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Multiannual hydrological responses in Scots pine radial growth within raised bogs in southern Sweden

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Highlights

- Annual growth of Scots pine (*Pinus sylvestris* L.) at Boreal raised bogs was found to reflect a synthesis of climate controlled moisture variability over the preceding one to four year period.
- Excessive soil moisture is a growth limiting factor for trees at raised bogs.
- River discharge data reflect hydrological conditions in peat bogs better than precipitation data.

Abstract

To explore interactions between climate and peatland hydrology, Scots pine (*Pinus sylvestris* L.) growing at four raised bogs in southern Sweden were subject to a dendroclimatological study. Radial tree growth reflecting climate and water table fluctuations over multiannual periods was detected as significant negative correlations between tree-ring width (TRW) chronologies and the preceding one to four years total precipitation or river discharge. Systematically stronger negative correlations were obtained when river discharge instead of precipitation was compared to radial tree growth. This indicates that river discharge reflect moisture variability of peat bogs better than what precipitation data does. Meanwhile, monthly precipitation and radial tree growth did not show any clear correlation, whereas spring and early summer temperatures had a positive influence on the tree growth. Our study shows that growth variability of bog pines in the Boreal zone reflect hydrological responses related to a synthesis of climate controlled moisture variability over several year periods.

Keywords peatland; hydrology; *Pinus sylvestris*; precipitation; river discharge; dendrochronology
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1 Introduction

Boreal peatlands provide ecosystem services as carbon sinks and water reservoirs (Limpens et al. 2008; Waddington et al. 2014). Moisture variability has a major influence on ecosystem processes in peatlands (Belyea and Malmer 2004; Ise et al. 2008), but a holistic understanding of how climate interacts with their hydrology is still lacking (Heijmans et al. 2008; Waddington et al. 2014). Natural proxy records that link hydrology and climate variability are therefore crucial for our understanding of peatland ecosystem responses to climate change (Waddington et al. 2014). Somewhat simplified, water table fluctuations in peatlands depend on the total seasonal moisture deficit, which relays on a combination of precipitation and temperature controlled evapotranspiration (Charman 2007). But, due to possible hydrological feedbacks (Waddington et al. 2014) and lag-effects (Kilian et al. 1995), peatland water table reconstructions are not that straight forward.

Annual growth rings from both subfossil (Eckstein et al. 2009; Edvardsson et al. 2012) and living (Scharnweber et al. 2015) peatland trees have been used for hydrological reconstructions. Water table fluctuations in peatlands have a significant impact on the radial growth of the trees (Boogie 1972; Linderholm 2001). Most often, increased effective precipitation result in a thinning of the water unsaturated zone (Schouwenaars 1988), and thereby reduced radial growth in the trees due to several physical, chemical and biological processes (Boggie 1972; Penttilä 1991; Mannerkoski 1991). Although dendroclimatological studies using living peatland trees have been performed (Linderholm 2001; Cedro and Lamentowicz 2011; Smiljanić et al. 2014), the exact influence climate dynamics has on the moisture status and associated tree growth is still not fully understood. In a pilot study by Edvardsson et al. (2014), moisture signals in stable carbon and oxygen isotope records was compared to growth responses of peatland pines that lived during the Mid-Holocene. The results showed an increased correlation between the records when shifted three years, which indicated that periods of weak tree growth did not occur synchronously with changes towards moister atmospheric conditions. Another study, by Linderholm et al. (2002), comparing growth responses of living pine trees growing at different substrates and meteorological data, indicated that tree growth at peatlands might be influenced not only by prevailing temperature and precipitation, but also by water table fluctuations caused by climate variability over several years. Further studies investigating the cumulative effect multiannual climate dynamics has on peatland moisture variability and associated tree growth is therefore highly motivated. The main objectives for this study are consequently to (1) compare radial growth of peatland trees to instrumental meteorological records, and (2) clarify if there are possible lag-effects or multiannual responses detectable in the growth patterns of the trees.

2 Material and methods

2.1 Study sites

Four raised bogs, Store Mosse (57°14´N, 13°55´E), Saxnäs Mosse (56°51´N, 13°27´E), Buxabygds Mosse (56°48´N, 14°13´E) and Hästhults Mosse (56°42´N, 13°29´E), all located in Småland, southern Sweden (Fig. 1), and habited by pine trees were chosen as study sites. With an area of almost 100 km^2, Store Mosse is the largest raised bog complex in southern Sweden (Svensson 1988). The other raised bogs are small in comparison; Saxnäs Mosse is 0.45 km^2, Hästhults Mosse is 0.25 km^2 and Buxabygds Mosse is 0.5 km^2. The bogs are located 160–175 m above sea level on the South Småland Archaean plane. Store Mosse, Saxnäs Mosse and Hästhults Mosse are situated in the Lagan River catchment area, while Buxabygds Mosse is located in the adjacent catchment area of the Helge Å River. The annual mean precipitation in the area is about 650 mm yr^{-1} and the mean temperature is 6.3 °C (Fig. 2).

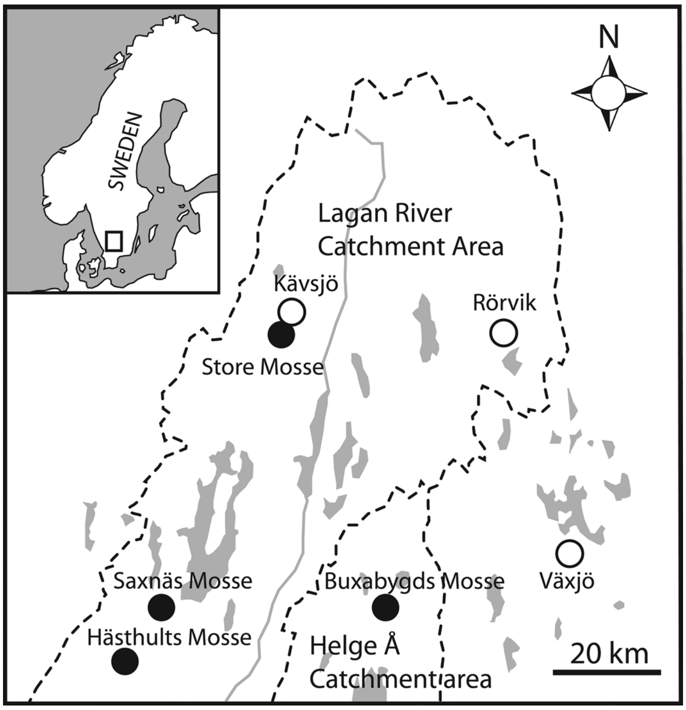

Fig. 1. Location of the study sites (black circles) and meteorological stations (white circles) within the study area in southern Sweden (inset). The dashed lines show the Lagan River and Helge Å catchment areas whereas lakes and rivers are shown in grey.

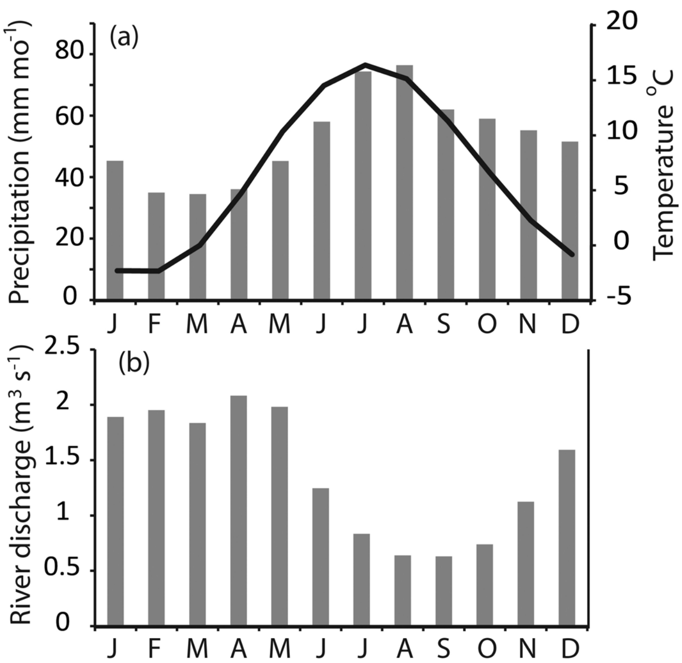

Fig. 2. (a) Average monthly precipitation (grey bars) and temperature (black line) recorded at the Växjö meteorological station for the years 1860 to 2013. (b) Average monthly river discharge data recorded at the Rörvik measuring station for the years 1909 to 2012.

2.2 Development of tree-ring width chronologies

Scots pine (*Pinus sylvestris* L.) is a common tree species on Swedish peatlands (Rydin et al. 1999), and several studies show an ongoing pine establishment at peatlands in the Boreal zone (Linderholm and Leine 2004; Edvardsson et al. 2015). Scots pine has also been used in comparable studies (Linderholm et al. 2002; Cedro and Lamentowicz 2011) and was therefore considered the most appropriate tree species to use. A total of 149 pine trees growing at Store Mosse (74), Buxabygds Mosse (22), Saxnäs Mosse (26) and Hästhults Mosse (27) were sampled with an increment corer. The tree cores from Store Mosse were collected in 2009 and 2012, whereas the remaining sites were sampled during spring 2012. The sampled trees were assumed to be slow growing and were therefore sampled not higher than 40 cm above the ground to maximise the number of growth rings in the increment cores. To obtain tree growth responses related to the hydrological conditions in the raised bogs, peat thickness was measured with a probe to avoid sampling of trees rooted in mineral soil. To be able to separate tree growth changes related to bog hydrology from temperature and precipitation signals, 20 pine trees growing at mineral soil adjacent to Store Mosse were sampled and analysed for comparison (Hansson 2013).

Tree-ring width (TRW) chronologies from each site were created based on measurements of annual growth rings with a precision of 0.01 mm, using standard dendrochronological equipment and common cross-dating techniques (Fritts 1976; Cook and Kairiukstis 1990). The cross-dating and measurement quality, as well as the strength of the TRW chronologies, were evaluated using the COFECHA software (Holmes 1983). To minimise the influence of non-climatic variations and trends (e.g., tree age and geometry) all TRW series were standardized and transformed into dimensionless TRW indices (Fritts 1976; Cook and Kairiukstis 1990). As no common growth trends were detected a flexible standardization method based on Friedman's variable span smoother (Friedman 1984) was used. The standardization was made using the software ARSTAN_41d (Cook and Krusic 2006). In order to assess the reliability of the TRW chronologies, the expressed population signal (EPS) was calculated and the limit at which the chronologies were considered as reliable and well replicated was set to EPS ≥ 0.85 (Wigley et al. 1984). The EPS value is dependent on the number of overlapping samples in the chronology and the degree of intercorrelation. The standardized TRW chronologies containing maximum low frequency variability and the residual chronologies corrected for autocorrelation (Holmes et al. 1986) were used for correlation analyses.

2.3 Meteorological data

Meteorological data was acquired from the Swedish Meteorological and Hydrological Institute (SMHI). Temperature (T; average mo temperature in °C) and precipitation (P; mm mo^{-1}) data was obtained from the meteorological station in Växjö (56°52´N, 14°47´E; Fig. 1–2), situated 35–70 km east-southeast of the raised bogs. The Växjö records cover the period from 1860 to 2012. As Store Mosse is located relatively far from Växjö meteorological station, complementary data from the Kävsjö station (Fig. 1), located 9 km north of this study site, were used for comparison. The Kävsjö data series cover the period from 1909 to 2012. River discharge measurements (R; m^3 s^{-1} Fig. 2) covering the period from 1907 to 2012 were obtained from the measuring station in Rörvik (57°14´N, 14°35´E; Fig. 1) in the Lagan River catchment area.

2.4 Correlation analyses

The TRW chronologies were initially used for correlation and response function analyses using monthly data from the meteorological stations in Växjö and Kävsjö, as well as river discharge data from Rörvik. These analyses were performed using DendroClim 2002 statistical software for analysis of climate and tree growth relationships (Biondi and Waikul 2004). The correlation values calculated in DendroClim 2002 are the median coefficients estimated from the 1000 bootstrap samples (Biondi and Waikul 2004). A significance level of $p<0.05$ was considered as reliable and all correlation coefficients generating $p>0.05$ were nullified. Then monthly correlation values were analysed using TRW of the considered year (n) and monthly meteorological values starting with September of the previous year (n–1) and ending with October of the considered year (n).

To investigate tree growth responses to long-term hydrological changes, correlation analyses using precipitation and river discharge data over increasingly longer periods were performed. The TRW chronologies were initially correlated to either total precipitation or river discharge over the considered year and thereafter the previous three years individually. In the subsequent step, analyses using precipitation and river discharge over periods from one to four years were made. All correlation analyses were performed on TRW chronologies in their full length and for periods with an EPS value of at least 0.85.

3 Results

Five TRW chronologies were developed, one from each of the four raised bogs and one from the pine trees growing at mineral soil adjacent to Store Mosse (Fig. 3; Table 1). With the exception of

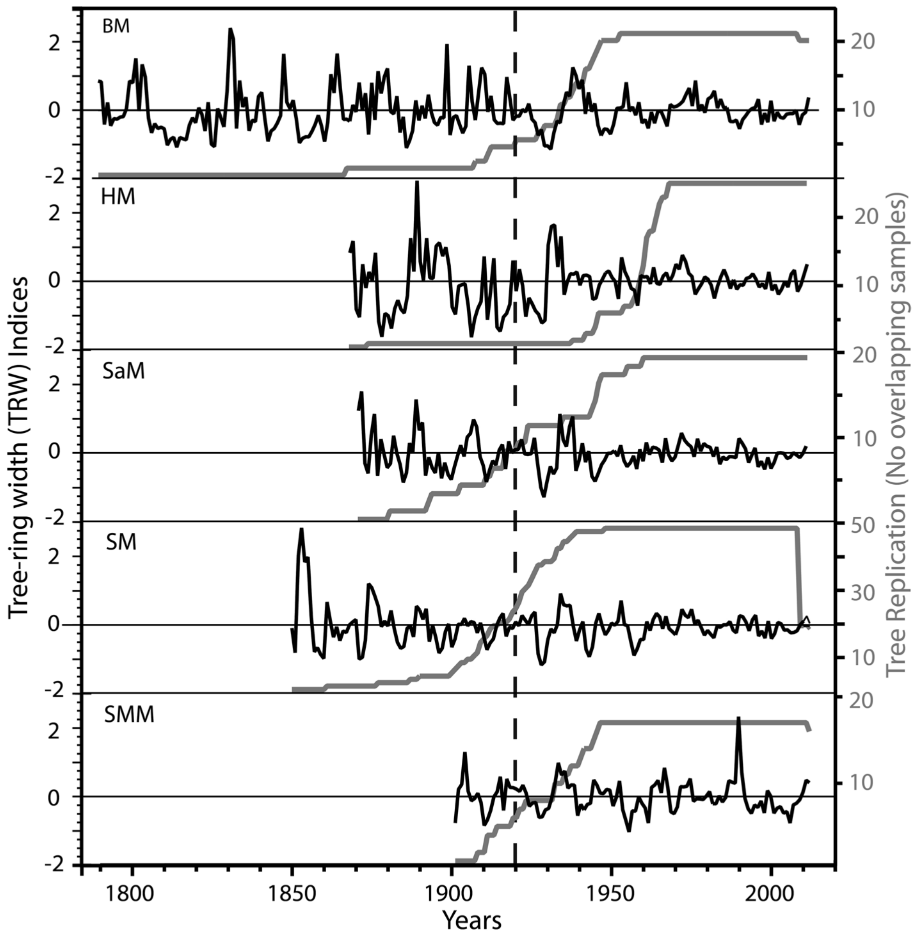

Fig. 3. The black curves show standardized tree-ring width (TRW) chronologies (dimensionless indices) from the raised bogs Buxabygds Mosse (BM), Hästhults Mosse (HM), Saxnäs Mosse (SaM), Store Mosse (SM), and mineral soil adjacent to Store Mosse (SMM). The grey curves show sample replication, and the vertical dashed line show the onset of the common period used for the correlation analyses shown in Fig 4 and 5.

Table 1. The table show number of trees used in each tree-ring width (TRW) chronology (No), length of the TRW chronologies (yrs), the period each TRW chronology covers, the period with EPS above 0.85, series inter-correlation (r), and average (Ave), maximum (Max) as well as minimum (Min) TRW (mm) for the EPS>0.85 periods. Two TRW chronologies are presented from Store Mosse, one for the bog trees (B) and one for the mineral soil trees (MS).

Site	Trees (No) / Length (yrs)	Total period / EPS>0.85	Series inter-correlation	TRW (mm) Ave / Max / Min
Buxabygds Mosse	21 / 227	1785–2011 / 1920–2011	0.530	0.85 / 1.79 / 0.22
Hästhults Mosse	25 / 144	1868–2011 / 1960–2011	0.506	1.11 / 3.24 / 0.32
Saxnäs Mosse	20 / 141	1871–2011 / 1915–2011	0.451	0.52 / 1.26 / 0.16
Store Mosse (B)	49 /163	1850–2012 / 1910–2012	0.513	0.68 / 1.56 / 0.28
Store Mosse (MS)	18 / 111	1902–2012 / 1915–2012	0.566	1.86 / 3.58 / 0.77

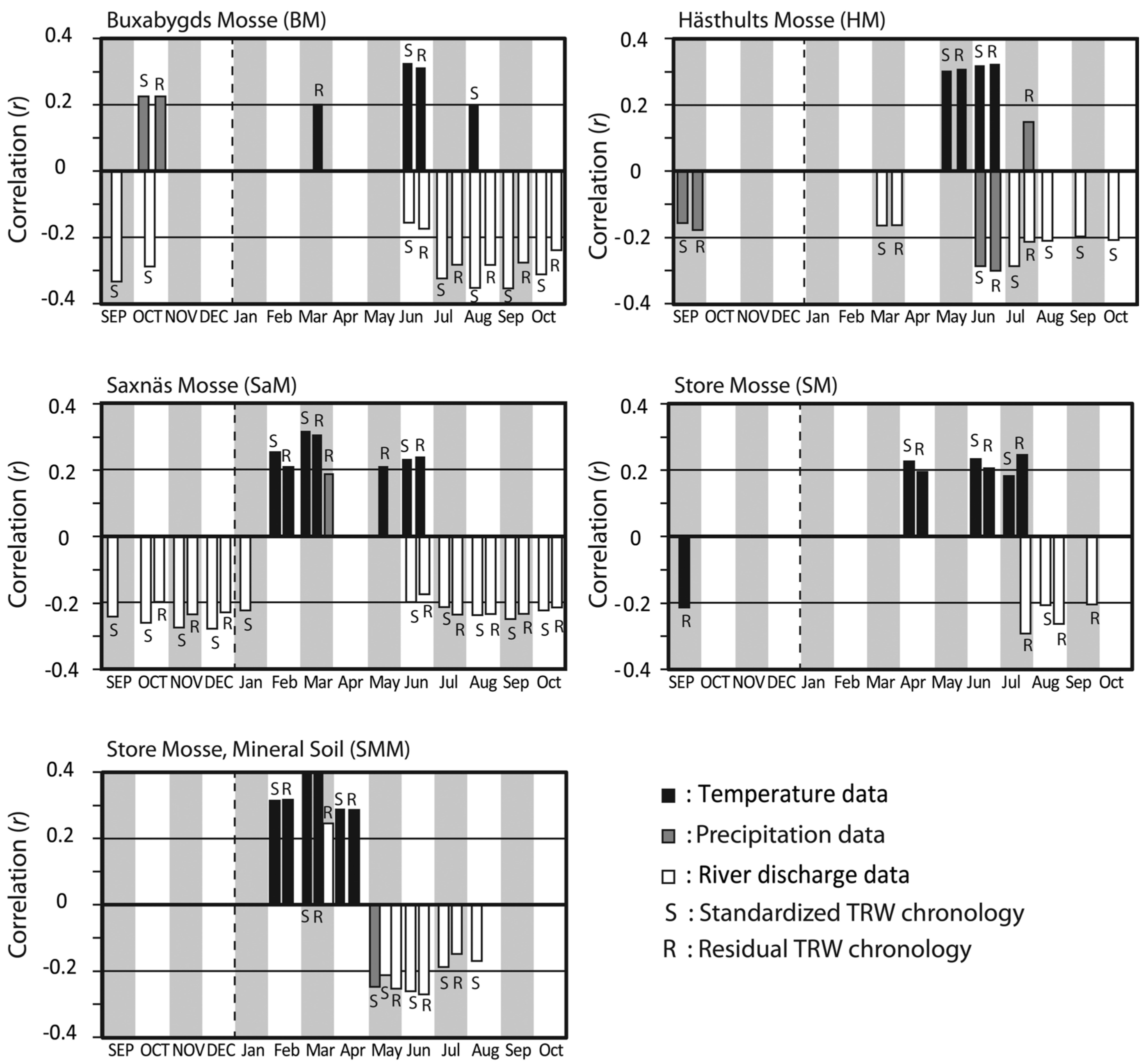

Fig. 4. Correlation analyses between tree-ring width (TRW) chronologies, average monthly temperature, total monthly precipitation and river discharge. The period September of the previous year (n–1) to October in the considered year (n) during the period 1920 to 2011 was used for all correlations analyses presented. Correlation values are displayed only if significance level corresponding to $p<0.05$ is reached.

Hästhults Mosse, the correlation analyses using the parts of the TRW chronologies representing EPS values above 0.85 generated stronger correlation to the meteorological data than when the total length of the chronologies were used. For the Hästhults Mosse TRW chronology the strongest correlation was obtained when the chronology was extended back to 1920. The two long lived overlapping trees that make up the early part of the Hästhults Mosse TRW chronology were therefore examined individually. The trees cross-dated well and comparisons with the other sites TRW chronologies show that the Hästhults Mosse chronology matches both statistically and visually from 1920 to 2011. This period was therefore considered to be the longest comparative phase, as EPS values above 0.85 were reached prior to 1920 among the other chronologies, and therefore used in the analyses presented in Fig. 4 and 5.

For the bog trees, significant correlation between radial growth and temperature was obtained for scattered months between February and August (Fig. 4). The analyses using monthly precipitation data show no common pattern, and the correlations were in most cases not significant. Negative correlations between TRW and river discharge for one to five months during the period June to October was recorded among all sites. As Store Mosse is the most remote site from the meteorological station in Växjö, complementary analyses using data from the nearby station in Kävsjö (Fig. 1) were made. Only a weak significant correlation with September precipitation of the considered year ($r=-0.25$) was however obtained. Meanwhile, the TRW chronology developed from trees growing at mineral soil was positively correlated to February, March and April temperatures.

The analyses over annual to multiannual periods showed significant negative correlations when the bog TRW chronologies were compared to total precipitation or river discharge (Fig. 5). On one occasion, previous year's precipitation and on four occasions the previous year's river discharge showed stronger correlation than for the considered year. The strongest correlations were however consistently obtained for the total values over several consecutive years (Fig. 5). By contrast, the trees sampled on mineral soil showed weak to absent correlations when compared to both multiannual precipitation and river discharge (Fig. 5). To visualize the observed multiannual moisture responses, the bog TRW, precipitation and river discharge records were smoothed using a three-year Gaussian filter (Fig. 6). Moist periods, visible as several consecutive years of precipitation and river discharge above average, coincide or precede prolonged phases of depressed tree growth at the bogs. Also the opposite, with dry periods followed by strong tree growth was observed. The analyses comparing radial growth to river discharge were consistently generating stronger correlation than the analyses using precipitation, especially for the multiannual comparisons (Fig. 5).

In most cases, the standardized TRW chronologies showed stronger correlation to the meteorological data than the TRW residuals do. This might be a result of some autocorrelation in the standardized chronologies, which is a common feature in TRW data (Grissino-Mayer 2001). The results using residual TRW chronologies from Saxnäs Mosse and Buxabygds Mosse were in general similar to those using standardized chronologies, whereas the Hästhults Mosse and Store Mosse records generated weaker correlations (Fig. 5). Significant correlations were however reached when residual TRW chronologies from all raised bogs except Store Mosse were compared to the multiannual precipitation and river discharge records. Further evidence which suggests that the multiannual effect is related to the bog environment and not the trees or the data treatment is the lack of the integrated multiannual effect in the data developed from the tree population growing at mineral soil.

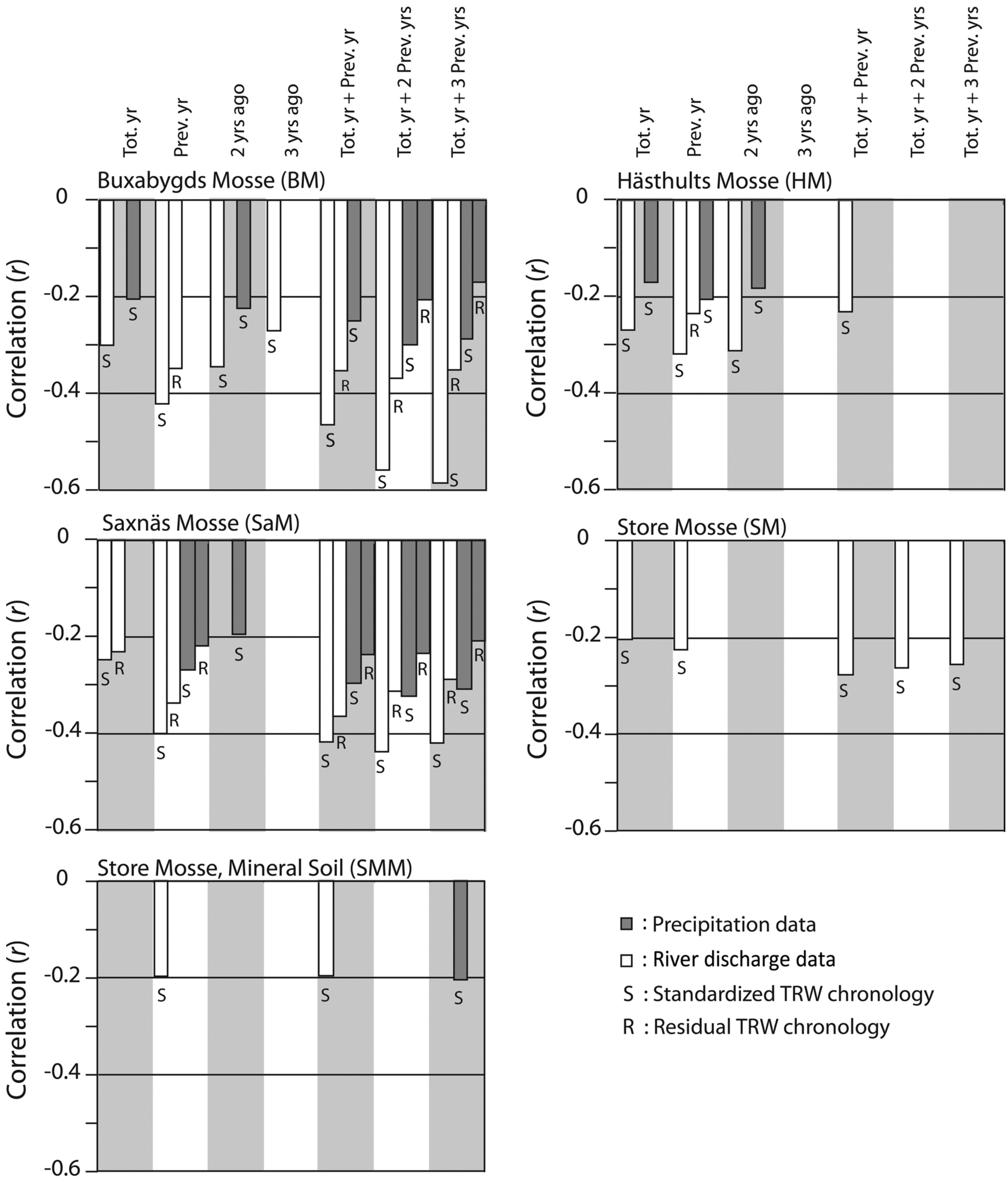

Fig. 5. Correlation analyses between tree-ring width (TRW) chronologies, total precipitation and river discharge for the entire year (Total yr.), for the preceding three years individually (Prev. yr., 2 yrs. ago, 3 yrs. ago), for the year plus previous year (Total yr. + prev. yr.), for the year plus the two previous years (Total yr. + Prev. 2 yrs.) and the year plus the three previous years (Total yr. + Prev. 3 yrs.). The period 1920–2011 was used during all correlation analyses presented and values are displayed only if a significance level corresponding to $p < 0.05$ is reached.

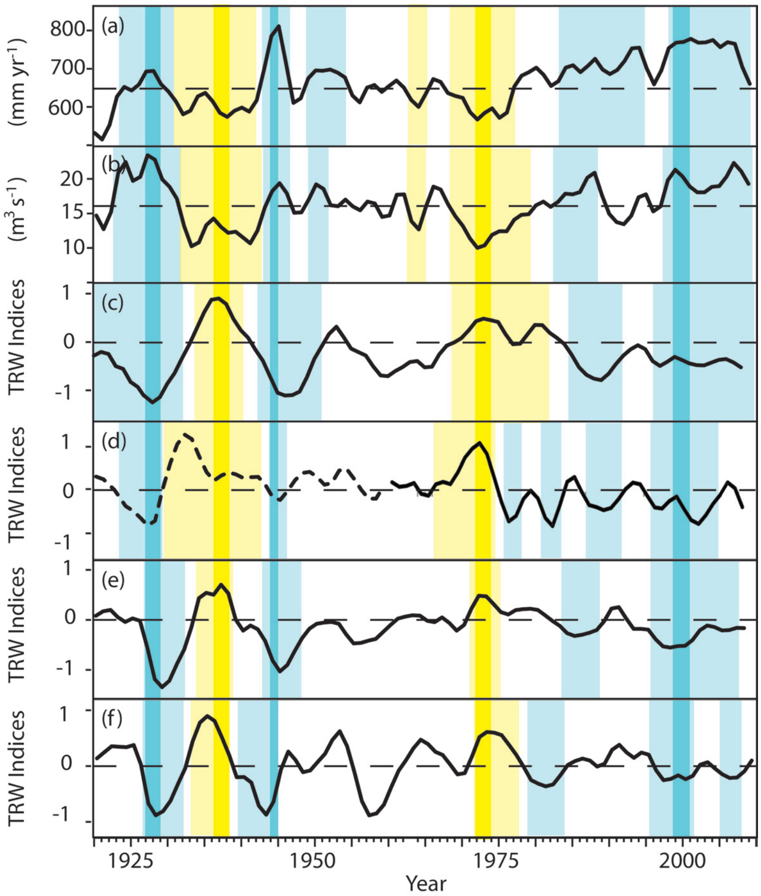

Fig. 6. Multi-year comparison between meteorological data and tree-ring width (TRW) chronologies. (a) Precipitation data from the meteorological station in Växjö, (b) river discharge data from the measuring station in Rörvik, (c) TRW data from Buxabygds Mosse, (d) Hästhults Mosse, (e) Saxnäs Mosse, and (f) Store Mosse. All records are smoothed using a 3-year Gaussian filter and unreliable segments are dashed. Moist periods are highlighted in blue whereas dry periods are highlighted in yellow. Periods showing synchronicity between all records are highlighted with darker colours.

4 Discussion

4.1 Possible linkage between climate, hydrological feedbacks and tree growth

Several studies show that radial growth of peatland trees reflects local hydrological conditions (Boggie 1972; Freléchoux et al. 2000; Scharnweber et al. 2015). Statistical and visual comparisons between the TRW chronologies show coherence which proves that radial tree growth at the studied peat bogs have been governed by regional climate dynamics. Moreover, comparative studies between radial growth at mineral soils and peat soils, as well as analyses using meteorological data show that moisture is a tree growth limiting factor at the bogs. Moreover, the trees at mineral soil adjacent to Store Mosse do on average produce 2.7 times wider growth rings and show less year by year growth variability than the bog trees (Table 1), which indicate harsher but more dynamic conditions at the bog. More importantly, the correlation analyses show differences as the trees at mineral soil respond more directly to changes in temperature than the bog trees whose growth appears to be more complex (Fig. 4). These initial results are supported by studies by Linderholm et al. (2002) and Cedro and Lamentowicz (2011), making similar comparisons between trees at different substrates.

Warm temperatures before and during the onset of the growth season proved to be important for all studied pine populations. Relatively warm conditions increase evaporation at the bogs, which would not only generate drier conditions in the unsaturated zone, but also accelerate phenological development, increase rates of photosynthesis, and increase possibilities for nutrient uptake through the root systems of the trees (Boggie 1972; Penttilä 1991). Meanwhile, the correlation analyses show weak to absent coherence between monthly precipitation and bog TRW (Fig. 4). Total precipitation or river discharge over several years however, have a significant negative impact on the radial growth (Fig. 5). These observations indicate retarded hydrological responses to precipitation in peatlands.

There are several possible internal and external factors causing slow hydrological responses in raised bogs. Water transportation through soils and empty ground water reservoirs at the end of the summer may create lagged responses between precipitation and soil moisture in the bogs (Cowan 1965; Hillel 1971). Water can also be accumulated in plants (Shukla and Mintz 1982; Seneviratne et al. 2010) instead of ending up in the bogs, and precipitation falling as snow is yet another factor creating lagged responses due to delays between snowfall and associated snowmelt (Price and Schlotzhauer 1999). Moreover, peat soils are compressible and changes in water content may result in volumetric fluctuations, detectable as variations in bog surface elevation (Almendinger et al. 1986; Price and Schlotzhauer 1999). The water storage capacity of peat bogs is restricted to the unsaturated zone, where water can replace air in the relatively large pore spaces in the fibrous network of plant fragments (Ingram 1983; Almendinger et al. 1986). Studies by Almendinger et al. (1986) indicate that the swelling mechanism is not a seasonal phenomenon; it may instead be related to long-term hydrological fluctuations. Changed amounts of water stored in a peatland may therefore initially result in relatively unchanged soil moisture around the tree roots until the volumetric change declines. Thereafter, hydrological variations are believed to more directly affect the thickness of the unsaturated zone and associated tree growth. This will generate slow water table responses and thereby weakened correlation between tree growth and short-term moisture variability, whereas the coherence with long-term changes might increase.

4.2 Regional moisture signal in the river discharge data

Stronger and more consistent negative correlations were obtained when river discharge was compared to bog TRW chronologies instead of more conventional precipitation data. This suggests that the moisture signal in the river discharge data better represent hydrological conditions in the bogs. There appears to be a divergence between river discharge and precipitation (Fig. 2), which might be similar to the assumed slow water table responses detected in many peatlands (Ingram 1983; Almendinger et al. 1986). The highest average annual precipitation is for example recorded for July and August, whereas August and September show the lowest monthly river discharge. Instead the peak months in the discharge data are April and May, suggesting a divergence of about eight to nine month between the maximum precipitation and the following peak in river discharge. Evaporation during summer months and snowmelt in spring are factors causing the observed deviations between precipitation and river discharge. These factors are also likely to affect the soil moisture in the bogs in a similar manner and thereby generate stronger agreement between bog TRW and river discharge than for precipitation.

4.3 Hydrology reconstruction

Our results show that the bog trees do not capture short-term moisture variations very well, but certainly long lasting changes. Individual years of depressed or strong tree growth might therefore be handled with caution, whereas prolonged periods of depressed growth, similar to those described by Eckstein et al. (2009) and Edvardsson et al. (2014) can be interpreted as prolonged or extreme wet phases. The recorded multiannual growth responses might also explain why there is an approximately three years delay in tree growth responses in relation to atmospheric moisture variations described by Edvardsson et al. (2014), and why the tree growth appears to reflect climate variability over several year periods as discussed by Linderholm et al. (2002). A study by Kilian et al. (1995) based on wiggle-match dated peat cores also suggests that gradual climate changes not instantly affect peatland hydrology, and that there might be lags in the water table responses of a few years up to several decades. Our results confirm the observations in these studies.

The visual comparison between smoothed TRW and moisture records (Fig. 6) shows that moist conditions during the 1920s not directly generated harsh growth conditions. A similar slow response, but in the opposite direction, is visible during the 1930s when increased tree growth due to relatively dry conditions is delayed among all tree populations except at Hästhults Mosse. Other episodes of slow tree growth responses can be visualised during the 1940s, 1970s and 1980s (Fig. 6). In recent decades, a trend of increased river discharge and precipitation can be observed. The response of the bog trees is not entirely clear, but generally the TRW indices show slightly below average radial growth during this period.

5 Conclusions

Our results show that radial growth of moisture sensitive bog pines reflect a synthesis of climate controlled moisture variability over several years. Correlation analyses based on TRW from Scots pines sampled at four raised bogs in southern Sweden, and local river discharge and precipitation records, show a one to four year integrated hydrological response to climate in the tree growth. Moreover, the analyses prove that moisture is a tree growth limiting factor, demonstrated by significant negative correlation between radial growth and river discharge, especially on a multi-annual scale. The slow tree growth responses are probably closely linked to retarded water table fluctuations in the bogs and may generate substantial information about the complex interaction between moisture variability in peatlands and climate dynamics. These results may therefore be valuable for continuous studies of peatland ecosystem processes as the moisture variability strongly influence both carbon budget and vegetation dynamics at peatlands. Our analyses also show that river discharge reflect the hydrological conditions in the bogs better than precipitation data, which was observed as stronger coherence between river discharge and radial growth of the bog trees.

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