

# **A dendroclimatic study at Store Mosse, South Sweden – climatic and hydrologic impacts on recent Scots Pine (*Pinus sylvestris*) growth dynamics**

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Department of Geology  
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2013



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**Abstract:** Scots Pines (*Pinus sylvestris*) from the Store Mosse peat bog complex, South-Central Sweden were sampled from twelve stands at the western edge of the bog, generating three transects, and three stands from the eastern edge. The aims of the project were to correlate tree-ring widths from different locations along the bog edges of Store Mosse in order to investigate to what extent climatological parameters govern the bog-tree growth, and to determine what impact the depth of the water table has on tree-growth at the different sites along the bog edges. Four different stand types were sampled; the solid ground, the marginal fen, the marginal hummock and the bog plain margin. The samples were measured under a microscope and a measuring table with the TSAPwin software. The samples were then cross-dated and the estimated year of germination was calculated for each sample. Chronologies were created for each stand type in the Cofecha and Arstan software, where the chronologies were detrended to better represent climatological changes over time. The chronologies were correlated with precipitation, temperature and river discharge data from nearby meteorological stations. The results show a relation between the estimated year of germination and distance from the marginal fen stream suggesting a lateral spread of trees during the 20<sup>th</sup> century, probably in response to drier site conditions. Peat depth, bog surface topography, nutrient availability and the water table height seem to govern the homogeneity and height of the stands. Drainage and peat mining do not seem to have had any effects on the sampled trees on Store Mosse. Events of depressed growth show a correlation with colder than normal winters, including the most wide-spread event at 1927-1929. Temperature and precipitation measurements show inconsistent correlations with the chronologies. River discharge measurements that better reflect the hydrologic status in the bog show coherent results for two to four years of added river discharge, suggesting that water table fluctuations is the governing factor controlling bog-tree growth at Store Mosse. The results indicate a response lag of two to four years between substrate moisture conditions and tree-ring width.

**Keywords:** Dendrochronology, Bog, Climate, Water Table Changes, Store Mosse

**Supervisors:** Dan Hammarlund, Johannes Edvardsson & Hans Linderson

**Subject:** Quaternary Geology

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# En dendroklimatologisk studie från Store mosse, södra Sverige – klimatologisk och hydrologisk påverkan på tillväxtdynamik hos recenta tallar (*Pinus sylvestris*)

ANTON HANSSON

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**Sammanfattning:** Tallar (*Pinus sylvestris*) som växer på Store mosse i Småland har provtagits. Tolv bestånd från den västra kanten, som tillsammans bildar tre transekter, och tre bestånd från den östra kanten ingår i denna dendrokronologiska undersökning. Syftet med projektet har varit att korrelera ringbreddsvariationer från tallar växande på olika platser längs mossekanten för att undersöka i vilken grad klimatiska parametrar styr tillväxten hos mossetallar och att bestämma hur mycket grundvattenytan påverkar mossetallarnas tillväxt längs mossekanten. Fyra olika tallbeståndstyper provtogs; fastmarksbestånd, laggkärrsbestånd, högmosseplansbestånd och högmosseplansbestånd. Proverna mättes med hjälp av ett stereomikroskop och mätbord i programmet TSAPwin. Proverna korsdaterades och gavs ett uppskattat groddår. Kronologier skapades för varje beståndstyp i programmen Cofecha och Arstan där kronologierna avtreddades för att bättre representera klimatologiska förändringar över tid. Kronologierna korrelerades mot nederbörd, temperatur och vattenflödesdata från närliggande meteorologiska stationer. Resultaten visar ett samband mellan det uppskattade groddåret för proverna och avståndet till laggkärrsbäcken som indikerar en lateral spridning av mossetallar under 1900-talet som förmodligen beror på torrare förhållanden på mossen. Torvdjup, torvtytans topografi, näringshalt och grundvattenytans läge verkar styra homogeniteten och höjden på tallarna i de olika typbestånden. Dikning och torvbrytning har inte påverkat de undersökta träden på Store mosse. Tillväxtkollaps i kronologierna kan korreleras med vintrar med lägre temperatur än normalt, inklusive den mest välrepresenterade tillväxtkollapsen 1927-1929. Temperatur- och nederbördsdata visar inkonsekventa korrelationer med kronologierna. Vattenflödesmätningar som kan antas att bättre avspeglar mossens hydrologiska situation visar tydliga resultat för två till fyra års adderat vattenflöde som indikerar att grundvattenytans läge är den dominerande faktorn som styr mossetallarnas tillväxt på Store mosse. Resultaten visar på en fördröjning på mellan två och fyra år mellan mossens hydrologi och trädringstjocklek.

**Nyckelord:** Dendrokronologi, torvmosse, klimat, vattenståndsförändringar, Store mosse

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## 1 Introduction

The field of dendrochronology was born in the early 20<sup>th</sup> century when it was discovered that tree-ring width was dependent on climatic and environmental parameters (Fritts 1976). Correlating tree-ring width with meteorological measurements has been proven useful in climatological studies in temperate regions (Briffa et al. 2002), as the results can be used to reconstruct climate back in time and to understand the factors controlling tree growth (Fritts 1976).

Trees growing close to, or at, their distributional limit holds climate information regarding changes in precipitation, nutrients and temperature (Fritts 1976). Distributional limits can be high altitudes and latitudes or environments with an extreme hydrological setting, such as peatlands or deserts. The annual resolution in the dendrochronological records is suitable for studying climate changes, in advantage of other geological records that have a decadal to centennial resolution at best (Edvardsson et al. 2012). In recent times of impending climate change, accurate high resolution climate reconstructions are of vital importance for predictions of the future climate.

The Earth has experienced a global average temperature rise of 0.7°C between 1850 and 2005, where high latitudes have experienced a temperature increase twice the global average (IPCC 2007). The present time of higher than normal temperatures was preceded by the Little Ice Age that had a mean temperature of approximately -0.5°C below the 1961-1990 mean (Ljungqvist 2010). Northern Europe, among other parts of the world, has also experienced significantly increased precipitation during the 20<sup>th</sup> century (IPCC 2007). Changes in precipitation and evaporation are described as the main contributors to alterations in peatland wetness in a study by van der Linden et al. (2008).

Peatlands cover about 15% of the Swedish land area (Borgmark & Wastegård 2008). Wood remains buried in peat deposits have been subject to a number of dendrochronological studies, mainly on *Pinus sylvestris* (Scots Pine) and other pine species (eg, Edvardsson et al. 2012; Freléchoux et al. 2000; Linderholm 2001; Linderholm et al. 2002; Vitas & Erlickyté 2007). The environment of a raised bog is that of poor nutrient availability with precipitation as the only moisture source (Andréasson 2006), and is therefore only present in areas with a positive water balance (Charman 2002). The adjacent marginal fen has a higher nutrient availability and receives moisture both from precipitation and inflow from the surrounding solid ground (Andréasson 2006). The vegetation on raised bogs is therefore sparse, and only about half of the Swedish peatlands and thin peat soils are forested (Rydin et al. 1999). Moreover, the bogs in western Sweden experience higher humidity than the ones located in eastern Sweden, and the humidity gradient has an influence on bog vegetation (Rydin et

al. 1999). Tree growth is according to Freléchoux et al. (2000) limited mainly by the water table, and therefore bogs in eastern Sweden are to a larger extent forested. Vegetation growing on south Swedish bogs includes *Sphagnum* (peat moss), *Eriophorum vaginatum* (cotton grass), *Calluna vulgaris* (heather), *Betula nana* (dwarf birch) and *Pinus sylvestris* (Rydin et al. 1999).

*Pinus sylvestris* is wind-pollinated and grows on a wide range of substrates, from peatlands to sand dunes. *Pinus sylvestris* reaches sexual maturity at an age of 10 to 15 years (Debain et al. 2003). The June-August temperature needs to be at least 10.5°C for *Pinus sylvestris* to produce fertile seeds (Øyen et al. 2006). Abundant amounts of seeds are produced every three to four years (Debain et al. 2003). Seeds that do not germinate the year they were dispersed do only have a small chance of germinating the next year (Karlsson 2000). The reproduction cycle is weather-dependent and is favoured by warm and windy conditions (Karlsson 2000).

Eckstein et al. (2009) have studied Mid-Holocene sub-fossil pines from numerous bogs in lower Saxony, north-western Germany. Pine was most widely distributed at the fen to bog transition of the investigated stratigraphies. As raised bogs developed the pines tended to die off synchronously. Elevated water levels were identified as the main trigger that caused the die-off events according to Eckstein et al. (2009). Warmer climate and drier bog surfaces have historically been interpreted as the main causes for bog tree growth during the Holocene (Gunnarson 1999). A similar study to Eckstein et al. (2009) by Edvardsson et al. (2012) indicates that the tree-ring width is closely linked to the regional climate as tree-ring records from bog pines in southern Sweden correlate with corresponding data obtained on the pines in Germany studied by Eckstein et al. (2009).

The studies by Eckstein et al. (2009) and Edvardsson et al. (2012) describe bog development and water level fluctuations during the Holocene. However, since meteorological records seldom extend more than 150 years back in time (Linderholm et al. 2002), the water level fluctuations of the bogs cannot be directly correlated to precipitation and temperature measurements. Moreover the sub-fossil studies tend to indicate decadal rather than annual water level fluctuations.

Studies of recent tree-ring records from bogs have been successfully compared to meteorological measurements. Linderholm et al. (2002) suggest that precipitation and temperature are the two limiting factors for Swedish peatland pines. However, water table fluctuations seem to play a role in the decadal-scale perspective.

An overwhelming 39% (25000 km<sup>2</sup>) of all peatlands in Sweden have been drained (Rydin et al. 1999), mainly since the late 19<sup>th</sup> century. This includes 10000 km<sup>2</sup> drained for forestry purposes, 6000-10000 km<sup>2</sup> for agriculture, 4000 km<sup>2</sup> of unsuccessfully drained peatlands and 1000 km<sup>2</sup> drained for peat

mining (Rydin et al. 1999).

The peat mining industry in Sweden had its glory days between 1850 and 1950 (Runefelt 2008). Domestic peat mining was the only realistic alternative to imported coal during the First World War. The peat industry then declined in the 1920's. The Second World War reinstated peat as a major fuel source, but the peat industry more or less vanished in the 1960's (Runefelt 2008).

Drainage of peatlands has a visible effect on the vegetation (Rydin et al. 1999). Grünig (1955) stipulates that bog drainage has an immediate positive effect on the tree-ring width of pine and spruce, most effectively within three meters of the drainage channel. Experiments from Scotland showed that a water level near the bog surface inhibited almost all tree growth, as root development was constantly constrained while trees growing at sites with a lowered water table grew healthy vertical roots (Boggie 1972).

Studies regarding different types of pine stands on raised bogs have been performed in the Jura Mountains of Switzerland (Freléchoux et al. 2000), but similar studies on Swedish bog pines are absent. This project aims at investigating bog pines with similar meteorological preferences but with different geological settings such as peat depth and water table. Dendrochronological analysis of pines growing on solid ground, the marginal fen and the raised bog surface is anticipated to give broad insight into when the local hydrological setting overrules the regional climate as the governing process for bog pine growth. By sampling multiple trees at each site the internal variance of germination of bog pines will be evaluated. The western edge of the Store Mosse raised bog complex in Småland, southern Sweden has not

experienced any anthropogenic alterations of its hydrology and was therefore targeted as a suitable study site for the project.

The primary objective of this project is to assess how ring-width records obtained from pines growing at different sites across and adjacent to the raised bog correlate with monitoring series of temperature and precipitation. Another main objective is to clarify the impact of hydrology and peat depth on the growth of bog pines and specifically at what time-scales these factors influence tree growth.

## 2 Study site

### 2.1 Geology and Holocene development

The study site is located at the south-western part of Store Mosse (57° 14' N, 13° 55' E), which is located northwest of Värnamo, south central Sweden (Fig. 1). With an area of almost 100 km<sup>2</sup> (Svensson 1988), Store Mosse is the largest raised bog complex in southern Sweden (Vattenmyndigheterna 2009). Store Mosse has been a national park since 1982, with the aim to preserve the rich flora and avian wildlife (Länsstyrelsen i Jönköpings län 2010). The bog complex is built up of three bog areas around Lake Kävsjön (Svensson 1988). The largest raised bog area lies south of Lake Kävsjön and is the focus of this study, where the anthropogenic impact is moderate. The bog rests on the South Småland Archaean plane circa 160-170 m above sea level (Svensson 1988).

The bedrock in the area consists of grey and red-grey gneisses and granite of the Småland type (Persson 2008). Store Mosse is situated on the northern edge of the South Småland peneplain, formed



Fig. 1. Map of south-central Sweden showing the location of Store Mosse and the meteorological stations in Växjö, Rörvik and Kävsjö (circles).



approximately 70 million years ago (Naturvårdsverket 1996). The bedrock is overlain by till and glaciolacustrine sediments, mainly fine sand in the Store Mosse depression. Eolian sediments that originate from the glaciolacustrine sediments are scattered west of Store Mosse (Persson 2008), and in patches on the north-western part of the bog (Svensson 1988).

The Scandinavian Ice Sheet retreated from the Store Mosse area around 14400 cal. BP (Lundqvist & Wohlfarth 2001). As the isostatic uplift progressed, an ice dammed lake called Fornbolmen was formed (Fig. 2). Fornbolmen covered a distance of almost 85 km in north-south direction (Nilsson 1953), where slow flowing water deposited fine sand in the vast Fornbolmen basin (Persson 2008). Fornbolmen later split into two lakes due to continuing isostatic uplift, one lake with an outlet in the Bolmån valley and one in the Lagan valley, and Fornbolmen was gradually drained.

In the Boreal (10000 - 9000 cal. BP) Store Mosse consisted of a small lake in the south and sandy areas to the north (Svensson 1988). The lake was overgrown with fen communities at the end of the Boreal. The northern part was also dominated by fen vegetation. In the early Atlantic (9000 cal. BP), a fen to bog transition was initiated, with a dominance of *Sphagnum fuscum* (Svensson 1988). *Pinus sylvestris* started to appear at the bog shortly after the transition. At the onset of the Subboreal (6000 cal. BP) the bog growth dammed areas to the north that led to a paludification of the northern parts of Store Mosse. In the early Subatlantic (2500 cal. BP) a more humid climate enabled the bog to expand. It was now dominated by *Sphagnum rubellum* and *Sphagnum fuscum* (Svensson 1988). A gradual increase in humification during the early Subatlantic suggests a shift towards a drier environment.

Around 1100 cal. BP the latest major shift in bog vegetation took place when *Sphagnum magellanicum* started to dominate the bog (Svensson 1988). This coincided with a rise of the mean water table. *Sphagnum magellanicum* still dominates the present surface of Store Mosse. A large fen soak, Blåöpet, crosses the bog in east-west direction from Lake Kalvasjön (Fig. 3) (Svensson 1988). The present surface is hummocky with a dominance of *Calluna vulgaris*, *Eriophorum vaginatum* and *Sphagnum* mosses. At the edges of the bog scattered stands of *Pinus sylvestris* are present (Svensson 1988). The present peat depth reaches over 5 m in the west central areas. The bog slopes south  $1.2 \text{ m km}^{-1}$  and  $3.2 \text{ m km}^{-1}$  towards the east (Svensson 1988).

## 2.2 Anthropogenic impact

During the 19<sup>th</sup> century many lake levelling and ditching projects were undertaken at Store Mosse. In 1840 Lake Kävsjön was lowered by 1 m, down to less than half of its original size (Naturvårdsverket 1996). The newly created land was used for grazing, but has since been abandoned. The ditches are

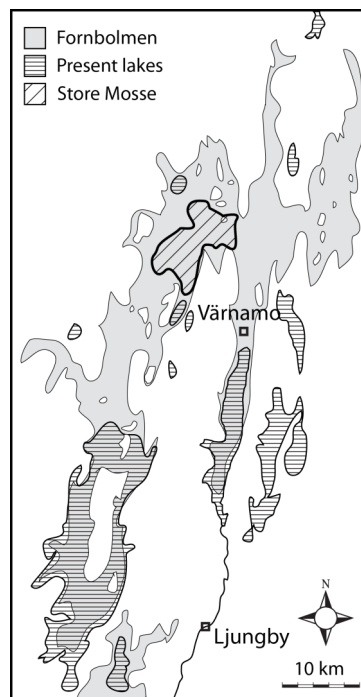


Fig. 2. Reconstruction of the ancient Lake Fornbolmen after Nilsson (1953). Horizontal striped areas indicate present-day lakes and diagonal stripes indicate the location of Store Mosse.

believed to have been 1 to 1.5 m deep (Länsstyrelsen i Jönköpings län 2010). In 1899-1902 the railroad Borås - Alvesta was built over the central part of Store Mosse. Peat mining at Store Mosse started in 1905 under the name of Hädinge Torfströ AB (Dahlberg 1988). The mined areas were located north of Lake Kalvasjön, by the villages Hädinge and Kittlakull. A factory with an 18 m high chimney was built along with hundreds of sheds for drying of the mined peat. The company was successful, particularly during the first and second world wars and was profitable in the post war period as well (Dahlberg 1988). A fire destroyed the factory in 1943, but it was rebuilt again. When fire struck again in 1966 the factory closed for good. The water level has since risen by about 1 m in the harvested areas, and the wounds in the bog surface are not believed to affect the hydrology of the bog at present (Länsstyrelsen i Jönköpings län 2010).

## 2.3 Lagan River catchment and meteorological data

Store Mosse is situated in the Lagan River catchment area (Vattenmyndigheterna 2009). The catchment is the largest in southern Sweden with  $6440 \text{ km}^2$  (Ångström 1974), and dewaters numerous lakes on its way towards the Kattegat Sea. The upper part of the catchment area is dominated by forest and mires, while the southern part is dominated by an agricultural landscape (Vattenmyndigheterna 2009). The mean river discharge of the Lagan River is  $82 \text{ m}^3/\text{s}$  and peaks at  $320 \text{ m}^3/\text{s}$ . The Lagan River is regulated and the river water is used extensively for agricultural

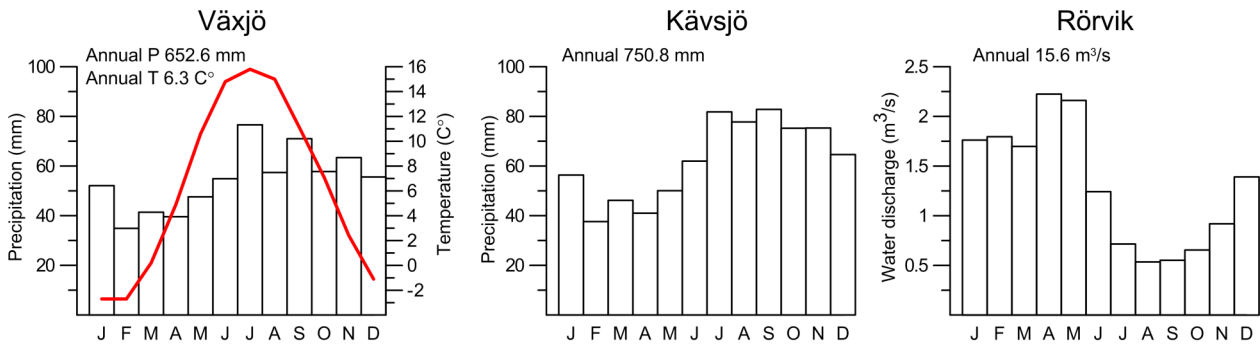


Fig. 3. Temperature, precipitation and water flow data from the Växjö (14°47' N, 56°52' E), Kävsjö (13°55' N, 57°19' E) and Rörvik (14°35' N, 57°14' E) meteorological stations used in this study. Values are 1961-1990 mean. Data received from SMHI.

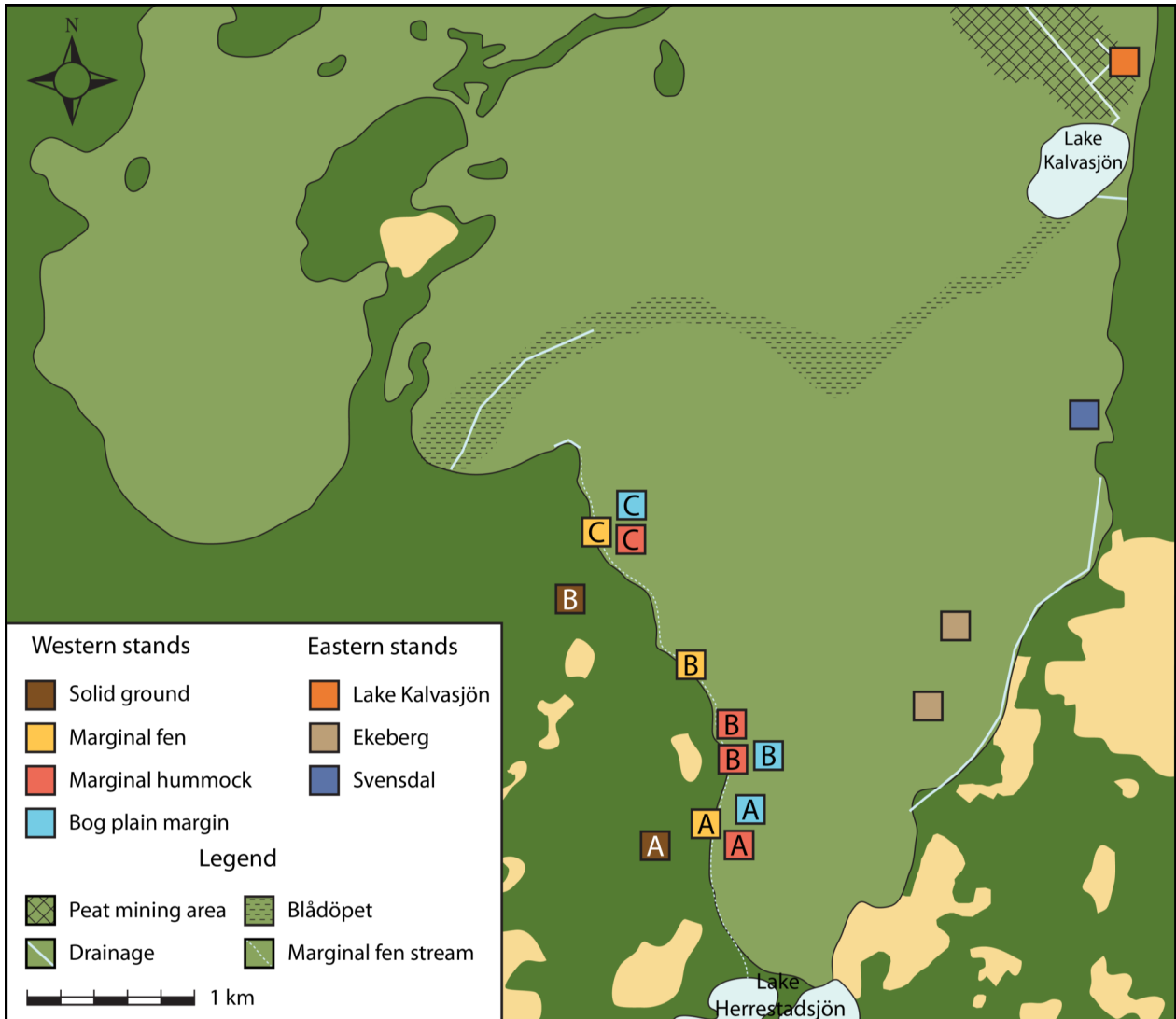


Fig. 4. Southern part of the Store Mosse peatland complex. Coloured boxes indicate sample stands. Letters A-C in the boxes indicate which sample stands that belong to transects A-C. Peatland areas (light green), forested areas (dark green) and cultivated areas (light brown) are represented in the figure. Present are also Lake Kalvasjön to the north and Lake Herrestadsjön to the south.

purposes.

Three meteorological stations from the Swedish meteorological institute (SMHI) were used in this study. Climate data for each station can be found in Fig. 3. The Växjö meteorological station contains temperature and precipitation measurements and

ranges from 1860 to 2011. Kävsjö meteorological station ranges from 1909 to 2008 and contains precipitation measurements. The Rörvik water discharge station ranges from 1907 to 2012 (water discharge is the amount of water passing the measuring station per second).

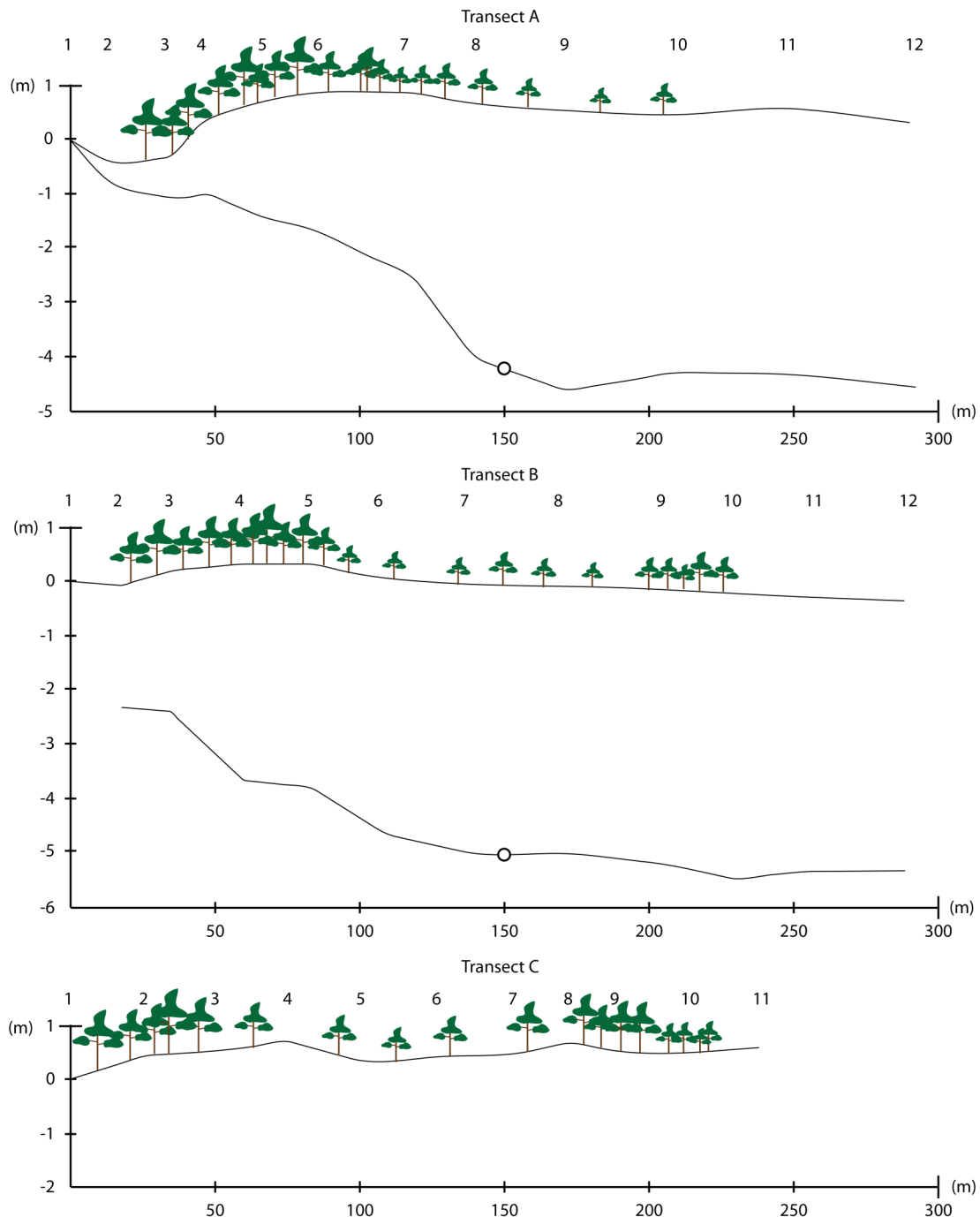


Fig. 5. Profiles of transects A-C. Each profile shows sample point 1-12 (Transect A), 1-12 (Transect B) and 1-11 (Transect C). The number of trees and their height in the profiles reflect the actual height and density variations at the sites. The lines with a central circle in transects A-B show the border between the peat deposit and the substrate. Note that no peat depth measurements were performed in transect C. The location of the marginal fen stream is just west of all transects.

## 2.4 Sample sites

The sample area consists of three east-west stretching transects along the western edge of the bog, and three separate sample sites at the eastern edge (Fig. 4). Transect A is the southernmost transect, and stretches 290 m from the marginal fen stream (Fig. 5). Some 400 m to the north lies transect B that stretches 289 m (Fig. 5). The northernmost transect is transect C, 1.7 km north of transect B. Transect C stretches 238 m (Fig. 5). Along each transect a marginal fen stand,

a marginal hummock stand and a bog plain margin stand were sampled (Fig. 4). Two solid ground stands lie outside the measured transects in the forested area to the west. The marginal fen and marginal hummock stands consist of trees taller than 5 m, while the bog plain margin stand is often not taller than 3 m. Due to inaccessibility the marginal fen stand of transect B lies some 700 m north of the other stands in the transect (Fig. 4).

One stand was sampled in the previously mined area north of Lake Kalvasjön consisting of taller trees

called the Lake Kalvasjön stand. The trees grew on peat surrounding the mined graves. A stand with shorter trees located south of Lake Kalvasjön was also sampled termed the Svensdal stand. Only eight trees were sampled in this stand due to a major drill malfunction.

Two stands of trees sampled in the spring of 2009 have also been incorporated into this study, one stand on the eastern part of the bog circa 500 m west of the eastern dry ground named the Ekeberg stand, and one stand on the western edge just north of transect B. The Ekeberg stand contains 21 trees while the western stand has 10 trees. Due to its location the western stand has been incorporated into the marginal hummock stand in transect B.

### 3 Methods

#### 3.1 Field work

The initial field work was performed during two days in October 2012, along the western edge of Store Mosse. Two transects (A and B) running from the solid ground out onto the raised bog were chosen after exploring the western edge of the bog for suitable stand sites. Each transect consists of four Scots Pine stands; a solid ground stand, a marginal fen stand, a marginal hummock stand and a bog plain margin stand (Fig. 7). Each stand contains at least 10 trees. Each tree was drilled with a hand driven 40 cm long increment borer at around 70 cm height. Two radii were sampled for each tree. Either by a single through going core, or by two individual cores some 180 degrees apart. The tree cores were drilled in a north-south direction, except in a handful of cases due to inaccessibility. A first estimation of the distance to the pith and the presence of bark were made for each sample. GPS position and the diameter of each tree were also measured. The samples were then labelled and stored in plastic tubes.

The two transects were levelled with a long ruler and a levelling instrument. The peat depth was measured with a depth probe along each transect. Four peat cores were sampled with a Russian corer in order to investigate the peat stratigraphy of the bog. The dominant flora at the sampling sites was noted. The depth to the water table were measured in a hole that was dug down to the depth of the water table. Water table measurements were performed at sample

point 5 and 9 at transect A and sample point 3, 5 and 9 at transect B.

Complementary field work took place in November 2012. A third transect (C) further to the north at the western edge of the peat bog was sampled. Due to time restraints the third transect lacks its solid ground stand. A profile of the third transect was levelled. Two stands at the eastern edge of the bog were also sampled; one stand of bog plain margin type trees from the same latitude as the western stands (Svensdal stand), and a stand of marginal hummock type trees in an area of previous peat mining further to the north (Lake Kalvasjön stand). Ten additional bog plain margin trees at the southernmost transect were also sampled.

In all, a total of 141 trees were sampled. Adding 31 trees sampled in the spring 2009 by Edvardsson, the total number of sampled trees available for this study amounts to 172 (Table 1).

#### 3.2 Lab work and chronological processing

##### 3.2.1 Preparation and measuring

In the lab each sample was further labelled and examined more closely for presence of bark and estimation of missing rings between the innermost ring of the sample and the pith. Moreover, the border between sapwood (living, outer part of the tree) and heartwood (dead, inner part of the tree) was marked. The samples were moistened for a few minutes in water before preparation. A razor blade was used to obtain clear surfaces and visibly sharp ring boundaries on the core samples. The core was cut so that the clear surface faced either the ground or the tree top.

Most of the core samples were measured in a Leica MZ6 stereomicroscope and a Rinntech Lintab 6 tree ring station with a precision of 0.01 mm. The measuring software used was TSAPWin. Some samples were measured with a Wild Heerbrugg stereomicroscope connected to an Isel-automation measuring table with a precision of 0.01 mm. If the ring borders were unclear, a layer of chalk was applied to the cores enhancing the visibility. Two radii of each sample were measured in order to get the mean thickness of each year's ring. For example, if a pine grows on sloping ground, the side of the pine facing the slope will grow thicker (Nilsson 1990). In some

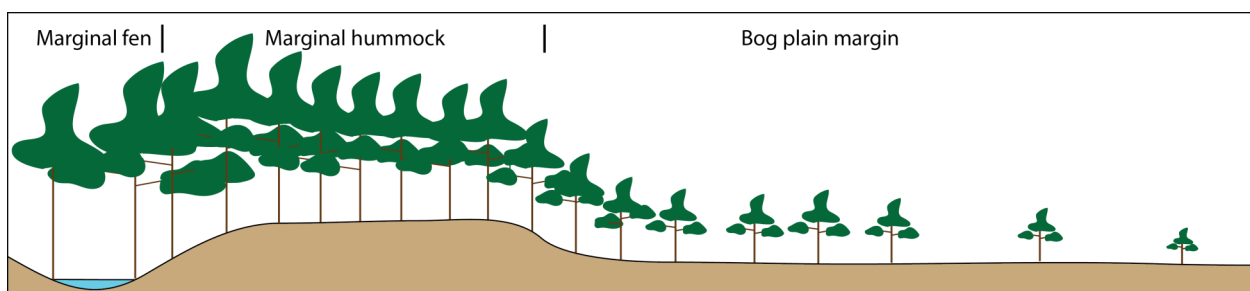


Fig. 6. Profile describing the location of the marginal fen, marginal hummock and bog plain margin sample sites along a typical raised bog edge.

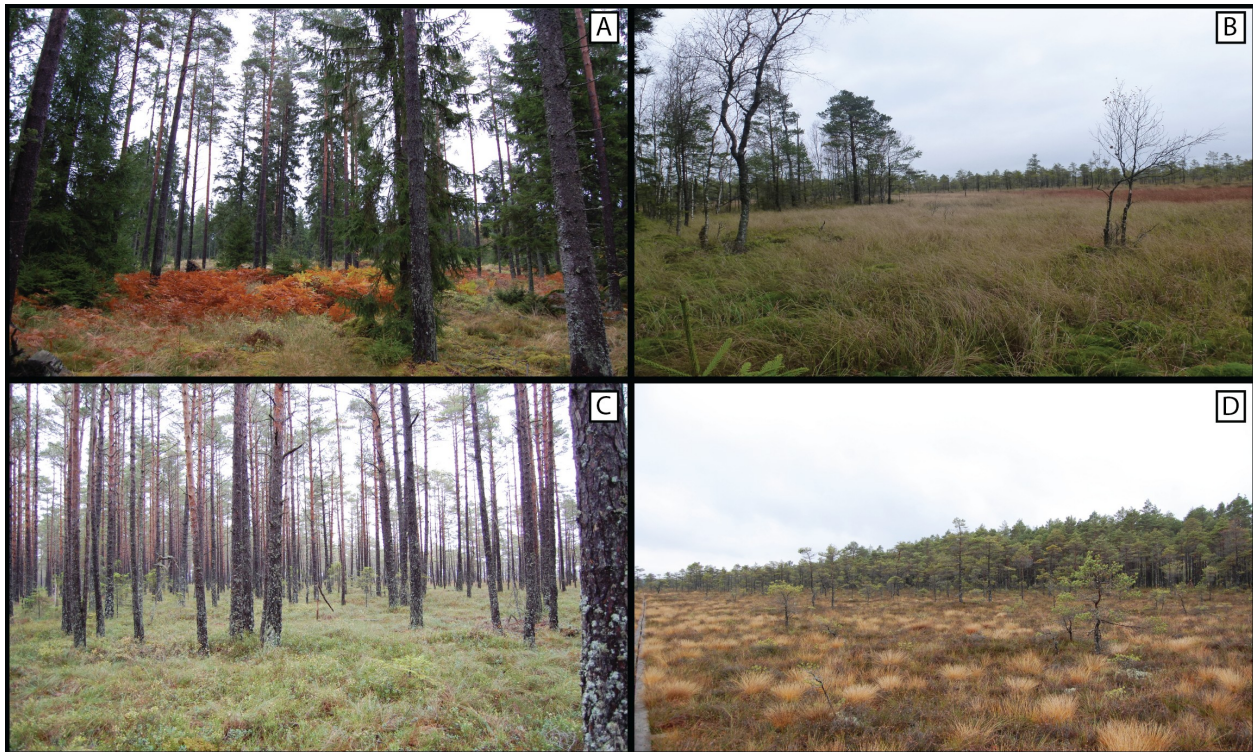


Fig. 7. Photographs showing typical environments at the (A) solid ground, (B) marginal fen, (C) marginal hummock and (D) bog plain margin stands. (Photograph: (A),(C) & (D) Johannes Edvardsson 2012 (B) Anton Hansson 2012).

cases the same radius was measured more than once, when the initial measurement was not satisfactory. During the measurements notes were taken on possible false rings, frost damages and other irregularities. A false ring occurs when a ring starts to develop but stops due to deteriorating growth conditions. Later the proper ring develops when growth conditions return to normal. This leads to two rings being formed the same year (Fritts 1976).

### 3.2.2 Cross-dating samples

Cross-dating is dependent on the number of available tree rings. A high number of rings increases the chance of a successful cross-dating (Eckstein 1984). Cross-dating and evaluation of the samples were performed in TSAPWin. Ocular matching of the two measured radii from each sample was performed along with statistical analyses in order to make a correct cross-dating. The measured curves were plotted on a logarithmic scale which amplifies the narrow rings and

Table 1. Summary of the sample locality (west or east side of the bog), the number of samples from each stand type and the date of sampling.

Stand	Location	Samples	Sample date
Solid ground	West	20	Autumn 2012
Marginal fen	West	30	Autumn 2012
Marginal hummock	West	40	Autumn 2012
Bog plain margin	West	31	Autumn 2012
Ekeberg	East	21	Spring 2009
Svensdal	East	8	Autumn 2012
Lake Kalvasjön	East	10	Autumn 2012
Other	----	3	Autumn 2012

dampens the thick (Fig. 8) (Eckstein 1984). The two statistical components used was T-value and sign test.

A sign test, also known as *gleichläufigkeit*, checks the similarity between two curves (Schwein-gruber 1988). The sign test was developed specially for dendrochronological cross-dating (Rinn 2003). Each point along the curves represent one year. If the two curves increase or decrease at a successive point, the value 1 is given for that year, independent of the magnitude of change (Fritts 1976). If one curve decreases and the other increases the value given is 0. If one curve has not increased nor decreased from the previous year, the given value is 0.5. All values are summed and compared to the total number of overlapping years. For example if 7 out of 10 points increase or decrease synchronously the total sign value is 70% (Schwein-gruber 1988), and so the total sign value represents the trend agreement between the two curves. In TSAPwin the compared curves are tested for all possible intervals and the five best matches are presented for further evaluation (Rinn 2003). The sign value is accompanied by a significance value of 1, 2 or 3 representing the 95%, 99% and the 99.9% significance level, where 99.9% is the best correlation.

The T-value is a common statistical parameter for correlation significance (Rinn 2003). The T-value is calculated in a similar way as the sign test and is related to the correlation coefficient (Eckstein 1984). Contrary to the sign test, the T-value can be overestimated if extreme ring width values happen to match. A T-value above 3 is assumed to be non-random

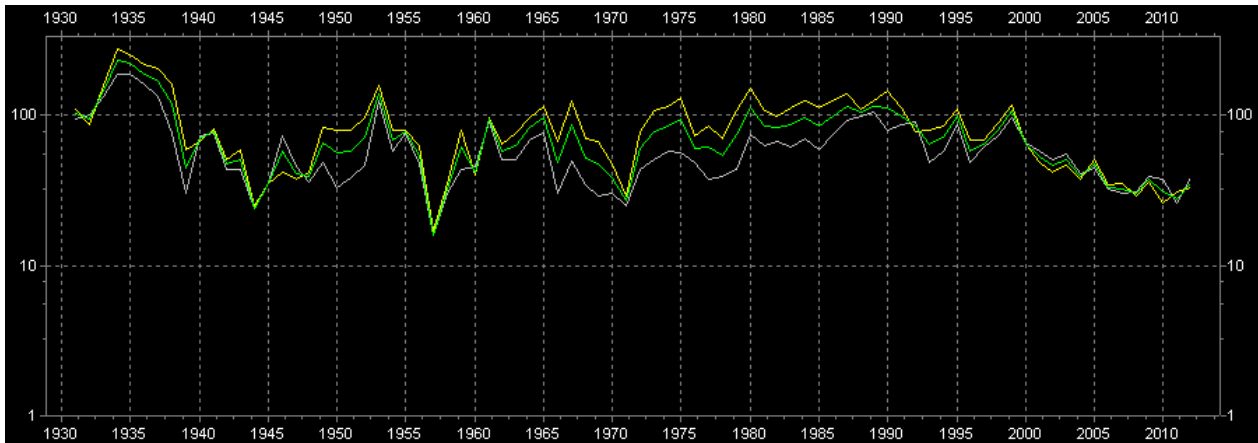


Fig. 8. A cross-dating example where the white line represents the ring widths of one radius and the yellow line those of the other. The green line shows the averaged curve for this sample. This match has a sign test value of 74% at the 99.9% significance level and a T-value of 15.5.

(Eckstein 1984).

The two radii from a sample were after a satisfactory statistical analysis and visual scrutiny merged into a single curve (Fig. 8). The mean curve was then cross-dated against some already dated reference series. The reference series originated from earlier field work from Store Mosse and bog sites south of Store Mosse; Åbuamossen, Saxnäs Mosse, Hästhults Mosse, Mycklemossen and Buxabygds Mosse (Edvardsson, J. unpublished data). Since the samples were collected in the autumn of 2012, the outermost ring should represent the 2012 growth season. Mean sample curves with a good correlation to the dated reference curve were given a start year. When mean curves had been created for each tree in the specific stand and given a dating, the mean curves were cross-dated against each other to build a single mean stand curve. A mean stand curve best represents the local growth conditions and some of the growth irregularities of the trees are averaged out (Edvardsson 2006). Some trees experienced growth collapses (several years with very narrow rings). In order to build a better chronology these collapse years were left out of the mean stand curve when possible. The chronologies were then run in the softwares Cofecha, Arstan and Dendroclim for further analysis and climatic correlations.

### 3.2.3 Cofecha

Cofecha is a software designed for cross-dating of tree-ring records and to find possible measuring and dating errors (Holmes 1999). Cofecha creates a master curve of all the curves in the stand and tests the master curve against each of the sample curves (Holmes 1999). The tested sample is removed from the master curve to avoid autocorrelation. A cubic smoothing spline is fit to the curves with a 50% cut-off of 32 years. This removes the low-frequency variance from the curves (Holmes 1999). The persistence is then removed by autoregressive modelling. After log transformation of the values only the high frequency is left. Each sample is then split in 50-year segments and

correlated against the created master curve. The segments are also tested to fit up to 10 years later or earlier than the suggested dated year to discover any missing or false rings, or other measuring errors (Holmes 1999). The program presents a text file with a chronology intercorrelation value and alerts if some samples seem to be incorrectly dated, and leaves suggestions for alternate dating.

### 3.2.4 Arstan

The Arstan software creates a single chronology from tree-ring curves by detrending and indexing (Cook & Holmes 1999). Arstan removes the low frequency variance in the tree-ring curves. The remaining high frequency variance is the part that contains the climatic variations (Cook & Holmes 1999). Arstan detrends each input curve and then applies autoregressive modelling, first multivariate and then univariate. The Friedman variable span smoother was chosen for the detrending. Arstan computes three different versions of the chronology, the STNDRD, RESID and ARSTAN versions. The STNDRD version consists of a mean value function of all detrended input curves (Cook & Holmes 1999). The RESID chronology is built up in the same way as the STNDRD chronology but with the residual values created in the univariate autoregression mentioned above (Cook & Holmes 1999). The ARSTAN chronology consists of the sum of the RESID chronology and the pooled autoregression model created in the multivariate autoregression. The ARSTAN chronology has the intention to represent the strongest climate signal (Cook & Holmes 1999).

### 3.2.5 Chronologies

Out of the 141 measured samples, nine could not be dated properly and were left out of the stand chronology analysis. One chronology for each stand was created in the Arstan software. The samples with the highest intercorrelation in Cofecha were selected for the stand type chronology created in Arstan, leaving out samples with high growth irregularities. An inter-

correlation value of 1 would mean identical tree-ring curves. The first 20 years from the estimated germination year were removed from the measurements. This removes the adolescent years when the tree-ring width does not signal climate variation to any noticeable extent. A running EPS (Expressed Population Signal) threshold value of 0.85 was chosen in accordance with Wigley et al. (1984). The running EPS value is dependent on the number of samples in the chronology and the degree of intercorrelation.

### 3.2.6 Germination year

All sampled trees were given an estimated germination year. A sample collected at the height of 50 cm misses the rings up until the year the tree reached 50 cm. Trees growing at the marginal fen and the marginal hummock are given an estimation of 14 rings per meter and trees in the bog plain margin 21 rings per meter (Linderson, H. personal communication). A germination year is calculated based on the sample height, number of missing rings to the pith at sample height and the dated year of the innermost ring at sample height. The estimation allows an uncertainty of  $\pm 5$  years. All trees were living at the time of sampling, therefore the last ring in all undamaged samples represents the year 2012.

### 3.2.7 Dendroclim

Dendroclim is a software for identifying climate signals in tree-ring chronologies (Biondi & Waikul 2004). The program compares annual tree-ring width with monthly climate parameters such as temperature and precipitation. Dendroclim uses two statistical models, the correlation function and the response function (Biondi & Waikul 2004). The correlation function was used in this study.

The correlation function used is the univariate estimates of Pearson's product moment correlation (Biondi & Waikul 2004). Pearson's product compares the linear relationship between two variables (Kutner et al. 2005). Pearson's product gives a value between +1 and -1, where +1 is a total positive correlation between the two variables, and -1 a total negative correlation. Values near 0 show no significant correlation (Kutner et al. 2005). A positive correlation value indicates that the climate parameter and tree-ring width both have a high value, for example a high temperature correlates with a thick tree ring. A negative correlation indicates that one value is high and another low, for example high precipitation correlates with a thin tree ring. Dendroclim uses bootstraps for more accurate results (Biondi & Waikul 2004). According to Efron (1979) bootstraps estimate the error rates, and introduce a way of testing the significance of the correlations produced (Guiot 1991). All chronologies were correlated against monthly precipitation measurements from Vaxjo and Kavsjo, temperature measurements from Vaxjo and river discharge measurements from Rorvik from June of the previous year until September of the current year.

Annual precipitation and river discharge measurements were added for up to ten years back in time. Multiannual total precipitation from Vaxjo and Kavsjo and river discharge measurements from Rorvik were then correlated with the chronologies. The annual and multiannual correlations were calculated in the Excel software. The Matlab software was used to calculate the significance level of the Pearson's product. A significance level of 95% was considered high and all correlations beneath that were nullified. Current year total, previous year total and added total of two up to 10 years of precipitation and river discharge measurements were correlated with the chronologies in order to determine any long term changes in the bog hydrology.

## 4 Results

### 4.1 Peat stratigraphy

#### 4.1.1 Transect A

The peat depth at sample site 6 is 240 cm and is situated circa 90 m from the marginal fen stream (Fig. 5). The lowermost part of the stratigraphy, unit 1-7, is dominated by fen communities such as *Carex* (sedges) and brown mosses (Table 2). The upper part of the stratigraphy consists of unit 8-12 and is dominated by raised bog plants such as *Sphagnum* with a varying degree of humification (Table 2). The dominant present-day flora consists of *Pinus sylvestris*, *Sphagnum* spp., *Eriophorum vaginatum*, *Vaccinium myrtillus* (bilberry) and *Betula nana*.

170 m from the marginal fen stream lies sample site 9 with a peat depth of 5 m (Fig. 5). Fen communities dominate unit 1-6, particularly *Carex* peat (Table 3). *Sphagnum* peat dominate unit 7-19 indicating a raised bog community (Table 3). The degree of humification varies between medium and low throughout the raised bog community units. *Calluna vulgaris*, *Sphagnum* spp. and *Eriophorum vaginatum* dominate the present-day flora.

#### 4.1.2 Transect B

Sample site 3 is located 40 m from the marginal fen stream and is 240 cm deep (Fig. 5). A fen community dominates the lower part of the stratigraphy consisting of unit 1-3 (Table 4). A raised bog community dominated by *Sphagnum* spp. builds up unit 4-10 (Table 4). The degree of humification varies from medium to low. *Pinus sylvestris*, *Vaccinium myrtillus* and brown mosses represent the dominant flora.

Sample site 5 is situated 90 m from the marginal fen stream. Its peat depth is 385 cm (Fig. 5). Unit 1-7 is a fen community dominated by *Carex* (Table 5). A raised bog community is present at unit 8-13 dominated by *Sphagnum* spp (Table 5). The degree of humification varies between medium and low in the stratigraphy. The dominant present-day plants are *Calluna vulgaris*, *Empetrum nigrum* (black crowberry) and *Eriophorum vaginatum*.

Table 2. Stratigraphic description of the peat core from transect A, sample point 6.

Depth (cm)	Unit	Stratigraphy	Degree of humification
0-14	12	<i>Sphagnum</i> peat with branches and roots.	Medium
14-22	11	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Low
22-68	10	<i>Sphagnum</i> peat.	Medium
68-73	9	<i>Sphagnum-Carex</i> peat.	Medium
73-135	8	<i>Sphagnum</i> peat with <i>Carex</i> .	Low
135-167	7	<i>Eriophorum vaginatum</i> peat.	
167-191	6	<i>Carex</i> peat. Many roots in the lower 6 cm.	
191-203	5	Brownmoss peat with <i>Carex</i> .	
203-214	4	<i>Carex</i> peat.	
214-222	3	Brownmoss peat.	
222-239	2	<i>Carex</i> peat with <i>Eriophorum vaginatum</i> .	
239-240	1	Charcoal.	

Table 3. Stratigraphic description of the peat core from transect A, sample point 9.

Depth (cm)	Unit	Stratigraphy	Degree of humification
0-6	19	<i>Sphagnum</i> peat with <i>Carex</i> .	Medium
6-57	18	<i>Sphagnum</i> peat.	Low
57-138	17	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Low
138-220	16	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Medium
220-229	15	<i>Sphagnum</i> peat.	Low
229-239	14	<i>Sphagnum</i> peat.	Medium
239-298	13	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Medium
298-314	12	<i>Sphagnum</i> peat	Medium
314-322	11	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Medium
322-330	10	<i>Sphagnum</i> peat.	Low
330-350	9	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Medium
350-374	8	<i>Sphagnum</i> peat.	Medium
374-390	7	<i>Sphagnum</i> peat.	Low
390-405	6	<i>Carex-Sphagnum</i> peat.	Medium
405-410	5	<i>Carex</i> peat with branches and roots.	
410-413	4	Fen peat.	
413-417	3	<i>Carex</i> peat.	
417-431	2	Fen peat with branches and roots.	
431-500	1	<i>Carex</i> peat with layers of coal and alder wood.	

Table 4. Stratigraphic description of the peat core from transect B, sample point 3.

Depth (cm)	Unit	Stratigraphy	Degree of humification
0-17	10	<i>Sphagnum</i> peat with branches and roots.	Medium
17-27	9	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Medium
27-59	8	<i>Sphagnum</i> peat.	Low
59-63	7	<i>Sphagnum</i> peat with branches and roots.	Medium
63-87	6	<i>Sphagnum</i> peat.	Low
87-115	5	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Low
115-131	4	<i>Sphagnum</i> peat.	Low
131-145	3	<i>Carex-Sphagnum</i> peat.	Low
145-153	2	<i>Carex-Sphagnum</i> peat.	Medium
153-240	1	<i>Carex</i> peat with coal layers and alder wood.	

Table 5. Stratigraphic description of the peat core from transect B, sample point 5.

Depth (cm)	Unit	Stratigraphy	Degree of humification
0-2	13	Living <i>Sphagnum</i> .	
2-9	12	<i>Sphagnum</i> peat.	Medium
9-22	11	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Low
22-95	10	<i>Sphagnum</i> peat.	Low
95-126	9	<i>Sphagnum</i> peat with <i>Eriophorum vaginatum</i> .	Low
126-174	8	<i>Sphagnum</i> peat.	Low
174-287	7	<i>Carex-Sphagnum</i> peat with <i>E. vaginatum</i> with roots and branches.	Medium
287-329	6	<i>Carex</i> peat with <i>Eriophorum vaginatum</i> and coal layers.	
329-336	5	<i>Carex</i> peat with brown mosses.	
336-361	4	<i>Carex</i> peat with <i>Eriophorum vaginatum</i> .	
361-367	3	<i>Carex</i> peat with brown mosses.	
367-380	2	<i>Carex</i> peat with <i>Eriophorum vaginatum</i> .	
380-385	1	Brown moss peat with <i>Carex</i> .	



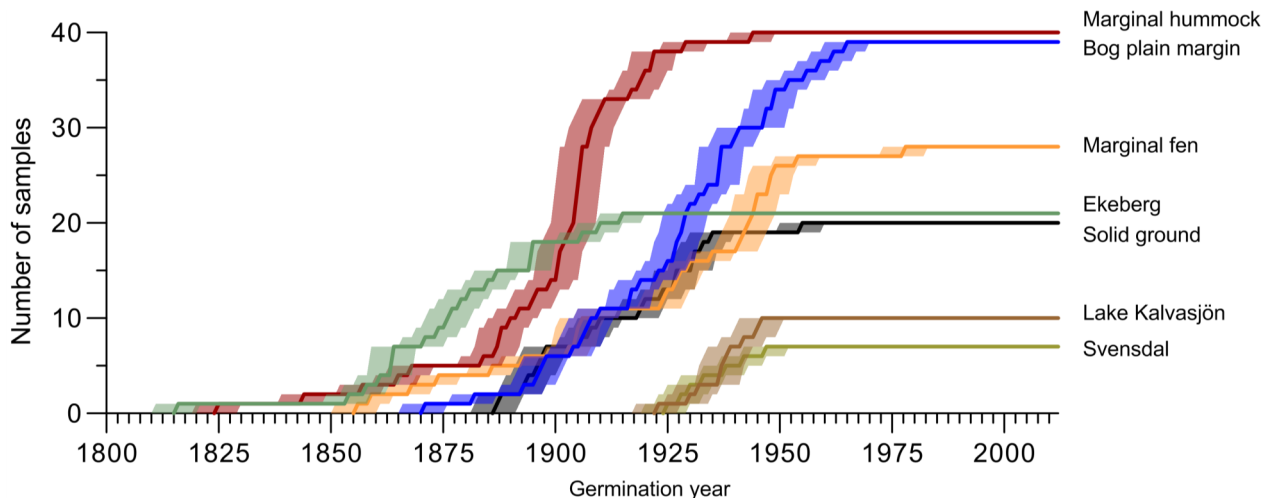


Fig. 9. Number of trees in the solid ground (black), marginal fen (orange), marginal hummock (red), bog plain margin (blue), Ekeberg (green), Svensdal (olive green) and Lake Kalvasjön (brown) stands based on the estimated germination year. The extended fields on each side of the lines represent a five year uncertainty span.

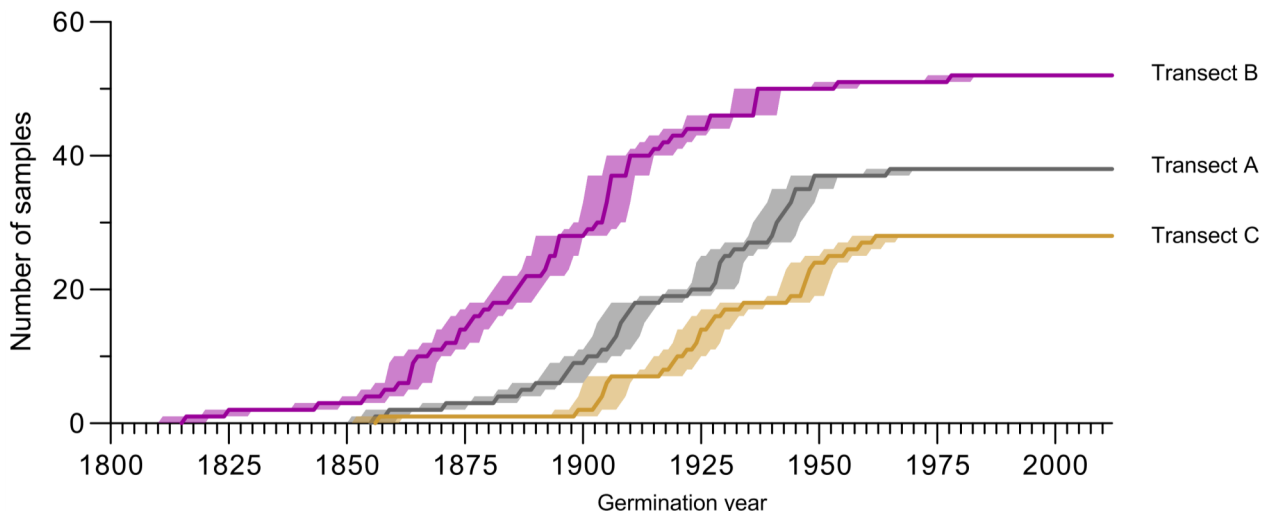


Fig. 10. Number of trees in transect A (grey), transect B (purple) and transect C (gold) based on the estimated germination year. The extended field on each side of the lines represents a five year uncertainty span.

## 4.2 Tree ages

Out of 172 trees, 166 have been given a germination year. The oldest sample has been given the germination year 1774 $\pm$ 5. It was sampled on the centre of the bog, outside the stand localities. The youngest tree sampled has the germination year 1978 $\pm$ 5. The mean year of germination of the sampled trees is 1911 $\pm$ 5. The most frequent germination year is 1906 $\pm$ 5 with eight samples. 28 of the samples have a germination year in the 1900's, making it the most productive decade with 17% of the germination years.

The solid ground stands include 20 trees and has a mean germination year of 1913 $\pm$ 5. The oldest tree has a germination year of 1887 $\pm$ 5 and the youngest tree 1955 $\pm$ 5 (Fig. 9). The three most frequent germination years in the solid ground stand are 1920 $\pm$ 5, 1927 $\pm$ 5 and 1931 $\pm$ 5, each with two samples.

The marginal fen stands have 28 dated trees. The mean germination year is 1920 $\pm$ 5. The oldest tree in the stand has a germination year of 1856 $\pm$ 5, and the youngest tree 1978 $\pm$ 5 (Fig. 9). The most frequent

germination years of the stand are 1905 $\pm$ 5, 1945 $\pm$ 5 and 1948 $\pm$ 5, with two samples each.

The marginal hummock stands have a mean germination year of 1899 $\pm$ 5. The oldest tree has a germination year of 1825 $\pm$ 5 and the youngest tree 1944 $\pm$ 5 (Fig. 9). The total number of dated trees in the stand is 40. The most frequent germination years are 1905 $\pm$ 5 and 1906 $\pm$ 5 with four samples each.

The bog plain margin stands have a total of 39 dated trees. The mean germination year is 1926 $\pm$ 5. The oldest tree has a germination year of 1871 $\pm$ 5 (Fig. 9). The youngest tree in the stand has a germination year of 1965 $\pm$ 5. The most frequent year of germination is 1937 $\pm$ 5 with four samples.

The Ekeberg stand has a mean germination year of 1877 $\pm$ 5. The oldest tree has a germination year of 1816 $\pm$ 5 and the youngest tree 1915 $\pm$ 5 (Fig. 9). 21 samples were dated in the Ekeberg stand. The most frequent germination year is 1864 $\pm$ 5 with three samples.

The Svensdal stand has seven dated trees.

The mean germination year of the stand is  $1935 \pm 5$ . The oldest tree has a germination year of  $1925 \pm 5$  while the youngest tree has a germination year of  $1947 \pm 5$  (Fig. 9). There is no frequent germination year in the Ekeberg stand since all trees have a unique germination year.

The Lake Kalvasjön stand consists of ten dated trees. The mean germination year of the stand is  $1937 \pm 5$ . The oldest tree has a germination year of  $1923 \pm 5$  while the youngest tree has a germination year of  $1946 \pm 5$  (Fig. 9). The most frequent germination year is  $1937 \pm 5$  with two samples.

The oldest stand is the Ekeberg stand on the eastern side of the bog followed by the marginal hummock stand (Fig. 9). The bog plain margin trees, the marginal fen trees and the solid ground trees are of roughly the same age. The youngest stands are the Svensdal and Lake Kalvasjön stands in the north-eastern part of the sample area, which are roughly of the same age. The marginal hummock and bog plain margin tree stands show defined sprouting events around 1905 and 1925, whereas the marginal fen stand show a more constant addition of new trees (Fig. 8). Around 1910-1915 all stands experience almost no new growth.

Transect B is the oldest transect with a mean germination year of  $1903 \pm 5$ , which is 14 years older than transect A with a mean germination year of  $1917 \pm 5$  (Fig. 10). The youngest transect is consequently transect C with a mean germination year of  $1927 \pm 5$ , although the oldest tree from transect B and C is only one year apart,  $1856 \pm 5$  and  $1857 \pm 5$  (Fig. 10). The solid ground stands has been left out of transect A and B since they are located outside the bog. All transects experience a sprouting event around 1905 (Fig. 10). The marginal fen stand also has a high increase of trees around 1945-1950. Almost no new growth of trees is visible around 1910-1915 (Fig. 10)

### 4.3 Chronologies

The solid ground chronology consists of 18 samples covering 104 years, from 1909 to 2012 (Fig. 11). The total number of samples in this stand is 20. 90% of the available samples are included in the chronology. The intercorrelation value of the chronology is 0.583, the highest intercorrelation value together with the Svensdal chronology. The running EPS value is constantly above the critical value of 0.85 (Fig. 11).

The marginal fen stand chronology consists of 15 dated samples stretching 124 years, from 1889 to 2012 (Fig. 11). The total number of samples available is 30, making this stand the worst in terms of included samples with only 50% of the available samples used in the chronology. The intercorrelation value of the chronology is 0.494. The running EPS value is above the threshold of 0.85 from 1960 to 1990 (Fig. 11).

The marginal hummock stand chronology consists of 35 samples out of a total of 40. 87.5% of the available samples are included in the chronology.

This stand includes 10 samples from previous field work (Edvardsson, J. unpublished data). The chronology covers 148 years from 1865 to 2012 (Fig. 12). The intercorrelation value of the chronology is 0.529. The running EPS is above the threshold value from 1920 (Fig. 12).

The bog plain margin stand chronology consists of 25 samples covering 105 years from 1908 to 2012 (Fig. 12). The total number of collected samples is 41. 61% of the available samples are included in the chronology. The intercorrelation value of the chronology is 0.474. The running EPS value is constantly above the threshold (Fig. 12).

The Ekeberg stand chronology consists of 15 samples covering 159 years from 1850 to 2008, making it the longest running chronology of the study (Fig. 13). The total number of collected samples is 21. 71% of the available samples are included in the chronology. The intercorrelation value of the chronology is 0.547. The running EPS value is above the threshold of 0.85 from 1935 (Fig. 13).

The Svensdal stand chronology consists of 7 samples that stretch from 1946 to 2012, covering 67 years (Fig. 13). The total number of samples is 8, the lowest of all stands. 87.5% of the available samples are used in the chronology. The intercorrelation value of the chronology is 0.583, the highest together with the solid ground stand. The running EPS value is above the threshold from 1980 (Fig. 13).

The Lake Kalvasjön stand chronology consists of seven samples covering 60 years from 1953 to 2012, the shortest chronology of the study (Fig. 13). The total number of samples is 10. 70% of the available samples are used in the chronology. The intercorrelation value of the chronology is 0.425, the lowest value of all chronologies. The chronology is too short for an evaluation of the running EPS value (Fig. 13).

### 4.4 Elevated and depressed growth

A standardized ring-width value that deviates more than one standard deviation is classified as elevated or depressed growth. A minimum of three consecutive years of deviated ring-width values is regarded as a depressed or elevated growth event.

The solid ground stand chronology does not show any depressed or elevated growth events (Fig. 11). The marginal fen stand chronology show depressed growth events at 1894-1896 and 1927-1930 (Fig. 11). An elevated growth event occurs at 1903-1906 (Fig. 11). The marginal hummock stand chronology shows events of depressed growth at 1882-1884, 1899-1902, 1927-1929 and 1942-1944 (Fig. 12). An elevated growth event occurs at 1890-1892 (Fig. 12). The bog plain margin stand chronology experiences depressed growth at 1910-1913 and 1927-1929 but do not have any elevated growth events (Fig. 12). The Ekeberg stand chronology has depressed growth events occurring at 1859-1861 and an event of elevated growth at 1852-1855 (Fig. 13). The Svensdal and Lake Kalvasjön stand chronologies do not

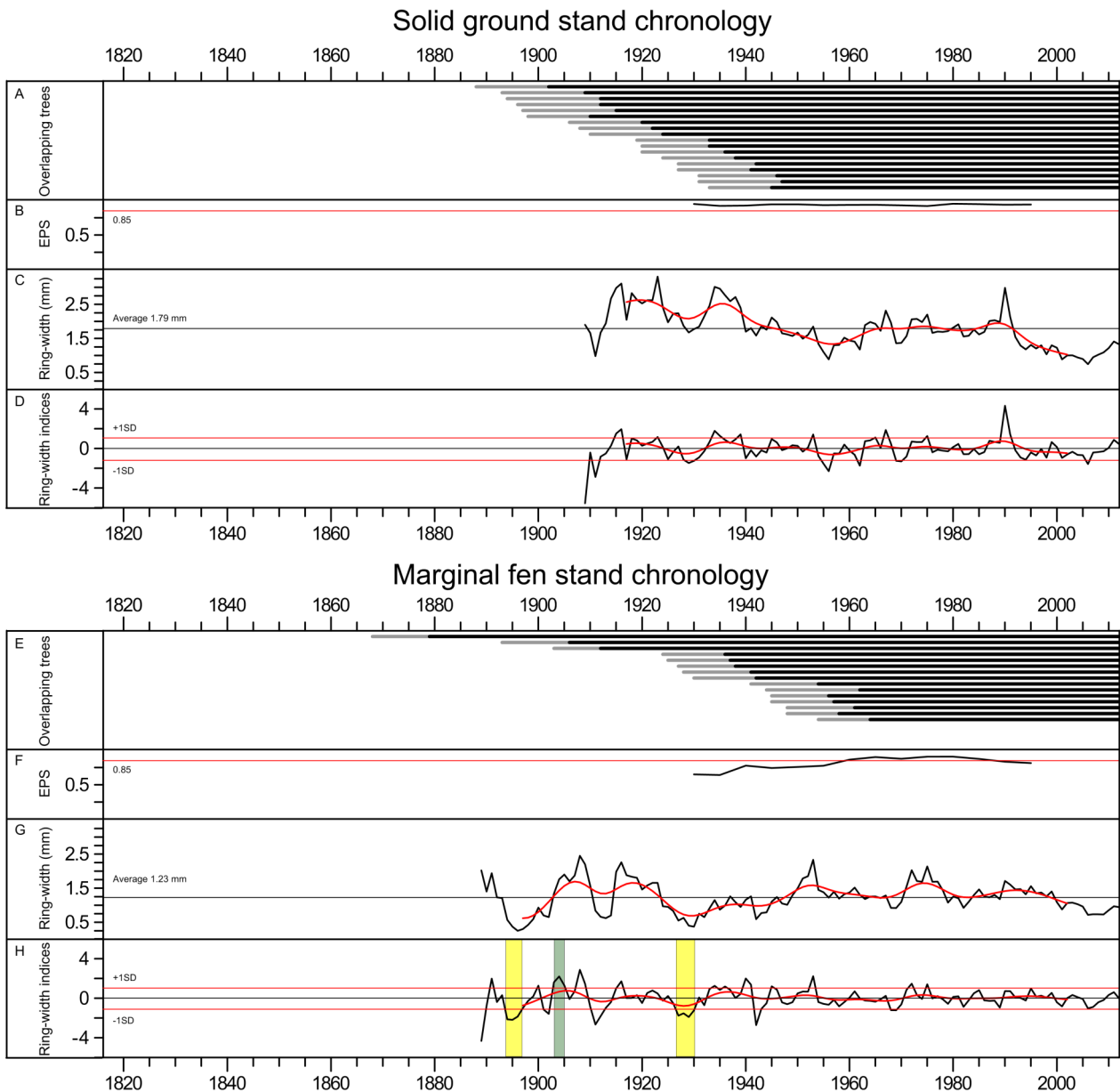


Fig. 11. The solid ground and marginal fen chronologies. (A and E) Overlapping trees included in the chronology. Black lines show rings represented in the samples. Grey lines extend back to the estimated germination year. (B and F) EPS values indicating chronology quality. Red line represents the threshold value 0.85. (C and G) Averaged ring-width chronology. Thick red line shows a 10-year Gauss filter. (D and H) Standardized Arstan chronology. Thick red line shows a 10-year Gauss filter. Thin red lines indicate +1 and -1 standard deviation (SD). Yellow fields indicate depressed growth events (defined as three years or more of ring widths below -1 SD). Green fields indicate elevated growth events (defined as three years or more of ring widths above +1 SD).

experience any events of either depressed or elevated growth (Fig. 13).

The marginal fen stand, the marginal hummock stand and the bog plain margin stand all experience an event of depressed growth at 1927-1929. Including the two years of depressed growth at 1928-1929 in the Ekeberg stand, all stands located on the bog and marginal fen experience depressed growth in the late 1920's.

## 4.5 Meteorological correlations

### 4.5.1 The solid ground stand

The solid ground stand has a high positive correlation with spring temperature of the current year (Table 6). November precipitation correlates negatively with the solid ground chronology both in Kävsjö and Våxjö (Table 6). May precipitation from Våxjö correlates negatively with the solid ground chronology (Table 6). A weak positive Kävsjö September precipitation of the current year correlates with the solid ground chronology (Table 6). River discharge measurements show a

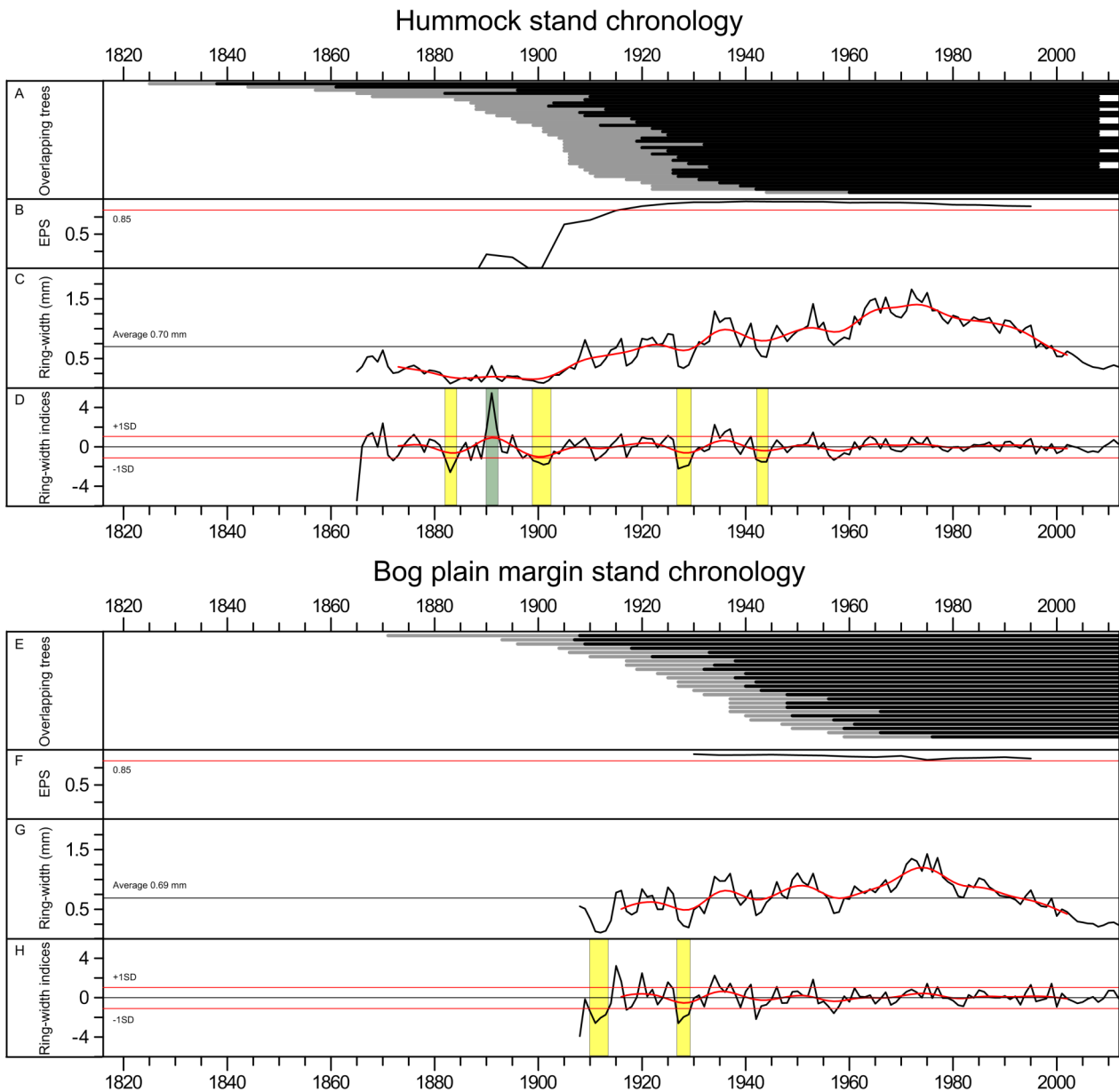


Fig. 12. The marginal hummock and the bog plain margin chronologies. (A and E) Overlapping trees included in the chronology. Black lines show rings represented in the samples. Grey lines extend back to the estimated germination year. (B and F) EPS values indicating chronology quality. Red line represents the threshold value 0.85. (C and G) Averaged ring-width chronology. Thick red line shows a 10-year Gauss filter. Thin red lines indicate +1 and -1 standard deviation (SD). Yellow fields indicate depressed growth events (defined as three years or more of ring widths below -1 SD). Green field indicate elevated growth events (defined as three years or more of ring widths above +1 SD).

negative correlation with the solid ground chronology in June, July, August and December of the previous year (Table 6), as well as with May and June of the current year (Table 6).

The total annual and multiannual precipitation from Väjjö show negative correlations at previous year and the current plus two to four years back in time with the solid ground chronology (Table 7). A weak Kävsjö precipitation correlation with the current plus eight years back in time can be seen in the solid ground chronology (Table 7). River discharge from the previous year, as well as the current plus previous

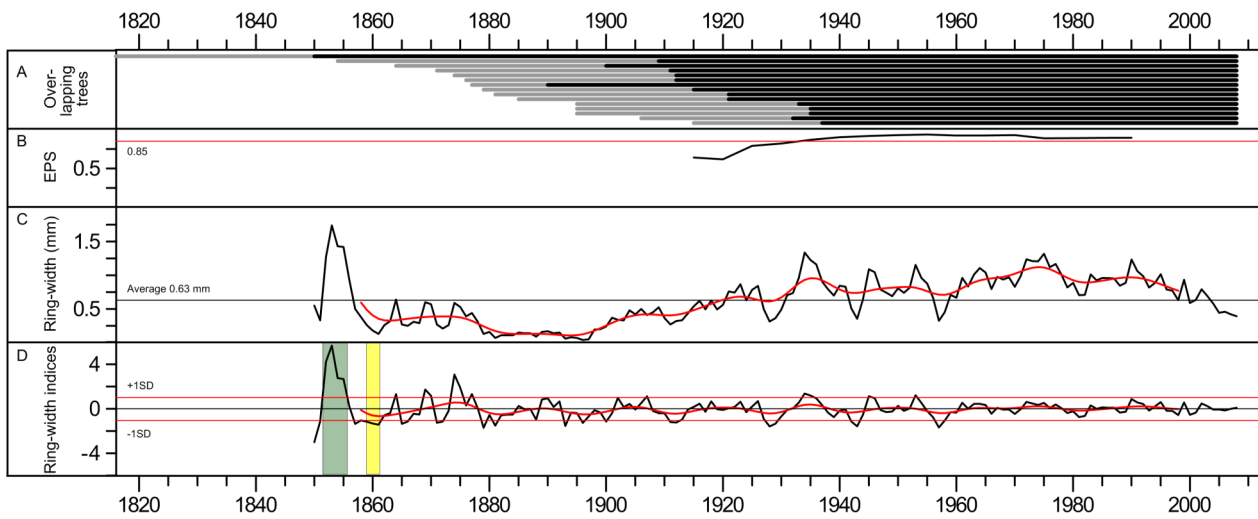
year correlates negatively with the solid ground chronology (Table 7).

#### 4.5.2 The marginal fen stand

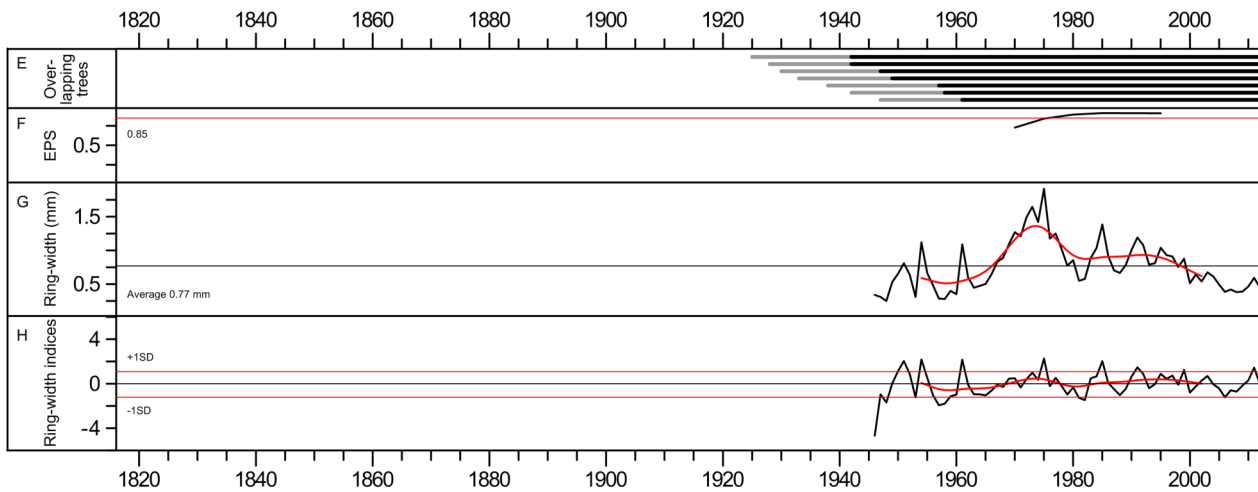
The marginal fen stand has no correlations that passed the 95% significance threshold for any monthly climate parameter.

Precipitation for the current plus two to four previous years shows a negative correlation with the marginal fen chronology in Kävsjö (Table 8). River discharge measurements from the previous year and the current plus previous one to seven years correlate

### Ekeberg stand chronology



### Svensdal stand chronology



### Lake Kalvasjön stand chronology

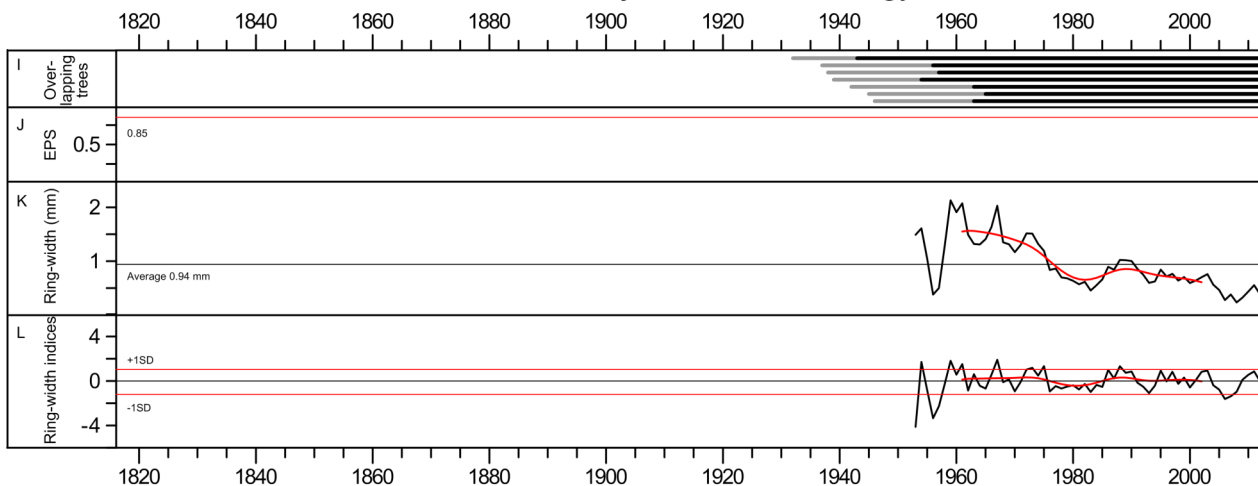


Fig. 13. The Ekeberg, Svensdal and Lake Kalvasjön chronologies. (A, E and I) Overlapping trees included in the chronology. Black lines show rings represented in the samples. Grey lines extend back to the estimated germination year. (B, F and J) EPS values indicating chronology quality. Red line represents the threshold value 0.85. (C, G and K) Averaged ring-width chronology. Thick red line shows a 10-year Gauss filter. (D, H and L) Standardized Arstan chronology. Thick red line shows a 10-year Gauss filter. Thin red lines indicate +1 and -1 standard deviation (SD). Yellow fields indicate depressed growth events (defined as three years or more of ring widths below -1 SD). Green field indicate elevated growth events (defined as three years or more of ring widths above +1 SD).

Table 6. Monthly temperature (T), precipitation (P) and river discharge (D) correlations for the solid ground stand. The table ranges from June of the previous year to September of the current year. No value indicate correlations below the 95% significance level.

The solid ground stand

Monthly	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Växjö T									0.33	0.34	0.29					
Växjö P						-0.21				-0.20						
Kävsjö P						-0.23										0.21
Rörvik D	-0.19	-0.23	-0.21				-0.23						-0.20	-0.21		

Table 7. Annual and multiannual precipitation (P) and river discharge (D) correlations for the solid ground stand. The table contains correlations from the current (C) year and up to nine previous (Pr.) years added together. No value indicate correlations below the 95% significance level.

The solid ground stand

Annual	C	Pr.	C+ Pr.	C+2 Pr.	C+3 Pr.	C+4 Pr.	C+5 Pr.	C+6 Pr.	C+7 Pr.	C+8 Pr.	C+9 Pr.
Växjö P		-0.22		-0.20	-0.20	-0.20					
Kävsjö P										-0.21	
Rörvik D		-0.25	-0.20								

Table 8. Annual and multiannual precipitation (P) and river discharge (D) correlations for the marginal fen stand. The table contains correlations from the current (C) year and up to nine previous (Pr.) years added together. No value indicate correlations below the 95% significance level.

The marginal fen stand

Annual	C	Pr.	C+ Pr.	C+2 Pr.	C+3 Pr.	C+4 Pr.	C+5 Pr.	C+6 Pr.	C+7 Pr.	C+8 Pr.	C+9 Pr.
Växjö P											
Kävsjö P				-0.20	-0.22	-0.22					
Rörvik D		-0.22	-0.19	-0.26	-0.30	-0.29	-0.24	-0.22			

Table 9. Monthly temperature (T), precipitation (P) and river discharge (D) correlations for the marginal hummock stand. The table ranges from June of the previous year to September of the current year. No value indicate correlations below the 95% significance level.

The marginal hummock stand

Monthly	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Växjö T																
Växjö P																0.18
Kävsjö P																
Rörvik D		-0.22														

Table 10. Annual and multiannual precipitation (P) and river discharge (D) correlations for the marginal hummock stand. The table contains correlations from the current (C) year and up to nine previous (Pr.) years added together. No value indicate correlations below the 95% significance level.

The marginal hummock stand

Annual	C	Pr.	C+ Pr.	C+2 Pr.	C+3 Pr.	C+4 Pr.	C+5 Pr.	C+6 Pr.	C+7 Pr.	C+8 Pr.	C+9 Pr.
Växjö P											
Kävsjö P											
Rörvik D	-0.22	-0.24	-0.30	-0.29	-0.27	-0.27	-0.26	-0.20			

negatively with the marginal fen chronology (Table 8). The strongest correlation appears at the current plus two previous years. The correlation value then decreases and disappears after the current plus previous six years.

#### 4.5.3 The marginal hummock stand

The marginal hummock chronology shows no temperature correlations, and only shows a weak positive correlation with precipitation in September of the

current year (Table 9). Previous July river discharge measurements show a negative correlation with the marginal hummock stand (Table 9).

There is no correlation with annual precipitation in the chronology (Table 10). River discharge measurements from the current and previous year as well as the current plus one to six previous years correlates negatively with the marginal hummock chronology, with the strongest correlation at the current plus previous year (Table 10).

Table 11. Monthly temperature (T), precipitation (P) and river discharge (D) correlations for the bog plain margin stand. The table ranges from June of the previous year to September of the current year. No value indicate correlations below the 95% significance level.

The bog plain margin stand

Monthly	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Växjö T																
Växjö P														0.20		
Kävsjö P																0.19
Rörvik D																

Table 12. Annual and multiannual precipitation (P) and river discharge (D) correlations for the bog plain margin stand. The table contains correlations from the current (C) year and up to nine previous (Pr.) years added together. No value indicate correlations below the 95% significance level.

The bog plain margin stand

Annual	C	Pr.	C+ Pr.	C+2 Pr.	C+3 Pr.	C+4 Pr.	C+5 Pr.	C+6 Pr.	C+7 Pr.	C+8 Pr.	C+9 Pr.
Växjö P	-0.22										
Kävsjö P											
Rörvik D		-0.22	-0.21	-0.23	-0.25	-0.25	-0.27	-0.23			

Table 13. Monthly temperature (T), precipitation (P) and river discharge (D) correlations for the Ekeberg stand. The table ranges from June of the previous year to September of the current year. No value indicate correlations below the 95% significance level.

The Ekeberg stand

Monthly	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Växjö T	0.15							0.20			0.19					
Växjö P																0.30
Kävsjö P																
Rörvik D		-0.25		-0.23												

Table 14. Annual and multiannual precipitation (P) and river discharge (D) correlations for the Ekeberg stand. The table contains correlations from the current (C) year and up to nine previous (Pr.) years added together. No value indicate correlations below the 95% significance level.

The Ekeberg stand

Annual	C	Pr.	C+ Pr.	C+2 Pr.	C+3 Pr.	C+4 Pr.	C+5 Pr.	C+6 Pr.	C+7 Pr.	C+8 Pr.	C+9 Pr.
Växjö P											
Kävsjö P											
Rörvik D		-0.24	-0.24	-0.21							

#### 4.5.4 The bog plain margin stand

The bog plain margin chronology has no temperature correlation (Table 11). A positive current year July correlation with the bog plain margin chronology can be seen for Växjö (Table 11). September precipitation from the current year in Kävsjö correlates positively with the bog plain margin chronology (Table 11).

The bog plain margin chronology correlates negatively with current year precipitation from Växjö (Table 12). Annual river discharge measurements show a negative previous year and current plus one to six previous years correlation with the bog plain margin chronology (Table 12).

#### 4.5.5 The Ekeberg stand

The Ekeberg chronology correlates positively with the previous year June as well as current year January and April temperature (Table 13). There is a strong

positive current year September precipitation correlation with the Ekeberg chronology (Table 13). River discharge measurements show a negative previous year July and September correlation with the Ekeberg chronology (Table 13).

Annual river discharge measurements from the previous year and the current plus previous one to two years show a negative correlation with the Ekeberg chronology (Table 14).

#### 4.5.6 The Svendsdal stand

The Svendsdal chronology has a strong positive correlation with the August temperature (Table 15). Previous July precipitation from Växjö correlates negatively with the Svendsdal chronology (Table 15). Current August precipitation correlates negatively with the Svendsdal chronology (Table 15). Current year September precipitation correlates positively with the

Table 15. Monthly temperature (T), precipitation (P) and river discharge (D) correlations for the Svendsdal stand. The table ranges from June of the previous year to September of the current year. No value indicate correlations below the 95% significance level.

The Svendsdal stand																	
Monthly	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	
Växjö T																0.25	
Växjö P		-0.19														-0.25	0.28
Kävsjö P																	
Rörvik D																	

Table 16. Monthly temperature (T), precipitation (P) and river discharge (D) correlations for the Lake Kalvasjön stand. The table ranges from June of the previous year to September of the current year. No value indicate correlations below the 95% significance level.

The Lake Kalvasjön stand																
Monthly	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Växjö T				-0.24						0.34						0.27
Växjö P																
Kävsjö P																
Rörvik D																

Svendsdal chronology (Table 15).

The Svendsdal chronology does not correlate with any annual measurement.

#### 4.5.7 The Lake Kalvasjön stand

The Lake Kalvasjön chronology correlates negatively with previous year September temperature and correlates positively with March and current year August temperature (Table 16).

The Lake Kalvasjön chronology does not correlate with any monthly precipitation or annual precipitation or river discharge measurements.

## 5 Discussion

### 5.1 Chronologies

When selecting samples in order to build the different stand chronologies, the samples which together have the highest intercorrelation values were selected. Samples with a large number of rings that can extend the chronology further back in time have also been favoured. The rejected trees generally have some missing rings and occasionally very thin ring-widths. Leaving these samples out of the chronology will enhance the possibility of a better correlation with meteorological measurements. In order to adjust for this climate-oriented bias, the number of rejected trees per chronology must be assessed. The series intercorrelation values are  $0.5 \pm 0.08$  in all chronologies, in accordance with other studies on bog pine trees in Sweden and Lithuania (Linderholm 1999; Linderholm et al. 2002; Vitas 2004). The solid ground stand and the Svendsdal stand have the highest intercorrelation value (0.583). The solid ground stand should have a higher series intercorrelation than the bog stands because the environment is not as extreme for tree growth at the solid ground, and therefore the tree growth should be more homogenized. The low amount of rejected trees, only 10%, in the solid ground stand

validates the stand uniformity. The high intercorrelation value in the Svendsdal stand could be an effect of the low number of samples in the chronology, and that the sampled trees grew on a small area without much change in the microenvironment. In general the Svendsdal and Lake Kalvasjön chronologies are short and contain few samples, so interpretation of these stands is not as reliable as the other chronologies.

Wigley et al. (1984) proposed a running EPS value above 0.85 as acceptable for correlating chronologies and meteorological measurements. Therefore, to correlate the chronologies with meteorological parameters only at periods when the EPS threshold is reached would seem appropriate. However all chronologies, apart from the marginal hummock chronology, do not reach a high enough EPS value until the 1920's-1930's (Fig. 11, Fig. 12, Fig. 13). This could be explained by the low number of samples in the early part of the chronologies, as the EPS value is also dependent on the number of samples (Wigley et al. 1984). Rather than removing the early parts of the chronologies, in some cases more than 50 rings, another method was applied. The juvenile growth of trees is characterized by thick ring widths (Fritts 1976). 20-30 years after germination the ring width starts to decrease with age (Schweingruber 1996). The juvenile tree-ring widths do not reflect the climate to a large extent, and so these rings can be left out of the samples in order to improve the chronologies. Therefore the first 20 years from the estimated germination year was removed from the samples before the chronologies were built. The advantage of this method is that the chronologies extend further back in time than they would have done if the EPS value had determined the chronology length. The EPS value should instead be used as a quality control for the period when all of the samples in the chronology are present.



## 5.2 Recent decline

All seven sampled chronologies show a decline in tree-ring width in the last few decades that cannot be attributed to ageing of the trees (Fig. 11, Fig. 12, Fig. 13). Briffa et al. (2002) observed a similar declining pattern in tree-ring width across the Northern Hemisphere in recent decades, and speculated that the decline could be caused by an anthropogenic factor, and that a weakened correlation with temperature is found in the analysed chronologies. However they give no definite explanation to the ring-width decline and state that more research is needed. Vaganov et al. (1999) proposed that increased winter precipitation and later snow melt in the spring could be the cause of a weaker tree ring correlation with temperature in subarctic Eurasia. The relationship does not, however, seem to be valid in other regions (Briffa et al. 2002). The recent decline in ring-width is seen both in the solid ground and the bog chronologies at Store Mosse, and also in other south Swedish bog pine chronologies (Saxnäs Mosse, Buxabygds Mosse, Hästhults Mosse and Mycklemossen (Edvardsson, J. unpublished data)).

Increased nitrogen deposition has a positive effect for vascular plant on nutrient limited bogs, both in abundance and size (Bubier et al. 2007; Juutinen et al. 2010). Nitrogen content in precipitation is partly dependent on anthropogenic emissions. Between 1990 and 2011 nitrogen emissions decreased with 46% in Sweden (Naturvårdsverket 2013), and nitrogen content measurements from precipitation show a steady nitrogen decline in south Sweden since the 1980's. Since bogs only receive their nutrients via precipitation, it is possible that the ring-width decline during the last decades can be contributed to the nitrogen content decrease in precipitation. An increase in ring-width during the early 20<sup>th</sup> century can be seen in the marginal hummock and the Ekeberg chronologies that can be correlated to the introduction of cars as transportation (the main contributor to NO<sub>x</sub> emissions in Sweden) during the same time suggesting that nitrogen emissions is a limiting factor on bog trees.

## 5.3 Store Mosse bog pine ages

The marginal hummock stand is older than the bog plain margin stand (Fig. 9). Since the age difference is at least 20 years between the stands, it is likely that the bog plain margin trees have parents from the marginal hummock trees. Fig. 9 shows that the oldest stand started to grow in the mid-19<sup>th</sup> century. Studies of similar sites show 19<sup>th</sup> century germination ages for recent trees (Freléchoux et al. 2000; Linderholm 1999; Linderholm 2001; Linderholm et al. 2002; Vitas 2004; Vitas & Erlickyté 2007). This indicates that bog pines do not generally reach an age of more than 150 to 200 years. Svensson (1988) found macro fossils of pine at Store Mosse in the peat stratigraphy dating to circa 9000 cal. BP. Pollen analysis in the same study shows the presence of pine pollen since the Preboreal, mea-

ning that pine has been present on or around Store Mosse for at least the last 10000 years. The ordnance map from 1865 over the area indicates mature conifers on the solid ground west of the bog. It is therefore likely to believe that bog pines have been present to some extent at Store Mosse earlier than the samples in this study suggest, just that these trees are not alive at present to be sampled.

Fig. 9 indicates that there is a lateral spread of trees from the marginal hummock outwards to the bog plain margin. Bog tree growth is dependent on the substrate moisture (Boggie 1972), which regulates the available oxygen (Boggie 1974). Charman (2007) describes the summer season as the driving force behind water table fluctuations. In wintertime precipitation exceeds evaporation and excess water will be lost as runoff. The winter season is therefore not important for changes in the water table over longer periods (Charman 2007).

Summer (June, July and August) temperature and precipitation have increased in Sweden during the 20<sup>th</sup> century according to measurements from SMHI. Charman et al. (2009) show that precipitation correlates better with summertime water level deficit in the 20<sup>th</sup> century than temperature does, both in Great Britain and Estonia. In contrast, a study by Słowińska et al. (2010) suggests that temperature is the main factor for water level fluctuations in Poland and other continental areas. This is supported by Schoning et al. (2005) who conclude that mean annual temperature is the main factor determining the bog surface wetness in central Swedish bogs.

The Store Mosse bog pines have evidently spread outward from the marginal hummock to the bog plain margin and to the generally wetter marginal fen (Fig. 9), indicating improved growth conditions, possibly caused by a lowered water table. Freléchoux et al. (2000) suggest that even a lowering of the water table with a few cm will promote bog tree growth. Since both precipitation and temperature have increased during the same time it may seem that temperature-driven evaporation could be the governing process for recent water table alterations at Store Mosse suggested by the bog pine spreading.

The germination years of transects A-C fit the age-distance scheme (Fig. 10). Trees from the older transects A-B were generally sampled closer to the marginal fen stream than the trees in transect C. The young age of the Lake Kalvasjön stand is explained by the location of the sampled trees, as they were located within the previously peat mined area. The trees would not have been able to grow at the Lake Kalvasjön site until peat mining had ceased. Anthropogenic disturbance should not affect the other young stand on the eastern bog edge, Svendsdal. The eastern edge of the bog is about 2-3 m lower than the western edge (Svensson 1988). The gradient allows a water flow towards the east that leads to a moister substrate there and consequentially less favourable growth conditions. The growth improvements

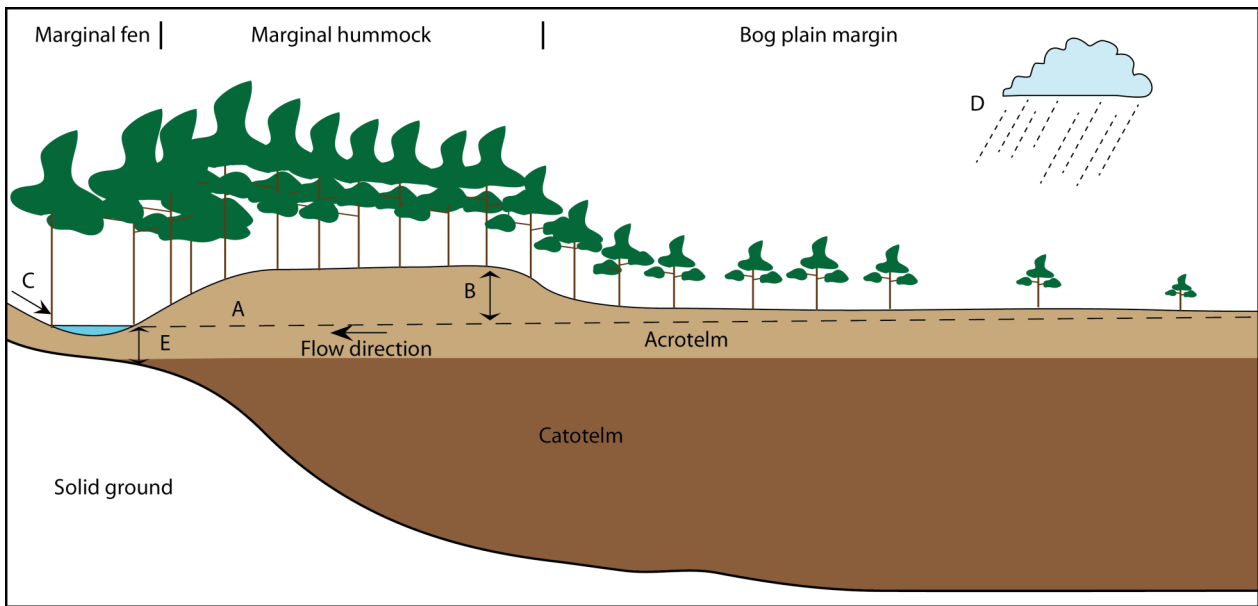


Fig. 14. Schematic profile of a typical raised bog edge. The borders of the marginal fen, marginal hummock and bog plain margin stands are defined at the figure top. Note that the height of the bog marginal hummock is exaggerated. Water flow is directed towards the marginal fen stream to the left. Dashed line (A) represents the general water table sloping slightly towards the marginal fen stream. (B) Indicates the possible root depth depending on the position of the water table. The arrow (C) shows an inflow of water and nutrients to the marginal fen from the adjacent solid ground. The only moisture input to the raised bog comes from precipitation (D). In the marginal fen area the distance between peat surface and substrate (E) is short allowing roots to penetrate the solid ground. The catotelm (dark brown) is anaerobic and has an almost constant water content. The Acrotelm (light brown) has a fluctuating water content and is periodically aerobic. Note the height gradient of the trees.

seen in the western part of Store Mosse was therefore delayed in the eastern part.

The Ekeberg stand consists of scattered trees 300-500 m from the eastern bog edge (Fig. 4). Parts of the eastern marginal fen, where the Ekeberg stand is located, have been drained sometime during the 19<sup>th</sup> century (Naturvårdsverket 1996). According to Schweingruber (1996) drainage affects tree growth up to approximately 250 m from the trench. However, it might be more likely that trees in the Ekeberg stand germinated on drier peat hummocks on the bog, since they are not located at the actual bog edge and that anthro-pogenic disturbance therefore should have had no or only minor influence on trees in the Ekeberg stand.

#### 5.4 Bog setting and pine growth

Peatlands consist of two layers, the upper acrotelm and the lower catotelm (Fig. 14). The acrotelm is active, where most of growth and decay processes occur (Charman 2002). The catotelm is constantly saturated and anaerobic with very slow water movement (Ingram 1983). In contrast, the acrotelm has a fluctuating water table and is periodically aerobic with a considerably faster water flow than in the catotelm (Charman 2002). Kilian et al. (1995) concluded that there is a time lag in bog reaction to climate changes. The central part of the bog reacts first, and as the water flow is directed towards the edges hydrological changes will occur over time. The water table in the acrotelm seldom drops more than a few decimetres

below the bog surface (Evans et al. 1999). Recharge of the water table is instantaneous and excess water exits mainly as runoff or as a flow in the upper 10 cm (Holden & Burt 2003). Tree growth on the bog surface is limited by the water table controlled oxygen availability, and as a consequence bog trees adapt with a shallow root system (Fig. 14) (Liefvers & Rothwell 1987). There is therefore a risk that a summer drought could lower the water table to such an extent that water uptake is inhibited by the shallow root system (Dang & Liefvers 1989).

The trees on the western edge of Store Mosse show a height gradient, similar to the study by Freléchoux et al. (2000). The tallest trees are located close to the solid ground and trees get progressively shorter outwards on the bog. The bog tree size seems to mainly depend on the height of the water table and the nutrient availability (Fig. 14). Even though the marginal fen is often waterlogged, due to the water flow directed towards the marginal fen stream, trees are taller there than at the actual raised bog. This could be explained by the nutrient availability that is greater in a fen as nutrient inflow occurs from the surrounding solid ground as well (Fig. 14). This is supported by the average ring width, which is greater in the marginal fen chronology than in the bog chronologies (Fig. 11, Fig. 12, Fig. 13). The peat depth in the marginal fen is approximately 50 cm. Shallow root systems prevent trees to grow tall, as the risk of windthrow is greater (Liefvers & Rothwell 1987). The tall trees in the marginal fen must therefore be anchored in the solid

ground, where their height can be supported and nutrients are readily accessible.

As peat depth increases tree height is reduced. The peat surface profiles (Fig. 5) show a hummocky landform reaching about 100 m out on the bog. The water table is relatively low here as the marginal hummock reaches about 30-50 cm above the main bog surface (Fig. 14). A measurement in October 2012 shows that the water table was standing 23 cm below the surface in an excavated observational hole in transect A, sample point 6. The relatively low water table allows roots to penetrate deeper and anchor in the substrate (Fig. 14). The average ring width is considerably smaller in the bog trees than in the solid ground and marginal fen trees, suggesting nutrient deficiency. A relatively low water table and poor nutrient availability is reflected in the intermediate height of the bog trees growing on the marginal hummock.

At the bog plain margin trees occur more scattered and are both shorter and show smaller stem diameter. Here the water table was only 3 cm below the bog surface at transect A, sample point 9 when measured in October 2012. The pH and nutrient availability is low, thus limiting tree growth together with the high water table that prevents any deeper root penetration (Fig. 14). Tree growth in this environment is more dependent on the microtopography, as small hummocks can provide dry sanctuaries for bog trees.

The number of samples that are absent from the chronologies is reflected in the site conditions. 50% of the samples are lacking from the marginal fen chronology, which suggests that even though nutrient availability is high and trees grow tall, frequent waterlogging affects the growth homogeneity of the stand. Observations by the author from the site describe the marginal fen trees as having hunched and twisted stems, suggesting periodically deteriorating growth conditions. The growth homogeneity is greatest in the marginal hummock stand, where 87.5% of the samples are present in the chronology, due to the relatively favourable water table conditions. As the water table gets closer to the bog surface at the bog plain margin waterlogging increases and growth homogeneity is reduced. Here 61% of the samples are present in the stand chronology.

## 5.5 Possible anthropogenic impact

There are several studies regarding drainage impact on bog pines (eg, Freléchoux et al. 2000; Grünig 1955; Linderholm 1999). However, these studies have been performed on substantially smaller bogs where the sampled trees have been situated close to the drained or peat mined area. Axbom (2012) found a correlation between anthropogenic drainage and tree replication on three bogs in Småland, south Sweden. It is tempting to draw similar conclusions for Store Mosse as rapid tree replication fits with the start of peat mining in the early 1900's according to Dahlberg (1988). However, Schweingruber (1996) described that a drainage

channel affects tree growth at a distance of up to 250 m. The situation on Store Mosse is quite different. The area where peat mining occurred is located over 3 km from the nearest transect (transect C). Also the large fen soak Blådöpet lies between the mined area and the sample sites (Fig. 4). Blådöpet should act as a hydrological neutraliser leaving the southern part of Store Mosse unaffected by drainage caused by peat mining. The drainage channel on the eastern side is located about 1.5 km from the western edge. Here the distance also seems too great for having an effect on the sampled bog trees.

## 5.6 Climate and hydrology

Climatic parameters are not the only factors that govern tree-ring width. Another factor influencing ring width variations is tree density, resulting in competition within the stand for light and available nutrients and water (Linares et al. 2009; Michelot et al. 2012). The age of a tree also affects the ring-width pattern (Fritts 1976). Reproduction limits ring width as extensive cone production some years allows less energy for growing thick rings than years where fewer cones are produced (Linderson, H. personal communication). Although on a bog environment competition for light and water will not be as limiting due to the low density of trees.

The solid ground chronology shows a high positive correlation with spring temperature. A warm spring extends the growth period as winter dormancy is broken earlier, and a thicker ring-width is obtained. Linderson (1992) presented similar results and suggests that pine metabolism requires a high temperature. The Ekeberg chronology shows corresponding results, with warm January and April resulting in thicker tree-rings. None of the stands from transects A-C show a temperature correlation exceeding the 95% significance level. Similar results were described in the study by Linderholm (2001). The two eastern stands, Svendsdal and Lake Kalvasjön, correlate positively with August temperature. Lake Kalvasjön correlates positively with March as well. A higher than normal summer temperature increases evaporation, resulting in a slightly lowered water table and better growth conditions that could explain the temperature correlations at the eastern bog edge. A higher than normal summer temperature would also mean less precipitation as high sun insolation is a result of a less extensive cloud cover. Due to the peatland surface slope the eastern bog edge should be more prone to waterlogging conditions. This might explain why the western stands show no temperature correlation.

All the chronologies have a normal distribution, defined as when at least two thirds of the values lie within one standard deviation from the average ring width (Schweingruber 1988). Three years or more of tree-ring widths deviating one standard deviation also defines depressed and elevated growth events, in accordance with Edvardsson et al. (2012). There are

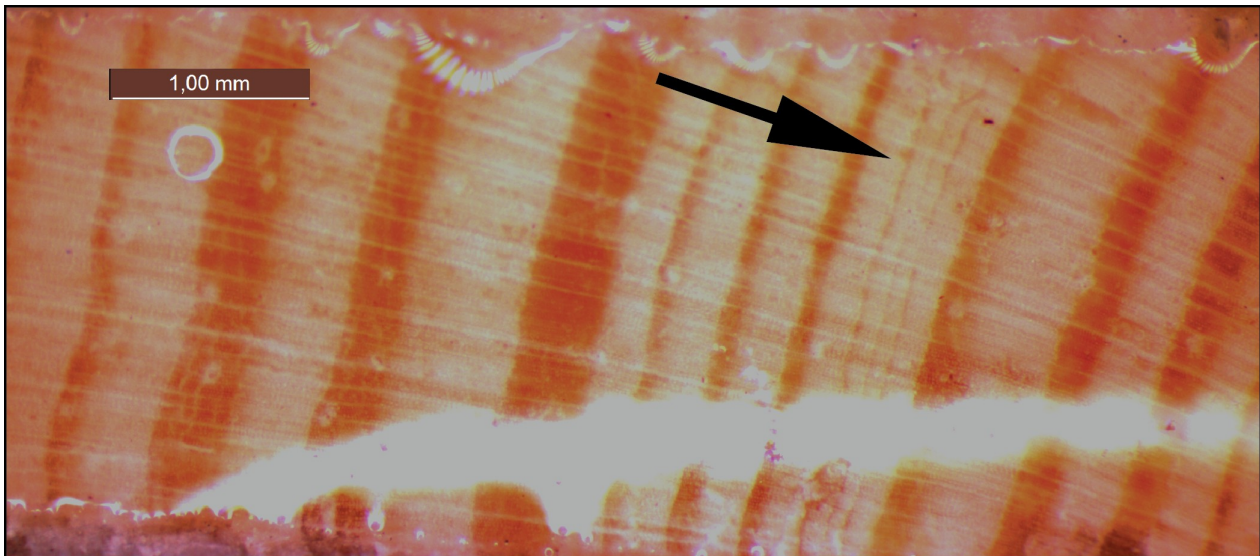


Fig. 15. Photograph showing a sample covering the 1927-1929 depressed growth event. The black arrow marks the three narrow rings representing the years 1927-1929. Note the thicker rings on each side of the event.

far more events of depressed growth than there are of elevated growth in the chronologies, suggesting that the growth conditions at Store Mosse are over time frequently deteriorating. Half of the depressed growth events can be correlated to low preceding winter temperatures, and half of the events can be correlated to higher than normal summer precipitation (Table 17). The most wide-spread depressed growth event at 1927-1929 correlates to both parameters (Fig. 15). Similar results from the Baltic States show that severe winter temperatures have a negative effect on tree-ring width (Läänelaid & Eckstein 2003; Vitas 2004). Depressed growth events can also be correlated to wet summers, as the water table would remain high and limit the uptake of oxygen and nutrients.

River discharge measurements are thought to better reflect the moisture content in the substrates than precipitation as the amount of water flowing in a stream is determined not only by precipitation, but also evaporation and other factors such as snow melt. This gives a more accurate representation of the hydrological status of Store Mosse as Rörvik is situated in the same catchment as Store Mosse. Also the river discharge reflects regional moisture conditions from all over the catchment area, whereas precipitation measurements are from local stations.

November precipitation measurements correlate

Table 17. Depressed growth events and meteorological correlations. Correlations relative to the 1961-1990 mean. The most widespread event (1927-1929) is correlated to both preceding winter temperature and high summer precipitation.

Event	Preceded by lower than normal winter T	Coincides with higher than normal summer P
1882-1884	No	Yes
1894-1896	No	Yes
1899-1902	Yes	No
1910-1913	No	No
1927-1929	Yes	Yes
1942-1944	Yes	No

negatively with the solid ground chronology. The amount of precipitation in November is above the monthly mean and as daylight and temperature decreases the evaporation process is limited. It might be that trees are sensitive to November precipitation as in wintertime precipitation mainly falls as snow that does not reach the groundwater flow until spring.

Vitas & Erlickytė (2007) discuss that low summer precipitation has a negative effect on Lithuanian bog pines as drought periods lower the water table beneath the root system. In contrast, summer droughts do not seem to affect the growth in Store Mosse. Lithuania has a continental climate and the annual precipitation there is lower than in south Sweden. Instead several stands correlate negatively with precipitation of the preceding summer.

Edvardsson et al. (in review) showed a lag in tree-ring width compared with growth depression events inferred from  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  data obtained from bog pines at Åbuamossen and Hällarydsossen. It was indicated that the ring width of the trees responded up to three years after the local climate conditions changed. A similar reaction could be interpreted from a strong negative correlation with previous summer precipitation in the Store Mosse chronologies. Low summer precipitation leads to a lower water table that improves growth conditions and the reaction lag discussed in Edvardsson et al. (in review) could explain the stronger correlation with the previous summer.

The positive September precipitation correlation in five of the stands could be explained by the increased number of days with a cloud cover as clear skies increases the chance of frost temperatures that has a negative effect on the tree growth. A longer growth period extending into September due to the recent changes towards a warmer climate are not likely to produce the September correlation as attempts to increase the correlation with only the latter half of the

Table 18. Compilation of water flow correlations with the solid ground (S.G.), marginal fen (M.F.), marginal hummock (M.H.), bog plain margin (B.P.M), Ekeberg (E), Svendsdal (S) and Lake Kalvasjön (L.K.) chronologies. The results show a peak in negative correlation at two to four years of added water flow measurements. The marginal fen, marginal hummock and bog plain margin chronologies show the highest correlations. The strength of the correlation fades away after four years of added water flow measurements.

River discharge	C	Pr.	C+1 Pr.	C+2 Pr.	C+3 Pr.	C+4 Pr.	C+5 Pr.	C+6 Pr.	C+7 Pr.	C+8 Pr.	C+9 Pr.
S.G.		-0.25	-0.20								
M.F.		-0.22	-0.19	-0.26	-0.30	-0.28	-0.24	-0.22			
M.H.	-0.22	-0.24	-0.30	-0.29	-0.27	-0.27	-0.26	-0.20			
B.P.M.		-0.22	-0.21	-0.23	-0.25	-0.25	-0.27	-0.23			
E.		-0.24	-0.24	-0.21							
S.											
L.K.											

chronologies gave insignificant improvements.

The monthly temperature, precipitation and river discharge measurements can explain some of the tree-ring width variations but the results are inconclusive and fragmentary. Two to four years of added annual river discharge measurements show coherent results from four of the six fen and bog stands, including all stands at the western edge (Table 18). The strongest correlation occurs with two to four years of added annual measurements. This is a clear indication of that there is a response lag to water level changes in tree-ring width, as suggested by Edvardsson et al. (in review). River discharge better reflects the hydrological setting in the bog as both precipitation and evaporation is accounted for in the river discharge measurements.

Annual climatic and environmental variations are better reflected in the tree-ring records than monthly precipitation and temperature measurements. Several similar studies have suggested that water level changes over several years are an important factor determining bog-tree growth (eg, Boggie 1972; Linderholm 2001; Linderholm et al. 2002). Therefore, chronologies from bog trees seem to be more reliable for studies regarding annual to decadal water level changes than for studying high-frequency reconstructions of precipitation and temperature. Since the chronologies show a consistent correlation with annual river discharge the bog water table is seemingly the governing factor for bog-tree growth regardless of the location of the stand. However, studies aiming to reconstruct temperature or precipitation based on trees growing on bogs should focus on marginal hummock trees, where the growth conditions are tolerable (a relatively lowwater table) and homogeneity among the trees is large. Trees residing in marginal fens are least suitable for climatic reconstructions as the frequent waterlogging severely disturbs the regional climatic signal.

## 6 Conclusions

- The peat depth and topography govern the height and size of the bog pines at Store Mosse as nutrient availability, water table fluctuations and shallow root depth limits tree growth. Bog pines situated at the marginal hummock

have relatively good growth conditions and uniform ring patterns that indicate a relatively good climate signal. The frequently waterlogged marginal fen is least suitable for climate correlations.

- Anthropogenic disturbance such as peat mining and drainage on Store Mosse has had no visible effect on the ring width of the sampled bog pines. Therefore, ring widths should reflect hydrological and climatological changes.
- Depressed growth events can be correlated with cold winters and wet summers including the most wide-spread depressed growth event 1927-1929.
- River discharge measurements show better correlations with the chronologies than precipitation, indicating that river discharge should better represent the actual substrate moisture conditions.
- Monthly temperature and precipitation correlate inconsistently with the different stands, suggesting that the main factor governing tree growth is water table fluctuations. Monthly correlations with previous summer precipitation and river discharge indicates a lag response in the tree-ring records. This is confirmed by annual water flow measurements that indicate a response lag of two to four years between substrate moisture conditions and tree-ring records from Store Mosse.

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