAL09 calibration dataset (Reimer *et al*., 2009). The depositional model used assumes a random deposition (in this case peat accumulation) with an approximate proportionality to depth (P_sequence in OxCal) (Bronk Ramsey, 2008). The amount of variability in deposition in this model is controlled by a factor specifying the number of increments per unit time (k-value in OxCal). If this value is high the model allows for a large amount of variability in peat accumulation through time and if it is low peat accumulation is constrained to be less variable through time. This value should be set so that the agreement index of the model is at least 60 % (Bronk Ramsey, 2008).

3.2.3 Bulk Density and Loss on ignition

Dry bulk density is a measure of density of the dried peat in a sample (including organic and mineral content). Organic bulk density (OBD) is the density measure of the dried peat exclusive of minerogenic content. Both can be used as proxies for the degree of humification of the peat (Chambers *et al*., 2011). A less decomposed peat contains larger plant remains (usually *Sphagnum*) and therefore has high water content and in turn low OBD (de Jong *et al*., 2009) Loss on ignition (LOI) is a method used for determination of percentage organic matter in peat (Chambers *et al*., 2011).

Subsamples of the approximately same volume ($1cm^3$) were taken from the initial samples from the CS focus interval. The samples were placed in marked, washed, dried and weighed crucibles. The samples were weighed in the crucibles before they were put in an air-circulation oven to dry for at least 12 hours at 105 °C, to evaporate all water from the samples and give the water content as a percentage (lost weight). The dried samples were then put in a muffle oven and burned at 550 °C, which results in combustion of all organic matter in the samples and gives the LOI as a percentage (lost weight).

The calculation of dry bulk density was made by first calculating the dry weight of the initial samples. This was done by subtracting a calculated amount of water from the wet weight of the initial samples (using water content in percentage derived from drying the subsamples in 105 °C). Dry bulk density was then calculated by dividing dry weight with volume of the initial samples. The organic bulk density was calculated by multiplying dry bulk density with LOI percentage derived from burning the subsamples at 550 °C.

3.2.4 Humification determination

The level of humification of the peat provides a measure of decay (Caseldine *et al*., 2000). High humification level means that organic material is more degraded and vice versa. Since decay in peatlands is closely linked to hydrology, at first hand local changes in water table, humification analysis provides a measure of changes in hydrology through time (Charman, 2002). In this study a colorimetric method was used that measures the amount of humic acids extracted from the peat when treated with 8% NaOH solution, since these are proportional to the humification level of the peat (Caseldine *et al*., 2000). The botanical composition can in some cases bias the level of humification (especially *E. vaginatum* peat), but taking this into account the results of a humification analysis can provide reliable evidence of large shifts in bog surface wetness (Borgmark & Wastegård, 2008).

The uppermost 81 cm of the TS and the focus interval of the CS were sampled for humification analyses. Approximately 1 cm contiguous samples of a non specified volume (no volume needed for this analysis) were sub-sampled from the initial samples. Every second sample (even start numbers) was frozen overnight and then freeze dried for 48 hours. After the samples were freeze dried they were ground with pestle and mortar.

The humification determination followed the protocol by Chambers *et al*. (2011). Samples of 0.2 g were heated near boiling point in 8% NaOH solution, to dissolve humic matter, and subsequently filtered. Absorbance and percentage of light transmission through the extracts were measured with a spectrophotometer at 540 nm.

3.2.5 Macrofossil analysis

Plant macrofossils, which include subfossil vegetative parts, seeds and fruits found in for example peat, are analyzed to gain knowledge of changes in plant communities at the surface of a bog over time (Charman, 2002). Plant macrofossils are mostly autogenic, which means that they represent remains of plants that have grown at the sample location, at a certain time in the bog's history. Changes in plant communities reflect changes in local bog surface wetness and in turn indicate changes in effective precipitation (Mauquoy & van Geel, 2007). In this particular study, any identified macrofossil remains of *Pinus sylvestris* would be highly interesting as they would constitute definite evidence of pine presence on the peat bog. One limitation of macrofossil analysis is selective decomposition, which means that some plants are overrepresented and that an accurate reconstruction of complete past vegetation communities is not possible (Mauquoy & van Geel, 2007). A complicating factor in interpretation is the non-linear response of plant communities to changes in water-table depth (Barber *et al*., 2003). For those reasons interpretation should be made with care.

Macrofossil sampling and sample treatment followed the protocol described by Mauquoy *et al*. (2010), with some adjustments to better suite this study. Approximately 2 cm^3 samples were subsampled from the initial samples from the focus interval of the CS and the uppermost 30 cm of the TS. The samples were put in previously tared boxes on a balance and the sample weights were recorded. A solution of 5 % NaOH was poured in a volume measuring cylinder. The sample was put into the solution in the cylinder and the sample volume was measured as the change in volume (water displacement method). The solution with sample was then poured back into the box and was left for at least 3 hours, to dissolve the humic and fulvic acids from the sample. After this treatment the samples were sieved through a 250 µm sieve and the sieved samples were put back in the box dissolved in water.

The macrofossil analysis followed the Quadrat and Leaf Count Macrofossil Analysis technique (QLCMA) developed by Barber *et al*. (1994), which includes estimation of the main peat components and identification of *Sphagnum* mosses. The main components of the peat were estimated by 1 cm^2 quadrat counts under a 150 x magnification stereo microscope. This was done on subsamples of 20 ml derived from 200 ml total dissolved samples. Fifteen random squares were counted for each sample and the main components of each square were calculated as percentages. Subsequently, an average of the percentages of the peat components for all fifteen squares was calculated.

Identification of *Sphagnum* was done by picking out 100 random *Sphagnum* leaves from each sample. These leaves were then identified to a section or to species level using a low magnification (150-625 x) stereo microscope or, if necessary, a high (78.8-1250 x) magnification microscope. Identification was made using literature (Mauquoy & van Geel, 2007), the reference collection developed from living plants collected at the study site and the reference collection present at the Department of Geology, Lund University.

In addition to the QLCMA technique (Barber *et al*., 1994) that was applied on subsamples, the complete samples were also systematically examined under a low magnification stereo-microscope. The main goal was to search for and identify any remains of pine (bark, needles, mycorrhiza etc), together with other macrofossils that are not represented by the main components of the sample (e.g. seeds, bark, mycorrhizal roots). These macrofossils were picked out and if possible identified using literature (Nilsson, 1952; Mossberg & Stenberg, 2003; Mauquoy & van Geel, 2007; Cappers *et al*., 2012) and the reference collection.

Visible roots that were found throughout the collected peat sequences were picked out and identified with a low and, if necessary, high power microscope. This was done to complement the macrofossil analysis and also to gain knowledge of which tree taxa were growing on the bog surface during the development of the peat bog.

4. Results

4.1 Peat stratigraphies

The master stratigraphies of the Complete Sequence (CS), Mid Sequence (MS) and Tree Sequence (TS) are presented in Fig. 5. The units are described in Tables 2-4.

4.2 Bog surface topography and peat depth

Fig. 6 shows a depth profile resulting from the levelling data and probing of the depth to the underlying minerogenic sediments along a 470 meter long transect across the bog in 155 °SSE direction (Fig. 4). Since much of the peat is cut away, the undisturbed, possibly domed bog surface has been lost. The currently highest point (1.40 m above ground level at the CS) is located approximately 50 m NNW of the CS, on what remains of the uncut peat surface. The deepest part of the basin relative to CS ground level (about 7 m below ground level at the CS) is located approximately 235 m SSE of the CS. Maximum peat depth relative to current ground level was recorded at the CS location. However, before peat-cutting activities started, peat depth may have been greatest at some distance SSE of the CS location, i.e. in the central part of the pristine bog.

The difference in depths of the correlated levels, representing boundaries of changing humification or peat composition that are thought to be synchronous between the sequences, does not correspond to the difference in ground level at the coring locations acquired from the levelling (Fig 6). In the TS the differences range from 1.15 to 1.36 m and in the MS the difference is approximately 0.90 m above the corresponding levels in the CS (Fig 6).

4.3 Radiocarbon dating and age-depth models

The radiocarbon dating (Table 4) and age-depth modelling resulted in two age-depth models, one for the CS and one for the TS. The age-depth plots created in OxCal 4.2 (Bronk Ramsey, 2008) are shown in Fig. 7 and 8. The CS age-depth model contains rather wide probability distributions from 390 to 336 cm. Peat accumulation rate increases above 336 cm. After this

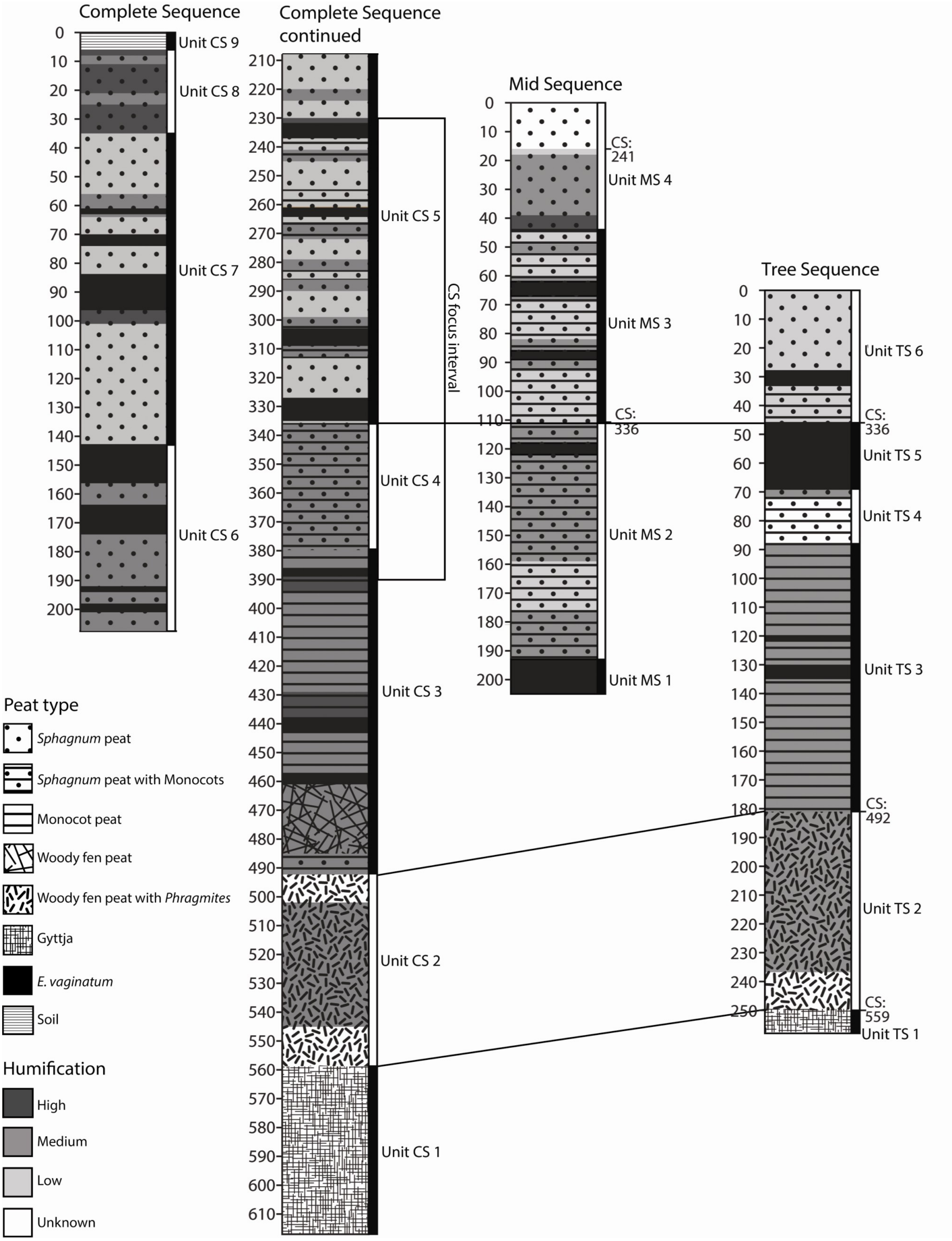


Fig. 5. Stratigraphies of the Complete Sequence (CS), Middle Sequence (MS) and Tree Sequence (TS) on a depth scale (cm) relative to ground level at each coring location. The different units, described in more detail in Tables 2-4, are shown on the right. Correlation levels are marked on the stratigraphies of the MS and the TS and connected with lines to the corresponding depths in the CS.

Table 1. Depth intervals and description of the stratigraphic units in the CS.

Complete Sequence Stratigraphy		
Unit	*Depth (cm)*	*Description*
Unit CS 1	617-559	Algae gyttja and algal rich fine detritus gyttja
Unit CS 2	559-492	Peat with *Phragmites* and wood remains
Unit CS 3	492-380	Medium to high decomposed fen peat dominated by monocots and thin rootlets, with presence of tree roots. Occasional *Eriophorum vaginatum* peat layers. Pine root present at 435-436 cm.
Unit CS 4	380-336	Medium decomposed *Sphagnum* peat with monocots and pine roots.
Unit CS 5	336-208	*Sphagnum* peat with occasional presence of monocots, interrupted by *E. vaginatum* peat layers. Decomposition shows recurrent and abrupt shifts between medium and low.
Unit CS 6	208-143	Medium decomposed *Sphagnum* peat alternated with layers of *E.vaginatum* and presence of roots.
Unit CS 7	143-35	Generally low decomposed *Sphagnum* peat with occasional thin layers with higher decomposition and *E. vaginatum* layers. Some bark and roots present around 100 cm depth.
Unit CS 8	35-6	High to medium decomposed, unidentified peat (probably *Sphagnum*) with fresh roots and bark.
Unit CS 9	6-0	Soil with fresh roots.

Table 2. Depth intervals and description of the stratigraphic units in the TS.

Tree Sequence Stratigraphy		
Unit	*Depth (cm)*	*Description*
Unit TS 1	258-250	Algal rich coarse detritus gyttja
Unit TS 2	250-181	Fen peat with *Phragmites* and wood, medium decomposed
Unit TS 3	181-86	Medium decomposed monocot dominated fen peat with roots. *E. vaginatum* is present around 120 and 130 cm depth.
Unit TS 4	86-69	*Sphagnum* peat with monocots, unknown decomposition
Unit TS 5	69-46	Medium decomposed *E.vaginatum* peat with roots.
Unit TS 6	46-0	Generally low decomposed *Sphagnum* peat (with monocot presence in the basal part). A layer of medium decomposed *E. vaginatum* peat is present at 33-28 cm.

Table 3. Depth intervals and description of the stratigraphic units in the MS.

Middle Sequence Stratigraphy		
Unit	*Depth (cm)*	*Description*
Unit MS 1	205-193	Monocot peat with high *E. vaginatum* presence.
Unit MS 2	193-111	Generally medium decomposed monocot/*Sphagnum* peat with roots. Lower decomposition between 166 and 159 cm
Unit MS 3	111-44	*Sphagnum* peat with monocots, with interjacent *E. vaginatum* layers. Decomposition alternates between low and medium. Presence of roots at 94-95 and 84 cm.
Unit MS 4	44-0	Medium to high decomposed *Sphagnum* peat with roots.

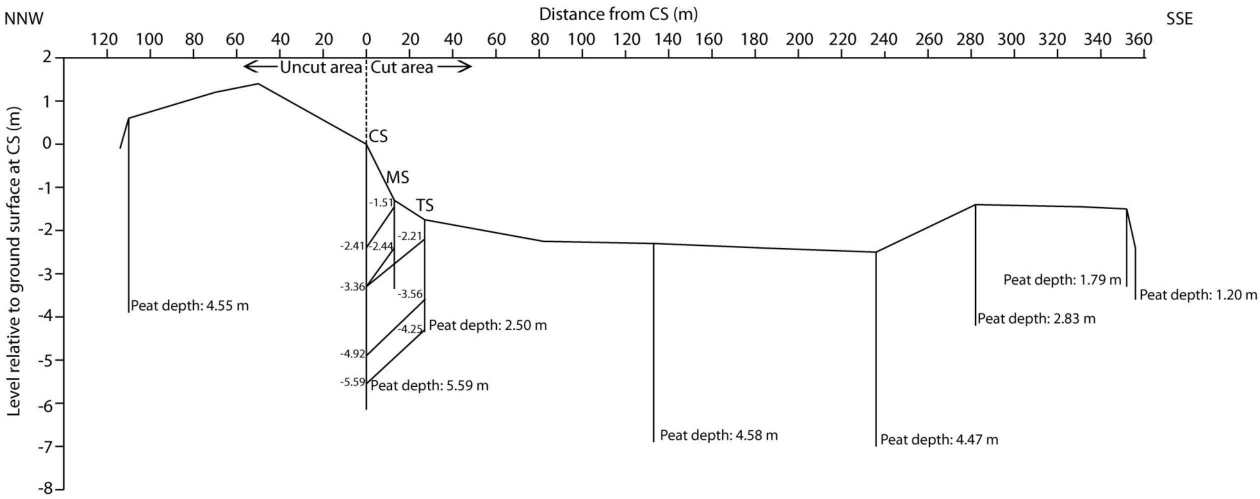


Fig. 6. Depth profile based on leveling data along a NNW-SSE transect across Stass Mosse, showing the ground level relative to the CS fix point location. Measured peat depth relative to present ground level is shown at most of the transect points and also gives information of the depth of the peat filled basin relative to ground level at CS.

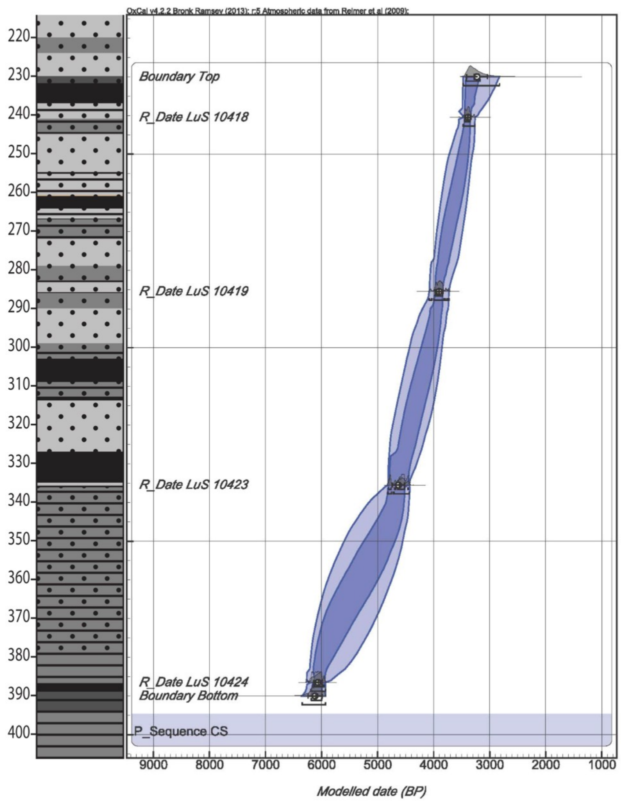


Fig. 7. Age-depth model for the CS produced by the OxCal online software version 4.2 (Bronk Ramsey, 2008). The ^{14}C dated samples are marked by their laboratory code and their calibrated and modeled age distributions with 1 σ (68.2%) and 2 σ (95.4%) probability ranges. Median (black crosses) and weighted mean (white circles) values for the dated levels and the top and bottom boundaries defined by OxCal are also shown. The stratigraphy of the dated sequence is shown to the left.

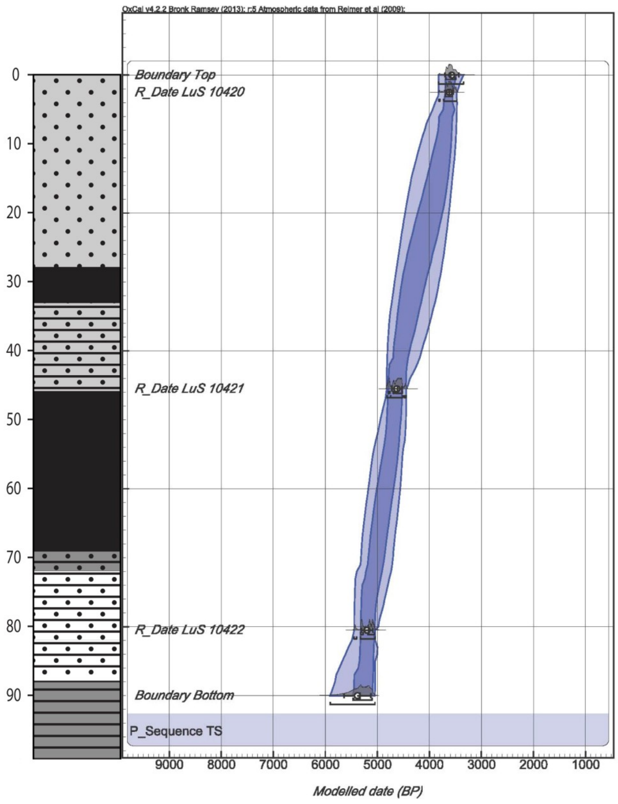


Fig. 8. Age-depth model for the TS produced by the OxCal online software version 4.2 (Bronk Ramsey, 2008). The ^{14}C dated samples are marked by their laboratory code and their calibrated and modeled age distributions with 1 σ (68.2%) and 2 σ (95.4%) probability ranges. Median (black crosses) and weighted mean (white circles) values for the dated levels and the top and bottom boundaries defined by OxCal are also shown. The stratigraphy of the dated sequence is shown to the left.

Table 4. Radiocarbon sample depth, laboratory code, peat component dated, obtained 14C ages and their calibrated age intervals (1 and 2 σ ranges) and median.

Peat sequence	*Depth (cm)*	*Laboratory code*	*Peat component dated*	*^{14}C age (yr. BP)*	*Cal. Date interval (cal BP, 1 σ*	*Cal. date interval (cal BP, 2 σ)*	*Cal. date median (cal BP)*
CS	240-241	LuS 10418	*Sphagnum*	3160 ± 50	3445- 3352	3476-3263	3389
CS	285-286	LuS 10419	*Sphagnum*	3590 ± 50	3971- 3841	4078-3727	3902
CS	335-336	LuS 10423	Bulk peat	4070 ± 50	4806- 4455	4818-4438	4608
CS	386-387	LuS 10424	Bulk peat	5305 ± 50	6156- 5949	6195-5932	6057
TS	2-3	LuS 10420	*Sphagnum*	3365 ± 50	3690- 3561	3820-3472	3616
TS	45-46	LuS 10421	*Sphagnum*	4100 ± 50	4789- 4522	4816-4443	4611
TS	80-81	LuS 10422	Bulk peat	4565 ± 50	5320- 5055	5446-5043	5168

increase it remains fairly constant throughout the sequence. The TS age-depth model also shows relatively wide probability distributions, especially between 46 and 0 cm. For the modelling in Oxcal 4.2 the k-value was set to k=0.1 (1 increment per 10 cm), giving the model a very high agreement index for the CS (Amodel=99.1). The same k-value (k=0.1) was set for the TS, assuming that the pattern of peat accumulation is similar at both coring locations, giving an equally high agreement index (Amodel=99.4). The k-value was selected so that the resulting age-depth models were compatible with the assumed synchronicity between the CS 336 cm and TS 46 cm levels suggested by stratigraphical correlation (Fig. 5) and calibration of individual radiocarbon dates obtained for samples immediately above these levels (Table 4). With k=0.1 the calibrated and modelled age intervals overlap and the median cal BP ages for these correlation levels are consistent between the two sequences (Table 4). The median value, rounded to whole centuries, was chosen for the age presentation in text.

4.4 Macrofossils

The results of the macrofossil analysis of the 16 samples from the CS focus interval, 380-230 cm (5900-3300 cal BP), are presented in Fig. 9. The main vegetation components show highly fluctuating *Sphagnum* moss abundances throughout the sequence: low relative *Sphagnum* abundances occur at 380 cm (5900 cal BP), 350-340 cm (5000-4700 cal BP, 310 cm (4300 cal BP), 270 cm (3700 cal BP) and 240 (3400 cal BP). At all other sample levels, *Sphagnum* is the dominant vegetation component (approx. 80 %). *E. vaginatum* has a higher relative abundance (5-10% of the main components) at 310 cm (4300 cal BP) and 270 cm (3700 cal BP). The CS focus interval contains a low relative abundance of monocots except for the lowermost sample at 380 cm (5900 cal BP), where these plant remains make up 30 % of the main components. Thin rootlets dominate this sample (60 % of main components). Compared to *Sphagnum*, all other main components show less magnitude of variation in abundance between samples. For example, the total number of thin rootlets varies between 300 and 900 in 15 squares, while the total number of *Sphagnum* remains varies between 80 and 2900 in 15 squares. Consequently, the relative abundance of thin rootlets, and to some extent most other main components, mirrors the *Sphagnum* variations when displayed as percentages as in Fig. 9.

The *Sphagnum* leaf count results show that *Sphagnum* section *Acutifolia* is dominant with some minor occurrences of *Sphagnum austinii* (formerly *S. imbricatum*).

Remains of Scots pine (*Pinus sylvestris*) were identified in the macrofossil samples as *Pinus* periderm (the outermost layer of the root bark) and *Pinus* mycorrhizal roots (roots colonized by symbiotic fungi). After being present only in small amounts, *Pinus* periderm shows a prominent peak at 340 cm (4700 cal BP). Above this peak, *Pinus* periderm is either absent or present in very small numbers. *Pinus* mycorrhizal roots do not occur below 350 cm (5000 cal BP), but increase dramatically with a very prominent peak at 340 cm (4700 cal BP). Above this level *Pinus* mycorrhizal roots are present in low numbers until 310 cm (4300 cal BP) when a second very prominent peak occurs. Numbers decline in the following two samples, 300-290 cm (4100-4000 cal BP) and become zero at 280 cm (3900 cal BP).

The taxon group “Other bark” contains all bark that was not identified as *Pinus* periderm or as species within the Ericaceae family. The peak at 340 cm (4700 cal BP) is consistent with the records of *Pinus* periderm and *Pinus* mycorrhizal roots. There is also an increase in “Other bark” between 260 and 240 cm (3600-3400 cal BP). Ericaceae bark is generally more abundant in the first half of the focus interval but also in the uppermost sample. *E. vaginatum* spindles peak at 270 cm (3700 cal BP) and are absent or only found

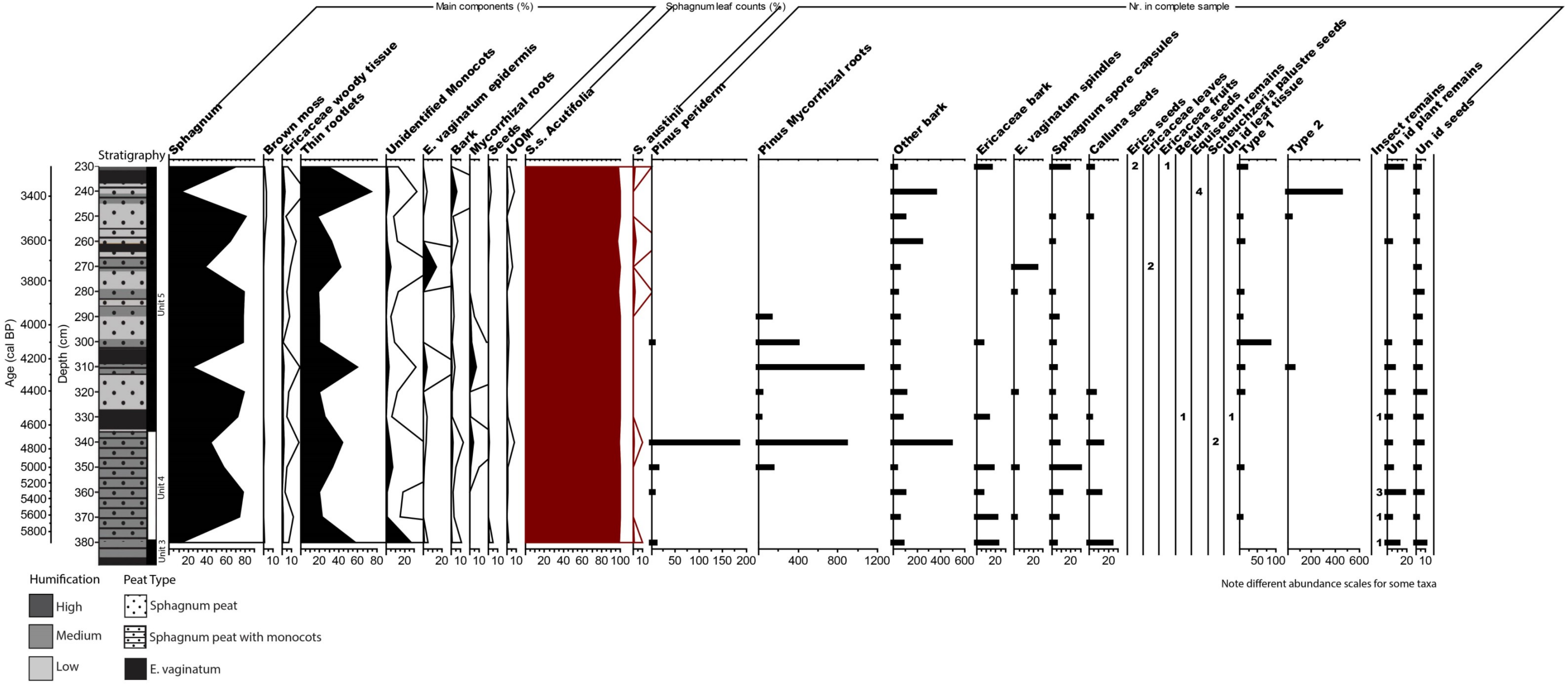


Fig. 9. Macrofossil diagram of the CS showing the results of the Quadrate and Leaf Count Macrofossil Analysis (Barber et al., 1994) and the complete sample examination. Main components are presented as the average of the percentages counted in 15 squares and the *Sphagnum* leaf counts are presented as percentages of 100 randomly selected leaves. Results of the complete sample examination are presented as total number of remains for each taxon or group of taxa in each sample. The macrofossil results are plotted, together with the stratigraphy, showing peat type and visually estimated humification, against depth. A non-linear age scale based on the OxCal age-depth model is also shown.

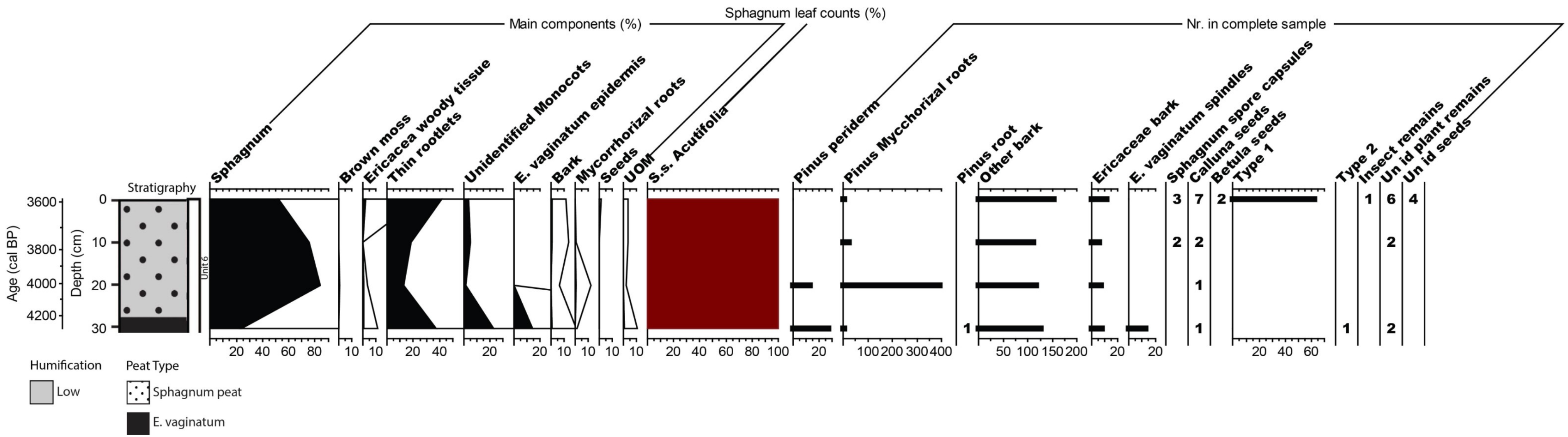


Fig. 10. Macrofossil diagram of the TS showing the results of the Quadrate and Leaf Count Macrofossil Analysis (Barber et al., 1994) and the complete sample examination. Main components are presented as the average of the percentages counted in 15 squares and the *Sphagnum* leaf counts are presented as percentages of 100 randomly selected leaves. Results of the complete sample examination are presented as total number of remains for each taxon or group of taxa in each sample. The macrofossil results are plotted, together with the stratigraphy, showing peat type and visually estimated humification, against depth. A non-linear age scale based on the OxCal age-depth model is also shown.

in small numbers in the remaining samples. *Sphagnum* spore capsules are present in low numbers throughout the sequence except for 270 cm (3700 cal BP) and 240 cm (3400 cal BP). They peak at 350 cm (5000 cal BP). *Calluna* seeds are present in the lower half of the analyzed interval, with maximum numbers at 380 cm (5900 cal BP). Single specimens of *Erica* seeds, Ericaceae fruits, *Betula* seeds, *Equisetum* remains, *Scheuchzeria palustre* seeds and unidentified leaf tissue were also found. Type 1 is an unidentified macrofossil described as matte black, relatively flat flakes, sometimes with 3-4 thin, black, stiff strands protruding in one direction from the surface. This type is found in most of the samples, peaking at 300 cm (4100 cal BP). Type 2 is an unidentified macrofossil (possibly bark) described as thin, yellow-beige, slightly patterned tissue, often with thicker dark semi-round areas incorporated. Type 2 is present in high numbers at 240 cm (3400 cal BP). All other unidentified plant remains and seeds are incorporated in those respective categories. Unidentified seeds are present throughout the sequence in relatively constant numbers. A few preserved insect remains were found in the lower part of the sequence.

Macrofossil analysis results of the four samples from the uppermost 30 cm (4300-3600 cal BP) of the TS are presented in Fig. 10. The results show that *Sphagnum* section *Acutifolia* dominated the peat with high occurrence of thin rootlets. In the lowest sample, 30 cm (4300 cal BP) thin rootlets dominate (40% of main components) and *Sphagnum* has a relatively low occurrence (25 % of main components). Monocots and *E. vaginatum* relative abundances are greater at 30 cm (25 % respectively 15 % of main components) than in the higher samples. From 20 cm (4000 cal BP) upwards, *Sphagnum* dominates (85-55 % of main components) and the relative abundance of monocots is low. Thin rootlets increase in relative abundance to 40 % towards the top of the TS sequence (3600 cal BP).

Pinus mycorrhizal roots are present throughout the sampled sequence, with a clear peak at 20 cm (4000 cal BP). *Pinus* periderm is present in the samples at 30-20 cm depth (4300-4000 cal BP), with decreasing numbers per sample and disappears from 10 cm upwards (3800-3600 cal BP). In the sample at 30 cm (4300 cal BP) a larger part of a *Pinus* root, with preserved wood covered by root bark, was found.

The “Other bark” category shows a constant great abundance in all samples throughout the TS sampled interval. Ericaceae bark is also constantly present. *E vaginatum* spindles are present in the lowermost sample at 30 cm depth (4300 cal BP) *Sphagnum* spore capsules, *Calluna* seeds and *Betula* seeds were found in low numbers, *Calluna* seeds increasing in the topmost sample (3600 cal BP). Type 1 unidentified macrofossil was present in relatively high numbers in the topmost sample, while Type 2 was only present with 1 specimen in the lowermost sample. Unidentified seeds were only present in the topmost sample. One insect remain was found in the topmost sample.

4.5 Humification, organic bulk density and loss on ignition

The results of humification, OBD and LOI analysis for the CS are shown in Fig. 11. Humification in the CS is relatively high (between 55 % and 60 % absorbance) from 388-376 cm (6000-5800 cal BP) above which absorbance values decrease to ca 45 % at 372 cm (5700 cal BP). Fluctuations between 45 % and 55 % absorbance continue until a rapid increase to 63 % at 358 cm (5300 cal BP) occurs. A decrease to 40 % absorbance follows between 358 and 356 cm (5300-5200 cal BP). At 348 cm (4900 cal BP) absorbance values increase again to almost 60 %. Above this peak values decrease gradually to 47 % between 348 and 328 cm (4900-4500 cal BP), followed by an abrupt decrease to 28 % between 328 and 318 cm (4500-4400 cal BP). Above 318 cm (4400 cal BP) absorbance shows a stepwise increase to 54 % at 308 cm (4200 cal BP). It remains around 50 % until 300 cm (4100 cal BP) when percentages abruptly decrease to 34 % at 296 cm (4000 cal BP). This low continues until an increase to 51 % occurs at 288 cm (3900 cal BP). Above the peak at 288 cm (3900 cal BP) absorbance shows a series of abrupt shifts between ca 50 % and ca 25 %.

The OBD of CS is low (ca 0.05 g/cm^3) below 380 cm (5900 cal BP). At 364 cm (5400 cal BP) OBD values rise to around 0.10 g/cm^3 and start to fluctuate between 0.08 and 0.11 g/cm^3 until a peak of 0.12 g/cm^3 is reached at 340 cm (4700 cal BP). OBD values then gradually decrease to 0.06 g/cm^3 at 326 cm (4500 cal BP) and stay this low until 316 cm (4400 cal BP). Between 316 and 300 cm (4400-4100 cal BP) OBD values increase to 0.10 g/cm^3, then decrease to 0.07 g/cm^3 and increase again to 0.10 g/cm^3 at 268 cm (3700 cal BP). Above 266 cm (3700 cal BP) abrupt shifts between 0.10 and 0.05 g/cm^3 are evident throughout the rest of the focus interval.

LOI shows minor variation throughout the whole CS focus interval (between 98 and 100% organic content). Still the curve indicates two distinct units separated by a shift from lower to higher LOI (98 -99 % organic content) between 340 and 334 cm (4700 -4600 cal BP). Below this shift the organic content is mostly fluctuating around 98 %. After the shift the maximum organic content (up to 100 %) is reached at 286 cm (3900 cal BP). The interval between 274 and 232 cm (3800-3300 cal BP) is characterized by a very constant organic content (99 %).

Results of the humification analysis of the TS are shown in Fig. 12. The results show that absorbance values are fluctuating around 60 % before a peak of 78 % at 58 cm (4800 cal BP). This peak is followed by a general decline to 33 % at 44 cm (4600 cal BP). The absorbance value again rises to a peak of 67 % at 38 cm (4500 cal BP). Another two-step decline, occurring

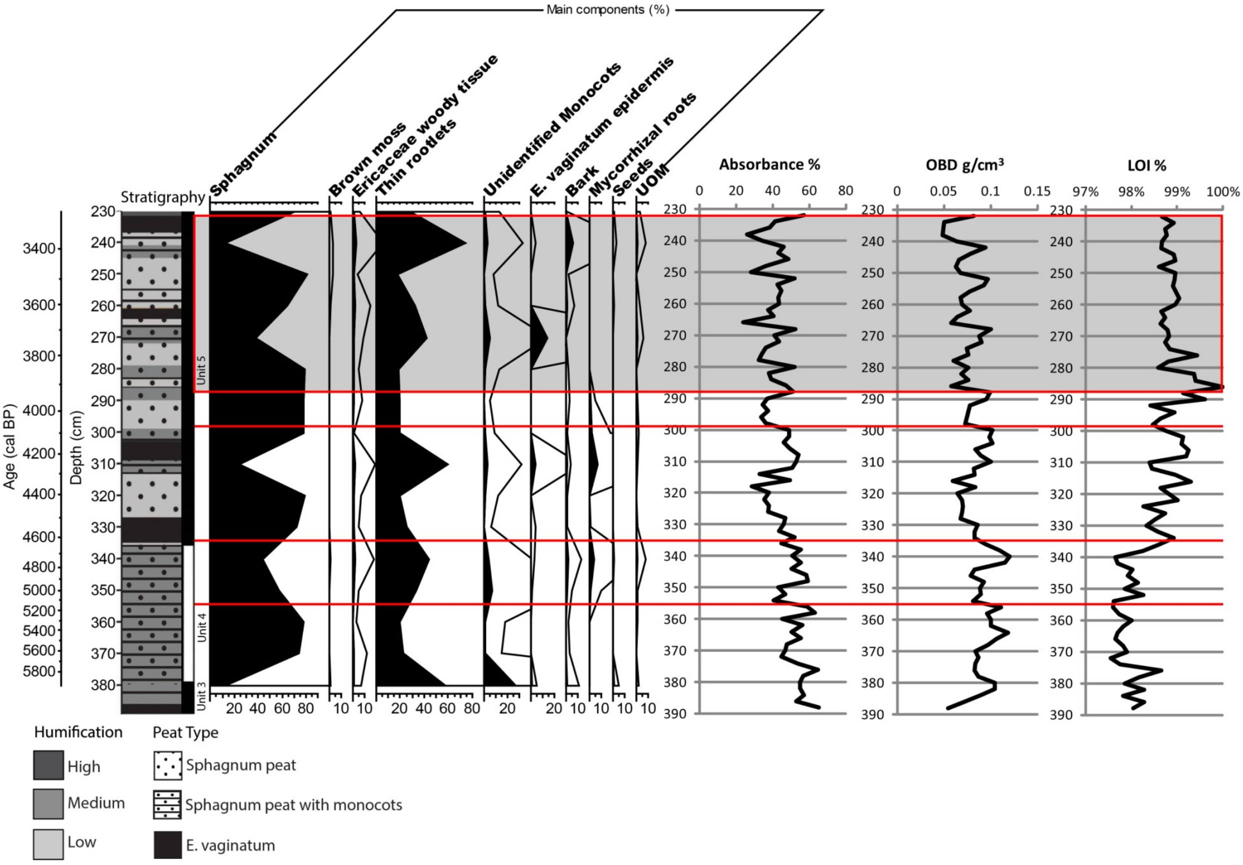


Fig. 11. Focus interval of the CS showing stratigraphy, main vegetation component percentages from the macrofossil analysis, humification (absorbance, %), organic bulk density (OBD, g/cm^3) and loss on ignition (LOI, %) plotted against depth. A non-linear age scale based on the OxCal age-depth model is also shown. Wet shifts (red lines) and fluctuations in bog surface wetness (grey area within red rectangle) are marked.

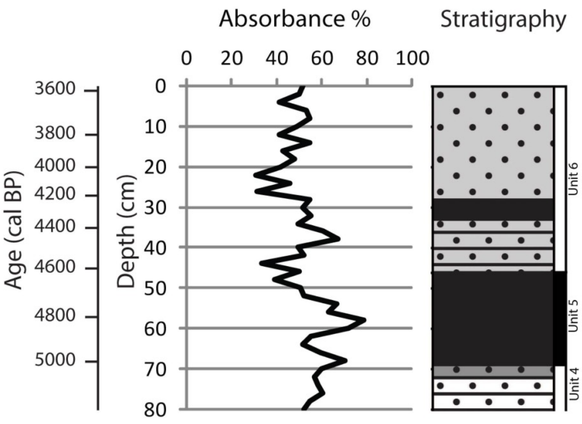


Fig.12. TS humification results (absorbance %) and stratigraphy plotted against depth. A non-linear age scale based on the OxCal age-depth model is also shown.

at 38-34 cm (4500-4400 cal BP) and 28-26 cm (4200 cal BP), with a stable period in between, brings absorbance values down to 30 %. This is followed by fluctuations and a slight increase in absorbance (to ca 50 %) until ca 20 cm (4000 cal BP) after which values are fluctuating between 55 % and 40 %.

4.6 Pine stumps

Of the well preserved pine stumps exposed on the excavated bog surface that were sampled and dendrochronologically analyzed by Edvardsson (2013a) about 1/5 were also radiocarbon dated. These pine trees were dated to an age interval between 4215 and 3779 ± 150 cal BP (Fig. 15). The dendrochronological analysis showed that individual trees lived for up to 400 years and showed depressed growth during most of their lives (Edvardsson, 2013a). The ring-width chronology developed from the dendrochronological data could not be cross dated with a coincident bog-pine chronology from a nearby bog. The pine stump at the TS coring location lived between 4120-3900 ± 150 cal BP, but missing rings indicate it may have lived another 50 years (Edvardsson, 2013b).

5. Discussion

5.1 Peatland development

The stratigraphy of the CS (Fig 6; Table 1) shows that peat initiation at Stass Mosse took place by terrestrialisation after a lake phase with gyttja formation (Unit CS 1). The lake was overgrown first with *Phragmites*, which initiated peat formation. Deposition of *Phragmites* peat enabled tree establishment (Unit CS 2) and development of an open woodland. Continued presence of *Phragmites* indicates at least periodical flooding (Mauquoy & van Geel, 2007). The *Phragmites* phase is followed by a short period of Monocot domination, with some presence of *Sphagnum* mosses, indicating a shift to more oligotrophic conditions (onset of Unit CS 3). After this short period a large number of wood remains together with monocots indicate a forested fen environment (Unit CS 3). The large number of tree remains indicates tree growth at or near the coring location during this time period. With the appearance of *Eriophorum vaginatum* dominated phases, tree remains decrease slightly, but are still regularly found in the peat indicating that the peatland remained forested. The decomposition (medium-high) indicates that relatively dry conditions prevailed during Unit CS 3.

Sphagnum mosses were permanently established and became dominant around 5900 cal BP (Unit CS 4), indicating increased ombrotrophy and possibly the fen-bog transition. The transition from fen to bog could, however, have occurred earlier in the peatland's history (Unit CS 3), by accumulation of Monocot peat raising the peat surface above the groundwater table as Hughes *et al*. (2000) found in British bogs. After *Sphagnum* establishment, regular finds of roots reflect continued presence of trees (including Scots pine) at Stass Mosse, indicating an open woodland. As peat accumulation continued over the following 2600 years, a *Sphagnum* and *E. vaginatum* dominated raised bog was developed (Unit CS 5). The woodland phase was eventually ended around 3800 cal BP, though some minor presence of pine remained (Fig. 15). Raised bog development continued with *Sphagnum* and *E. vaginatum* peat accumulation under relatively wet bog surface conditions (derived from medium-low decomposition), probably until major human disturbance (peat cutting and drainage) started (Units CS 8-9).

The TS Stratigraphy suggests broadly the same pattern of peatland development as the CS, as is expected by their proximity (26 m distance). The *Phragmites* phase appears, however, to have been followed by a more homogenous Monocot dominated community (*Sphagnum* missing, less wood remains) at this location (Units TS 2-3). The timing of *Sphagnum* moss establishment was seemingly later (5300 cal BP). A 400 year long period with dominance of *E. vaginatum* (Unit TS 5) stands out, between 5000-4600 cal BP, after which a shift to *Sphagnum* dominance and lower decomposition (Unit TS 6) occurs, roughly at the same time as in the CS.

The MS stratigraphy does not cover the early peatland development and was retrieved mostly for aid in correlation between the CS and the TS, but the interval covered shows roughly the same pattern, although permanent *Sphagnum* establishment was seemingly earlier. It should be noted however, that the MS peat composition was not as carefully examined as the two other sequences and was not verified with low power microscope.

The levelling data shows there is a depth difference of up to 1.36 m between the correlated levels in the stratigraphies (Fig 5). In the CS stratigraphy, cored close to the edge of the uncut peat surface, all the correlated levels are situated lower in relation to the same correlation levels in the TS and MS, both cored on the excavated surface. The correlation levels are thought to be stratigraphically accurate which is in one case confirmed by corresponding radiocarbon dates at the correlated levels in the CS (336 cm) and the TS (46 cm) (Fig. 7; Fig. 8; Table 4). The fact that the upper boundary of the gyttja layers in the CS and the TS show similar depth difference as the other correlated layers also strengthen the correlation accuracy. The levelling data measured were verified a second time in the field and are thought to be accurate. One explanation for the difference between the correlated levels in the stratigraphies could be that the peat and gyttja mass was lifted up in the cut area, possibly due to a rising groundwater table after peat mining was abandoned. The differences could also be explained by a collapse and/or compaction of the peat and gyttja mass near the edge of the uncut bog surface, possibly due to the increased weight of the dense tree cover established after drainage. The downward sloping surface of the uncut peat toward the cut area strengthens this explanation (Fig. 6). It could also be a combination of the two mentioned explanations.

5.2 Confounding factors regarding hydrological interpretations

The age-depth models (Figs 7-8) are highly simplified in their depiction of peat accumulation rates since the radiocarbon-dated samples used in the models are few. The models include quite large (95.4 %) probability ranges, within which the median values are used for the age-depth models in figures 9, 10, 11, 12, 13 and 14. This means that all the dates presented throughout this discussion include errors of ±100-200 years.

The CS age-depth model suggests that the focus interval in CS covers the age-span 6100-3300 cal BP. Since the stratigraphical interpretation of the peatland development suggests that the fen-bog transition occurred at the latest around 5900 cal BP, Stass Mosse was ombrotrophic during most, if not all, of the focus interval. This makes the data suitable for interpretation of climatic conditions, since ombrotrophic bogs depend on rainfall for their water balance (Langdon *et al*., 2003; de Jong *et al*., 2009).

A general decline in OBD is not necessarily a climate signal. It could also reflect a change in peat composition, as commonly observed at the fen-bog transition (de Jong *et al*., 2009). To be reliable as a proxy for regional climate change, OBD and humification records need to be compared between different sites and preferably be confirmed by other proxies from the same sequence. Another problem with both OBD and humification as proxies for BSW is that different plant species and different parts of the same species differ in their decay rate (Yeloff & Mauquoy, 2006; de Jong *et al*., 2009). Local vegetation changes therefore influence both these proxies. It is possible that vegetation changes, mainly the *E. vaginatum* horizons, have an influence on both OBD and humification results in this study. The correlation between the absorbance and OBD curves in the CS, with the lowermost samples considered outliers removed, is rather weak (R^2 = 0,36). Therefore it is important to account for vegetational changes evidenced by the macrofossil and stratigraphic data when interpreting hydrological conditions during a certain period in the bog's development.

Hydrological interpretation based on macrofossil analysis can be complicated because of the non-linear response to water table changes of plant communities. However, distinct vegetation changes, especially disappearance of certain species from a macrofossil record are more reliable (Barber *et al*., 2003). The main characteristic of the macrofossil diagram from Stass Mosse is a fluctuating *Sphagnum* abundance, from up to 80 % to less than 20 % (Fig. 9). These fluctuations were also observed in the stratigraphical data. Since *Sphagnum* remains are mostly counted as individual leaves and *Sphagnum* leaves are small, an increase in decomposition causing loss of more plant material from the peat may have a stronger influence on total numbers of *Sphagnum* leaves compared to other macrofossil types like roots or bark. If this was the case, *Sphagnum* peaks would be coincident with low humification. This is, however, not consistent for all the CS samples (Fig 11, e.g. at 320 and 250 cm). Additionally, Charman (2002) claims that *Sphagnum* mosses slow down decomposition due to their release of various organic acids. The observed *Sphagnum* fluctuations are therefore interpreted as reflecting actual vegetation changes at the bog surface, which may in turn reflect fluctuating BSW, since *Sphagnum* production is favored by increased wetness (Charman, 2002).

Sphagnum section *Acutifolia*, to which the vast majority of the *Sphagnum* leaves identified belongs to, contains a diverse group of *Sphagnum* species, including some growing on hummocks with deep water tables and some growing under wetter conditions (Langdon *et al*., 2003; Mauquoy & van Geel, 2007). No conclusion can therefore be made concerning BSW based on the dominance of this *Sphagnum* section, but the characteristic alternations between *Sphagnum* s. *Acutifolia* and *E. vaginatum* seen in the CS stratigraphy can, according to Langdon *et al*. (2003), be interpreted as reflecting fluctuations in water table depth. *Sphagnum austinii* (formerly *S. imbricatum*) is adapted to tolerate dry conditions, but can also grow under wetter bog surface conditions (Mauquoy & van Geel, 2007). The relative abundance of S. *austinii* is very low (1-3 %) in the samples where it was found, and for this reason its appearance does not add much to the interpretation of the macrofossil results.

The thin rootlets, beside *Sphagnum* a major peat component throughout the focus interval, are taxonomically uncertain. They likely belong to the Ericales order (Mauquoy & van Geel, 2007). Many common Ericales species growing on Swedish peatlands (*Calluna vulgaris*, *Empetrum nigrum, Andromeda polifolia*) indicate rather dry conditions, although for example *Erica tetralix* and *Vaccinium oxycoccus* can tolerate relatively wet surface conditions (Mauquoy & van Geel, 2007). The relative abundance of confidently identified Ericaceous remains is low (below 10 %) throughout the focus interval, and peaks in the data coincide with low *Sphagnum* values. The same is true for thin rootlets, although plotting the actual numbers from square counts (not shown) indicates that fluctuations follow *Sphagnum* fluctuations relatively well, although numbers increase and decrease with much less magnitude.

5.3 Peat characteristics and local hydrological conditions within the focus interval

The stratigraphical data reflect continuous deposition of medium humified *Sphagnum* peat with monocots, suggesting stable hydrological conditions, between 5900 and 4600 cal BP, but the humification, OBD and macrofossil analyses do not entirely support this notion (Fig. 11). The initial increase in *Sphagnum* inferred from the macrofossil analysis (between 5900 and 5600 cal BP) coincides with a decrease of unidentified monocots, which after this time occur relatively sparsely. Monocots is a very broad group of vascular plants, which makes it difficult to make any hydrological interpretation from their presence. Humification decreases at the same time (5700 cal BP) as *Sphagnum* increases and this indicates a shift to wetter conditions at the time of *Sphagnum* increase and Monocot decrease. As Hughes & Barber (2003) showed, the fen-bog transition may be induced by hydrological changes. OBD is, however, rather constant between 5900 and 5600 cal BP. Since the different proxies show inconsistent results it is difficult to infer any BSW change. Humification stays rather constant after the decrease at 5700 cal BP, except for some fluctuations around 5300-5000 cal BP with a peak around 5200 cal BP, also seen in OBD. The peak is followed by a rapid decrease, indicating a fluctuating water table followed by a rapid wet-shift. Relatively stable humification and OBD are then followed by increases at 4900 cal BP and 4800 cal BP, respectively, when OBD peaks at the highest values measured throughout the focus interval.

The CS stratigraphy and age-depth model suggest a major shift in conditions from relatively constant medium humification to generally lower and more fluctuating humification at 4600 cal BP (Fig. 7), with a subsequent clear increase in peat accumulation, especially during the first 200 years. An increase in peat accumulation may either be caused by decreased decomposition, an increase in productivity or a change in the vegetation composition (Kylander *et al*., 2013). Changes in decomposition indicating hydrological changes can be stratigraphically evaluated from the colour and structure of the peat, but reliable results are obtained only when the peat type remains the same (Rundgren, 2008). In the Stass Mosse stratigraphies, a change to lighter peat colour and more well-preserved plant remains occurs and the shift can be interpreted as a wet-shift. However, a coincident vegetational change to high *E. vaginatum* presence just after the shift inferred from the CS stratigraphy followed by an increase in *Sphagnum* derived from both the stratigraphy and macrofossil analysis, make this interpretation less secure (Fig. 11). According to Hughes *et al*. (2000) *E. vaginatum* is a good indicator of strongly oligotrophic conditions, and often establishes during the fen-bog transition. The species tolerates a wide range of moisture conditions, having deep roots enhancing survivability during drought, but is neither harmed by high water table and can even grow in pools (Mauquoy & van Geel, 2007). If occurring together with Ericales species, especially *Calluna vulgaris*, it may indicate dry conditions (Hughes *et al*., 2000; Barber *et al*., 2003; Mighall *et al*., 2004). Confidently identified Ericaceae remains (woody tissue as well as bark) show a decrease during the time of the shift (Fig. 9) and so do thin rootlets. For this reason it is unlikely that this *E. vaginatum* phase reflects a lower water table during this time. The wet-shift interpretation is strengthened by the colorimetric humification analysis of the CS, showing a decrease in absorbance at the same time, although the decrease starts already at 4900 cal BP and becomes more rapid between 4500 and 4400 cal BP (Fig. 11). Decreasing OBD in the CS between 4700-4500 cal BP also supports the interpretation of a wet-shift (Fig. 11). The low absorbance in the CS at 4400 cal BP is consistent with low OBD values. LOI results show a very slight, but rapid increase in organic material in the peat, probably reflecting a change to more pure *Sphagnum* peat with lower content of non-organic components in for example supporting tissue of higher plants. A major shift in conditions is evident in all proxies, but it is uncertain if it is climatically driven or caused by local hydroseral succession.

A corresponding shift in humification, although not as clearly visible, was identified in the TS stratigraphy at 46 cm, and radiocarbon dating, providing an age of 4600 cal BP, confirmed this correlation (Fig. 7-8; Table 4). Peat accumulation rate remains similar throughout the focus interval (Fig 8).

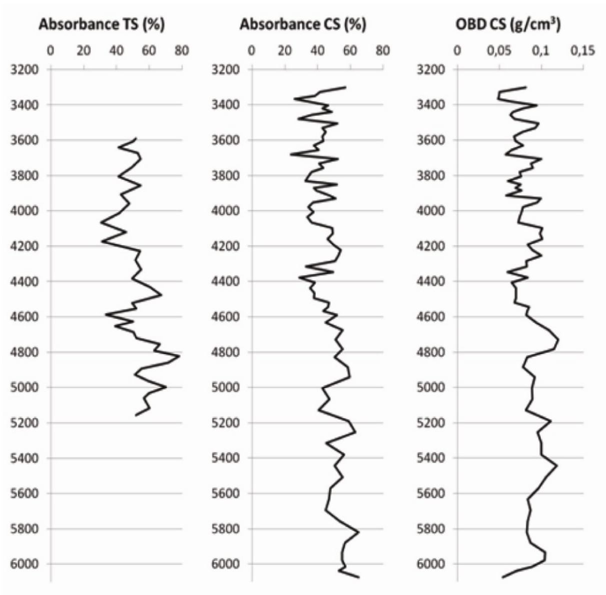


Fig. 13. The humification (absorbance %) of the TS and humification (absorbance %) and organic bulk density (OBD g/cm) of the CS plotted against age for comparison.

In the TS there is an earlier onset of *E. vaginatum* dominated peat, occurring before the correlated shift level (46 cm). This might explain why the shift is not as clearly visible as in the CS. The TS is also slightly compressed compared to the CS and MS. The colorimetric humification analysis of the TS shows decreasing humification between 4800 and 4600 cal BP, falling within 100 years of the humification decrease in the CS (Fig. 13). The low humification in the TS at 4600 coincides with low OBD in the CS, although the increase in humification in the TS from 4600 cal BP to 4500 cal BP coincides with more constant OBD and a continued decrease in humification in the CS (Fig 13). The MS stratigraphy shows a similar shift to lower humification as the CS at 111 cm, although verification with laboratory methods was not conducted and the wet-shift level was not dated.

After the wet-shift around 4600 cal BP, hydrological conditions were in general more variable, alternating between higher and lower humification in all stratigraphies. This is supported by the colorimetric humification analysis and OBD analysis of the CS and TS. A drier period between 4300 and 4100 cal BP is inferred from increased humification and OBD in the CS. This coincides with an *E.vaginatum* layer in the CS stratigraphy and a decrease in *Sphagnum* in the macrofossil results (Fig. 11). A wet-shift at 4100 cal BP follows this drier period, evident in both humification and OBD records and coupled with a *Sphagnum* increase and an *E. vaginatum* decrease. After the shift, 200 years of high BSW follows, before more rapid oscillations in humification and OBD begins around 3900 cal BP, implying unstable hydrological conditions. The MS stratigraphy also shows the onset of these fluctuations. The humification derived from absorbance of the TS, after the inconsistency around the 4600 cal BP wet shift, is for the most part consistent with the CS with a few deviations (Fig. 13). They indicate a wet-shift at 4200 cal BP with relatively wet conditions prevailing until an increase in humification at 4000 cal BP occurs followed by a period with only small fluctuations in humification until the record ends at 3600 cal BP.

In summary, hydrological conditions at Stass Mosse appear to have been fluctuating during the time of the focus interval. Pronounced wet-shifts derived from more than one proxy occurred at 5200 cal BP, around 4600 cal BP and 4100 cal BP. Rapid fluctuations in BSW began after 3900 cal BP.

5.4 Local hydrological conditions in the context of regional palaeo-hydrological records

Climate change in Southern Sweden during the late Holocene (approx. 4000 cal BP to present) was characterized by a general change from the warm and dry conditions that prevailed during the Holocene Thermal Maximum (HTM) (approx. 8000-4000 cal BP) to an increasingly colder and wetter climate after approx. 4000 cal BP (Seppä & Birks, 2001; Hammarlund *et al*., 2003; Jessen *et al*., 2005, Seppä *et al*., 2009). This decline in temperature and increase in wetness is termed the late Holocene Thermal Decline (HTD) or the Neoglacial (Jessen *et al*., 2005). It is believed to be caused by changes in North Atlantic ocean circulation and production of North Atlantic deep water (sinking of saline water in the North Atlantic), which in turn caused disrupted atmospheric circulation patterns (Jessen *et al*., 2005). According to de Jong *et al*. (2009), precipitation patterns in south-western Scandinavia during the late Holocene have been highly variable with increased frequency of winter storms after 2500 cal BP. The same increase in precipitation variability was shown by Hammarlund *et al*. (2003). The increased variability during the late Holocene is explained by a varying degree of maritime influence and westerly air flow (enabling cyclone passage) from the North Atlantic (de Jong *et al*., 2009). Before the onset of the Neoglacial, atmospheric blocking (caused by a high pressure zone) over Scandinavia seems to have been the dominant state (Seppä & Birks, 2001).

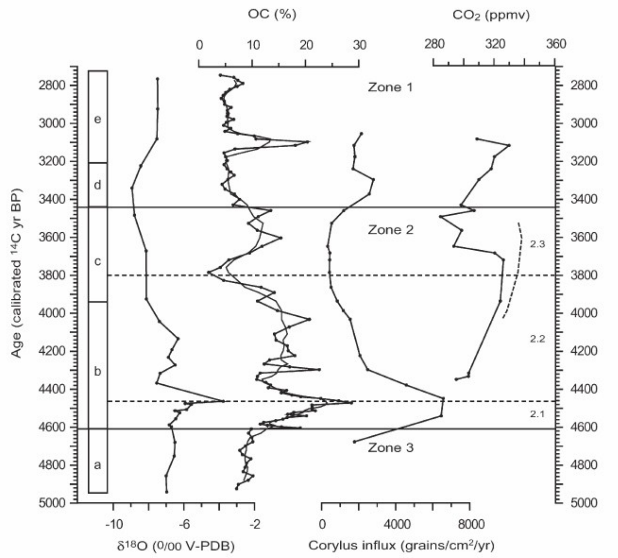


Fig. 14. Oxygen isotopes ($\delta^{18}O$), organic carbon and *Corylus* pollen influx data from lake Igelsjön compared with atmospheric CO_2 concentration. Zone 2 (4600-3450 cal BP) represents the climatically unstable transition period between the Holocene Thermal Maximum (HTM) and the Neoglacial. From Jessen *et al.* (2005).

The wet-shifts found at Stass Mosse especially at around 4600 cal BP and 4100 cal BP are comparable to wet-shifts found in several other palaeoclimatological studies in Sweden focusing on hydrological conditions. When comparing results based on different climate proxies it is important to recognize that they might differ in responses due to different thresholds and buffering capacities (Jessen *et al*., 2005).

At Lake Igelsjön, Västergötland, southern Sweden (Fig. 1), the Neoglacial began with a period of increased instability in numerous proxies (organic carbon, $CaCO_3$ from algal production, oxygen isotopes, *Corylus* pollen influx) recorded by Jessen *et al*. (2005; Fig. 14). Their results indicate rapid changes in temperature and effective precipitation during a period of around 200 years. This highly variable period began at 4600 cal BP, at first showing increased warm and dry conditions peaking at 4450 cal BP followed by a first cold/wet-shift at 4450-4350 cal BP. The cooling/moistening then ceased between 4350 and 4100 cal BP followed by a second cold/wet-shift between 4100-3800 cal BP characterized by both increased effective precipitation and decreased algal production (inferred from organic carbon). The unstable transition found by Jessen *et al* (2005) ended at 3450 cal BP and a stabilization of the climate at a new state that was colder/wetter than before 4600 cal BP followed. Hammarlund *et al*. (2003) noted a clear depletion of stable carbonate isotopes ($\delta^{13}C$ and $\delta^{18}O$) in sediments from Lake Igelsjön at ca 4000 cal BP. Both these records are proxies for algal calcification, which responds to changes in the hydrological budget, where depletion indicates a high lake level. The shift to more humid conditions is thought to be caused by increased effective precipitation.

OBD from Store Mosse bog and Undarsmosse bog, both in Halland, southern Sweden (Fig. 1), was compared by de Jong *et al*. (2009) with multiple records of effective precipitation and BSW from several lakes and bogs in the region. A dry period between 4800 and 4400 cal BP followed by a wet-shift was observed in all records. This coherence indicates a regional period of drought caused by large-scale climatic factors.

Peat humification data from Store Mosse bog in Småland, southern Sweden (Fig. 1) indicate a change towards drier conditions between ca 5000 and 4500 cal BP, followed by a stable relatively dry period lasting until 3200 cal BP (Kylander *et al*., 2013). Bulk density data from the same bog suggested drier conditions between ca 5100 and 4150 cal BP and ca 3850 and 3450 cal BP.

A study of peat humification data from Fågelmossen, Kortlandamossen and Strömyren, three raised bogs in Värmland, central Sweden (Fig 1), was conducted by Borgmark & Wastegård (2008). They found a decrease in humification in Fågelmossen at ca 4500 cal BP, synchronous with the onset of peat accumulation in parts of the basin, indicating a shift towards wet conditions. A slight increase in humification after 4000 cal BP was followed by a decrease at ca 3600 cal BP after which low humification lasted until around 3200 cal BP. At Kortlandamossen humification was low until 3200 cal BP. At Strömyren humification was low, indicating wet conditions (with some short dry phases between 8000 and 4500 cal BP), followed by a dry phase until 3000 cal BP. Combined humification data from all bogs indicated a period of high BSW between 4000-3200 cal BP.

Expanding the discussion beyond Scandinavia, comparing patterns of hydrological change in the North Atlantic region, some interesting similarities appear. Eckstein *et al*. (2011) coupled die-off phases in German bog pines with rapid wet-shifts at 4800 cal BP and 4100 cal BP. In Britain, Barber *et al*. (2003) found a major synchronous wet-shift in three bogs dated to 4400 cal BP, using macrofossil analysis. Also in Britain, Langdon *et al*. (2003) used a multi-proxy approach to detect BSW changes in an ombrotrophic bog. They noticed that wet-shifts occurred with a periodicity of around 1100 years, linked by the authors to a similar periodicity in oceanic circulation patterns in the North Atlantic. They dated specific wet-shifts to 5850 cal BP, 5300 cal BP, 4500 cal BP and 3850 cal BP.

Although some of the above described records are less consistent, several palaeohydrological studies of Swedish, German and British sites show coherent wet shifts as at Stass Mosse around 4600 and 4100 cal BP (Barber *et al*., 2003; Langdon *et al*.,2003; Hammarlund *et al*., 2003; Jessen *et al*., 2005; Borgmark & Wastegård, 2008; de Jong *et al*., 2009; Eckstein *et al*., 2011). The unstable hydrological conditions during the transition from the HTM to the Neoglacial suggested by Jessen *et al*. (2005) and de Jong *et al*. (2009) are also apparent in the Stass Mosse humification data. The wet shift at 5200 cal BP at Stass Mosse has less regional coherence, which increases the probability of local causes.

5.5 The Stass Mosse bog-pine period: when and why?

The early part of the focus interval in the CS (between 6000 and 4600 cal BP) before the 4600 cal BP wet-shift, is supposedly representative of the late part of the warm and dry period known as the Holocene Thermal Maximum (HTM). The HTM began around 8000 cal BP and ended between 5000 and 4000 cal BP in Scandinavia (Seppä *et al*., 2009). The pine remains found in the macrofossil analysis consist mainly of periderm (epidermis of root remains) and mycorrhizal roots (Fig. 15). Because roots are likely to penetrate downwards into previously deposited peat, the recorded pine remains are expected to be younger than the surrounding peat deposits. Consequently, it cannot be inferred from the macrofossil analysis that pine grew at Stass Mosse during the HTM. However, well-preserved pine roots at a lower level (435-436 cm) were identified during the stratigraphic investigation and could possibly originate from pines growing at Stass Mosse during the HTM, as is the case in many other raised bogs both in southern Sweden and north-western Germany (Eckstein *et al*., 2011; Edvardsson *et al*., 2012a; Edvardsson *et al*., 2012b). It is probable that the warm and dry climate during this period, resulting in relatively low BSW, enabled widespread establishment of pine trees on bog surfaces and enhanced the annual growth of bog-pines (Edvardsson *et al*., 2012a; Edvardsson *et al*., 2012b).

At 4700 cal BP, both *Pinus* periderm and *Pinus* mycorrhizal roots show large peaks in the macrofossil results (Fig. 15). The number of periderm remains is remarkably high compared to any other level in the focus interval. As said above, root remains are usually found at a deeper level than the peat layer accumulated during the time when the trees grew, even though bog-tree root systems are often shallow to avoid water logging during periods of high water table (Edvardsson *et al*., 2012b). It is possible that the remains found at this level originate from the pine stump horizon exposed at the excavated bog surface dated to be 400-900 years younger (Fig. 15; Edvardsson, 2013a). In that case, the root systems of these pines must have penetrated 40-70 cm down into the peat, which is certainly possible. Another possibility is that there has been more than one bog-pine period at Stass Mosse. In this case there may be several bog-pine horizons deeper down in the peat that have not been exposed because peat cutting was abandoned when reaching the first bog-pine horizon, probably due to practical problems with removing the numerous stumps and roots during peat cutting. There are also many pine stumps that were sampled from the excavated surface but not dated. Since several other macrofossil taxa peak at 4700 cal BP (Fig. 9), the large peaks observed might also be caused by a concentration effect of more durable macrofossil remains stemming from the high humification during this time period.

Both macrofossil evidence and radiocarbon dating of the exposed pine stumps found on the excavated surface at Stass Mosse, suggest that bog-pines were present in relatively large numbers after the end of the HTM, during the climatically unstable

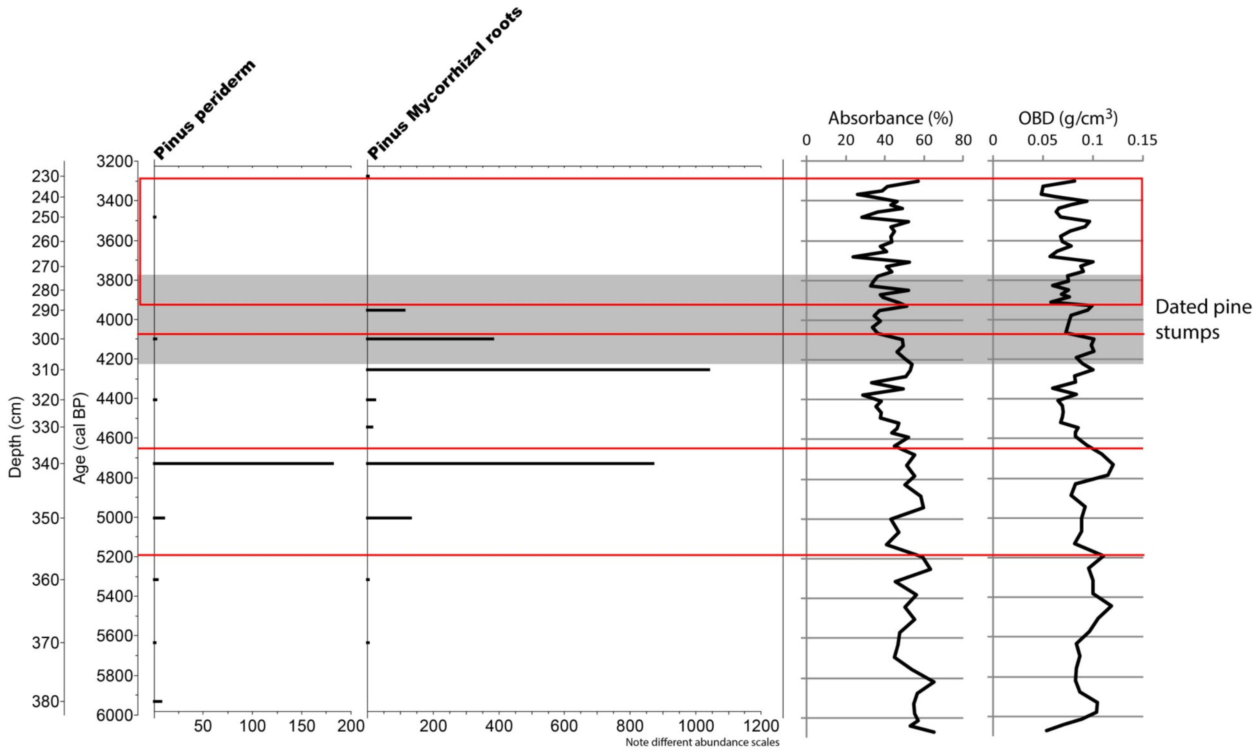


Fig. 15. Pine remains in complete samples from the macrofossil analysis of the CS focus interval together with absorbance and OBD data for the CS plotted on age. A non-linear depth scale based on the OxCal age-depth model is also shown. The grey area marks the age interval of the radiocarbon dated pine stumps (4215-3779 ± 105 cal BP) sampled from the excavated bog surface (Edvardsson, 2013a). Wet shifts (red lines) and rapid fluctuations in bog surface wetness (area within red rektangel) are also marked.

transition to the Neoglacial dated by Jessen *et al.* (2005) to begin at 4600 cal BP. Both *Pinus* periderm and *Pinus* mycorrhizal roots are recorded after the 4600 cal BP wet-shift (Fig. 15). *Pinus* mycorrhizal roots are very abundant at 4300 cal BP and are numerous until 3900 cal BP (possibly due to a similar concentration effect as at 4700 cal BP). The radiocarbon dated pine stumps falls into the age interval between 4215-3779 ± 150 cal BP (Fig. 15; Edvardsson, 2013a). It is very likely that the *Pinus* periderm and mycorrhizal roots preserved at these levels belong to the same pine horizon as the dated pine stumps. Since pine trees were evidently numerous, it is interesting to look at the hydrological conditions during this period in increased detail.

During the first 100 years of the dated bog-pine phase, both absorbance and OBD of the CS indicate relatively dry surface conditions, which might have aided tree establishment as inferred by Eckstein *et al.* (2011) and Edvardsson *et al.* (2012a). The CS stratigraphy also indicates higher humification and *E. vaginatum* presence. A low abundance of *Sphagnum* mosses and a large peak in *Pinus* mycorrhizal roots coincide in the macrofossil analysis results (Fig. 11; Fig. 15). Around 4100 cal BP a rapid decrease in humification is inferred from absorbance and OBD as well as the CS stratigraphy (Fig. 11; Fig. 15). This wet-shift coincides with wet-shifts around 4000-4100 cal BP noted by Hammarlund *et al.* (2003), Jessen *et al.* (2005) and Kylander *et al.* (2013). Eckstein *et al.* (2011) found rapid phases of die-off in German bog pines around 4000 cal BP, interpreted as being caused by a wet-shift. The macrofossil analysis shows a large increase in *Sphagnum* dominance and a decrease in *Pinus* mycorrhizal roots at this time. The high BSW continues during the following 200 years according to the humification and OBD analyses (Fig. 15). By 3900 cal BP, humification again increases according to absorbance, OBD and stratigraphy. This increase denotes the start of rapid oscillations in the humification data, especially noticeable in the absorbance values that show alternating peaks and lows. OBD is more constantly low. The pine stump period ends after a decrease in humification at 3800 cal BP inferred from humification analysis and the CS stratigraphy. OBD is inconsistent with the other proxies, showing onset of an increase at 3800 cal BP. Interestingly, little vegetational change occurs during the last 300 years of the dated bog-pine phase, with *Sphagnum* section *Acutifolia* remaining dominant. This makes humification proxies more reliable, since changes in vegetation composition can bias humification as an effect of differential degradation of species (Borgmark & Wastegård, 2008; de Jong *et al.*, 2009).

The interlude in pine mycorrhizal presence in the CS macrofossil samples (280-240 cm) after the pine-stump period, represents an approximately 500 year long period of absence after an almost continuous, often very large, presence throughout the focus interval. Just at the end of the focus interval, approx. 3300 cal BP (230 cm), there is again a minor presence of *Pinus* mycorrhizal roots. In the stratigraphic study there was also a pine root found at 232 cm. Few subfossil bog-pines dated in both Sweden and Germany are younger than 3000 years (Edvardsson, 2013a). Sparse numbers of small pines with depressed growth are however a quite common feature in Northern Hemisphere raised bogs also after this time (Eckstein *et al.,* 2011).

According to radiocarbon dating, the pine stump at the TS coring location belonged to a tree that lived between 4120 and 3900 ± 150 cal BP, but missing rings indicate it may have lived another 50 years (Edvardsson, 2013b). The pine macrofossil remains are numerous in the TS record before 4000 cal BP, then decrease, which is consistent with the CS macrofossil results. It is possible that the pine root remains originate from the tree stump at the TS coring location.

Edvardsson (2013a) argues that the pines at Stass Mosse were more influenced by local than regional hydrological changes, because of the pines inhibited growth, missing tree-rings and poor correlation with each other and other ring-width chronologies from the region coinciding in time. The results of this study shows that even if the tree-ring chronologies themselves lack usability for hydrological interpretation (because of severe growth conditions) the bog-pines at Stass Mosse were probably affected by hydrological changes linked to regional climatic variations.

6. Conclusions

Stass Mosse developed from a lake to a woodland fen and later to an ombrotrophic bog, which remained relatively densely forested throughout the Holocene Thermal Maximum into the transition to the Neoglacial between 5000 and 4000 cal BP. This transitional period is noticeable in Stass Mosse peat records by several wet-shifts (5200 cal BP, 4600 cal BP and 4100 cal BP), also recorded in other studies in the region, and followed by rapidly fluctuating bog surface wetness beginning around 3900 cal BP. The pine remains exposed on the peat-mined surface today derive from pine trees living between approximately 4200 and 3800 cal BP. It is believed that the increasingly wet and unstable conditions during the time that they grew caused the reduced growth and eventual die-off of the bog pines around 3800 cal BP.

7. Future implications

To further research the hydrological conditions at Stass Mosse during the bog-pine period, testate amoebae analysis is recommended as another proxy for BSW. The usefulness of the macrofossil data could be improved by higher resolution sampling and further identification of taxa. In addition, statistical methods modelling wet-shifts from macrofossil data could be applied, for example detrended correspondence analysis (Langdon *et al.*, 2003). Pollen analysis focusing on Scots pine could be used to explore if the occurrence of pines growing at the bog coincide with increased abundance of pine pollen found in the peat. More of the subfossil pine stumps on the excavated bog surface could be radiocarbon dated to see if the bog-pine period is expanded in time compared to current knowledge.

This study has shown that bog-pine occurrence at Stass Mosse was likely affected by regional hydrological changes in the past. This provides specific knowledge of the forested raised bog as an ecosystem and it's sensitivity to effective precipitation changes linked to large scale climate development during the Holocene. This study also adds new hydrological data from the transition between the HTM and the Neoglacial. Knowledge of the cause and effect of this highly unstable climatic period is of great interest for future research.

The sensitivity of ombrotrophic bogs to effective precipitation changes and their potential feedback effect on atmospheric concentration of the greenhouse gases CO_2 and methane make them key ecosystems to study and monitor. If also recent bog-pines are affected by regional hydrological changes they are an invaluable source of information on annual hydrological variations in pristine raised bogs and their connection to the on-going climate change.

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