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REGULAR ARTICLE

Exploring the impact of regional climate and local hydrology on *Pinus sylvestris* L. growth variability – A comparison between pine populations growing on peat soils and mineral soils in Lithuania

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Abstract
Aims To compare growth variability of Scots pine (*Pinus sylvestris* L.) on different soil types, and to assess the potential of peat-soil pines for climatological and hydrological studies.
Methods We used extensive dendrochronological analyses to investigate temporal and spatial responses of pines growing on peat soils and mineral soils in three regions of Lithuania.
Results Significant correlations were observed between tree populations growing on similar soil types in different geographical regions, whereas synchronicity was absent between neighbouring stands growing on different soil types. At mineral soils, tree growth was significantly correlated with winter and early summer temperatures, whereas a more complex response was detected in peat-soil trees, presumably reflecting a multi-annual synthesis of moisture variability and changing hydrology. Synchronous long-term peat soil tree-growth variations observed over large parts of the Baltics point to a possible regional hydrological forcing. Our results may therefore improve hydrological reconstructions using living and subfossil peat-soil trees, and could be of prime importance given the major influence peatland water-table fluctuations have on a range of environmental processes.
Conclusion Results reveal that peat-soil pines are unsuitable for high-frequency climate reconstruction, but demonstrate their potential for the reconstruction of multi-annual to decadal hydrological fluctuations. Mineral-soil pines, by contrast, should be used for temperature reconstructions.

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Introduction

Scots pine (*Pinus sylvestris* L.) has an extensive geographical distribution across Eurasia due to its ability to establish and survive in a wide range of environments (e.g., Carlisle and Brown 1968; Poyatos et al. 2007; Krakau et al. 2013). Findings from subfossil tree remains show that pines repeatedly have established on peat soils in Eurasian over the present interglacial period called the Holocene, i.e., the past 11,700 years (Gunnarson 1999; Pukienė 2001; Eckstein et al. 2009; Edvardsson et al. 2012). By contrast, studies from living trees point to an ongoing colonization, likely related to climatic and land-use changes (Linderholm and Leine 2004; Edvardsson et al. 2015). Due to the absence of reliable, high-resolution proxies for the reconstruction of hydrology and precipitation covering the Holocene, increased interest has recently been addressed to the study of moisture-sensitive subfossil peat-soil pine trees (Eckstein et al. 2009; Edvardsson et al. 2012). Several authors have presented hydrology as an important factor limiting growth of trees on peat soils (Boggie 1972; Edvardsson et al. 2012), but the exact interpretation of tree-ring data is not necessarily straightforward in these environments. At the same time, however, the role of hydrological variability of peatlands in relation to precipitation and temperature is essential for any prediction of the vulnerability, future vegetation dynamics and carbon storage capacity of northern peat soils to changing climatic conditions (Waddington et al. 2014), especially as peat soils represent substantial terrestrial carbon reservoirs of the boreal and subarctic regions (e.g., MacDonald et al. 2006; BACC 2008). Increased knowledge of factors controlling tree growth on peat soils is therefore needed to improve our understanding of peatland development, long-term climate change and moisture variability over the Holocene. It may also enable more robust predictions for future climate dynamics. Yet, despite the global importance of peatlands and the possible link between tree growth on peat soils and hydrology, few dendrochronological and dendroclimatological studies have been performed using living peat-soil trees. In Sweden, peat-soil trees have been studied by Linderholm (1999; 2001), in Finland by Hökkä et al. (2012), and in the Baltic region by Cedro and Lamentowicz (2011), Dauškane et al. (2011) and Smiljanić et al. (2014). Furthermore, attempts to make large-scale comparisons of climate response of trees growing on peat and mineral soils are even scarcer (Linderholm et al. 2002; Cedro and Lamentowicz 2011).

The combination of humid conditions, with effective precipitation ranging from 20 to 45 % (Gailiušis et al. 2001; Galvonaitė et al. 2007), and the existence of appropriate landscape relief formed during the last deglaciation, have generated favourable conditions for peatland development in Lithuania (Kabailienė 2006). At present, more than 25 % of Lithuania is covered by wetlands of which 7.8 % has developed into peat bogs (Povilaitis et al. 2011). A recent study by Edvardsson et al. (2015) shows that pine trees are currently establishing in various peatlands in Lithuania, sometimes even at accelerating rates for the recent past. Due to the frequent presence of tree-covered peatlands, Lithuania has been considered to be a relevant area for a regional comparative study of tree growth on peat soils vs. mineral soils. In the past, hydrological processes have been studied in Lithuanian peatland ecosystems (Gaigalas et al. 2008; Linkevičienė et al. 2008; Taminskas et al. 2008; Mažeika et al. 2009), whereas analyses on peat-soil trees mainly focused on subfossil material (Pikšrytė 1996; Pukienė 2001; Karpavičius 2005) or on the impacts of ecological changes (Vitas and Erlickytė 2007; Edvardsson et al. 2015).

In this study, we therefore aim at (i) comparing growth patterns of pine trees growing in peat soils and on adjacent, yet well-drained mineral soils in three different regions of Lithuania. Based on extensive dendrochronological analyses of 228 trees, we (ii) identify high- to low-frequency wavelengths embedded in annually resolved ring-width series; (iii) use response function and pointer year analyses to investigate growth responses in pine trees to instrumental temperature and precipitation records at the inter-annual scale; (iv) compare smoothed and annual ring-width chronologies from all sites with monthly, annual, and smoothed mean temperature and precipitation data; and (v) discuss the interactions between hydrology, tree growth and climate.

Methods

Selection of study sites

Three pine-covered raised bogs called Aukštumala (S1), Kerėplis (S2), and Rėkyva (S3) were selected for tree-ring analyses (Fig. 1; Edvardsson et al. 2015). Sampling was limited to areas without visible scars so as to minimize the impact from anthropogenic activities such as ditching or peat mining. Pine stands growing on mineral soils in the surroundings of or, if possible, adjacent to bogs were sampled as well.

The Aukštumala raised bog is situated in southwestern Lithuania (55°23′ N, 21°22′ E, 3018 ha, 1 m a.s.l.). The central and western parts of the bog remain preserved from anthropogenic activities and have therefore been selected for tree sampling. The area is characterised by scattered groups of trees, often separated by hundreds of meters of open surface. The mineral-soil stand is located 1 km to the east of the bog. At Kerėplis raised bog (54°27′ N, 24°32′ E, 144 ha, 140 m a.s.l.), the sampled area in the northwestern part of the bog is characterized by relatively dense tree coverage. Mineral-soil trees were sampled on adjacent slopes where the underground consists of sandy glacio-fluvial sediments. The Rėkyva peatland complex (55°51′ N, 23°15′ E, 2608 ha, 130 m a.s.l.) is composed of six raised bogs. The selected peat bog, the only one exempt from exploitation, is sparsely covered with different generations of pine trees. Trees growing on mineral soil were sampled on sandy slopes 10 km to the southwest of the bog.

Chronology development and statistics

During fieldwork campaigns in May and September 2013, cores from 228 pine trees were collected using a Pressler increment borer. In total, 171 pines (56 at Aukštumala, 63 at Kerėplis and 52 at Rėkyva) growing on peat soils exceeding 3 m in thickness were sampled. In addition, in order to isolate tree-growth variations specifically related to bog hydrology, we cored 57 pine trees (22, 20, and 15 in the surroundings of S1, S2 and S3, respectively) growing on well-drained mineral soils.

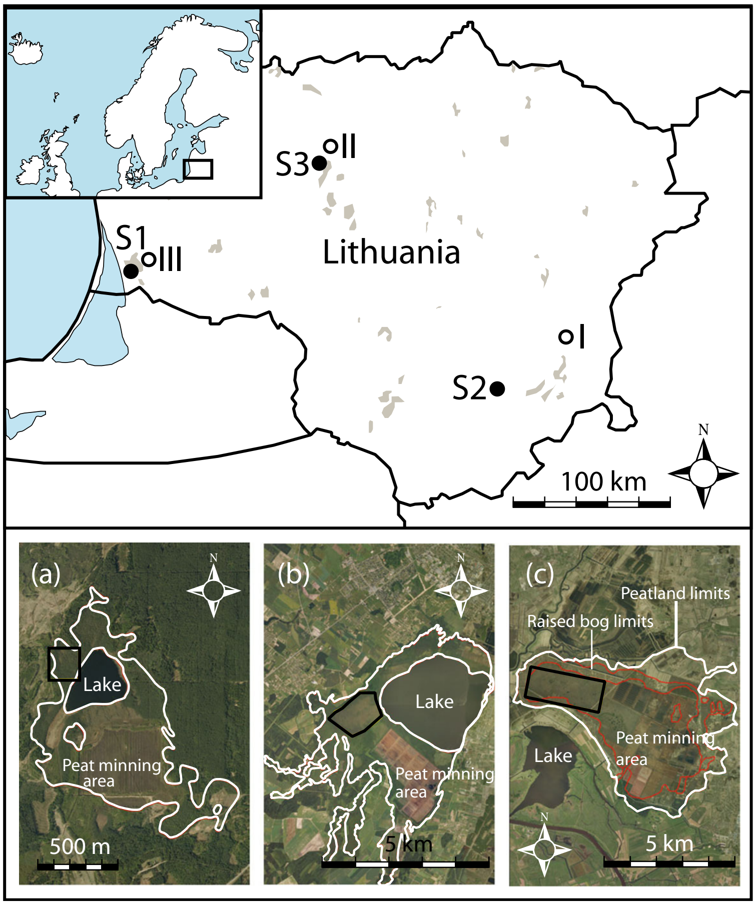


Fig. 1 The *black dots* show the location of the study sites: (*S1*) Aukštumala, (*S2*) Kerėplis and (*S3*) Rėkyva, all located in Lithuania (inset). The white *dots show* the meteorological stations (*I*) Vilnius, (*II*) Šiauliai and (*III*) Šilutė. Large peatland complexes are shown in *grey*. Overviews of the three study areas are shown in (**a**–**c**). The borders of peatlands are shown in white and the main study areas are indicated in *black*. Orthophotos were obtained from the National Land Service under the Ministry of Agriculture, Lithuania

Increment samples were analysed and data processed following standard dendrochronological procedures (Bräker 2002). Ring widths (RW) were measured to the nearest 0.01 mm using a digital LINTAB positioning table connected to a Leica stereomicroscope and TSAPWin Scientific software (Rinn 2003). Prior to standardization, all RW series were cross-dated for missing rings and dating errors using COFECHA (Cook and Holmes 1984). To minimise the influence of non-climatic variations and trends, related to e.g., tree age and geometry, the RW series were standardized and transformed into dimensionless indices (Fritts 1976; Cook and Kairiukstis 1990) using either ARSTAN_41d (Cook and Krusic 2006) or dedicated packages in R (R Development Core Team 2012). As non-significant synchronism was detected between the peat soil and mineral soil pines, and to preserve potential low-frequency variations in the tree growth, a flexible Friedman's variable span smoother (Friedman 1984) was used for standardization. We also analysed Expressed Population Signal (EPS) statistics which quantifies the strength of the common climate signal in the tree-ring proxies (Wigley et al. 1984) and used the commonly applied quality threshold of 0.85 to determine the reliability of our chronologies.

Because tree-growth persistence cannot be readily discriminated from climatic persistence (e.g., Cook 1985), residual chronologies corrected for autocorrelation were developed using autoregressive modelling (ARIMA, 1,1,1) and thereafter used for comparison with meteorological data. Pointer years were then calculated on the basis of the distribution of RW indices. RW indices within the fourth (PY-IV) and the first (PY-I) quartile were associated to strong and depressed growth, respectively.

Climate growth relationships

On the inter-annual scale, climate–growth relationships have been tested with response function analyses, a form of principal component regression designed to account for collinearity of monthly climate predictors (Fritts 1976). We have used the "DENDRO" script (Mérian 2012) developed under the R software (Development Core Team 2012) for this purpose. In detail, bootstrapped response coefficients have been calculated over the 1951–2012 period using residual RW chronologies as dependent variables (Guiot 1991) and 24 successive climatic regressors from the closest meteorological station from each site. These were represented by 12 temperature and precipitation values each organized from September of the previous growth season (n-1) to August of the year during which the annual growth ring was formed (n). Meteorological data, namely monthly mean, maximum and minimum air temperature (°C) and total monthly precipitation (mm) from the Šilutė, Šiauliai and Vilnius meteorological stations (Fig. 1), located at the vicinity of the sample sites, have been used as climatic regressors. Missing monthly values in meteorological series were filled with the ratio method and by using supplementary data from other nearby meteorological stations.

In a second step, based on similar meteorological series, we determined climatic factors associated with extreme years as identified during the pointer year analysis. Mean monthly climatic anomalies during years characterized by strong and depressed growths (i.e., PY-I and PY-IV, respectively) were compared and the significance in mean differences evaluated based on a Student's *t*-test.

At the decadal scale, monthly air temperature (1852–2013) and precipitation (1887–2013) time-series from Vilnius meteorological station have been used to assess climate-growth relationships. The data series from Vilnius were considered to properly reflect the meteorological conditions in Lithuania as (i) Pearson's correlation analysis between monthly temperature in Šiauliai and Šilutė and the meteorological series of Vilnius exceed 0.9 for the interval for which all the series overlap (1951–2012); and as (ii) monthly precipitation in Šiauliai and Šilutė are significantly correlated ($p<0.05$) with monthly precipitations in Vilnius except for May. For further statistical and visual comparisons, smoothed chronologies and meteorological data series were developed using either an 11-year moving average or flexible spline functions. Finally, in order to investigate the possible delay in response of tree growth to hydrological fluctuations, lagged correlations were computed between tree-ring chronologies and yearly rainfall totals in Vilnius. For this purpose, the meteorological series was shifted back in time with a time-offset varying from 1 to 10 years.

Results

Ring-width chronologies

Six RW chronologies were developed in this study (Fig. 2, Table 1), three from trees collected at the Aukštumala (S1PS), Kerėplis (S2PS) and Rėkyva (S3PS) peat soils, and three from trees sampled on mineral soils in the periphery of each of these bogs (S1MS, S2MS, and S3MS). The chronologies are between 76 and 212 years in length, and were developed from 66 % of the peat-soil trees and 96 % of the mineral soil trees collected. The annual tree growth was stronger at the mineral-soil sites as these trees produced two to four times wider annual growth rings, on average, than the peat-soil trees (Table 1). Interestingly, no significant correlations were observed between chronologies from the same geographic region but from trees growing on different soil types. Meanwhile, correlation coefficients computed between RW chronologies from mineral soil trees range from 0.40 to 0.62 ($p<0.05$), while lower, yet significant correlations (0.26–0.35, $p<0.05$) were obtained for the peat-soil tree RW chronologies (Table 2). After smoothing, weaker (yet not significant) correlations were computed between the mineral-soil chronologies (0.01–0.20), whereas increased values (0.30–0.69) were observed between the RW chronologies from peat-soil trees.

Years characterized by depressed growth (PY-1) were observed synchronously (Fig. 3) in the three peat-soil tree chronologies in 1979 and in two out of three chronologies in 1956, 1960, 1965, 1966, 1974, 1982, 1984, 1986, 2000, 2002, 2008, and 2009. Conversely, two positive extreme years (PY-4, 1957, 1994) were detected in all the peat-soil tree RW chronologies and 9 in at least two (1953, 1955, 1969, 1972, 1973, 1977, 1978, 1980, and 1995). At the mineral sites, depressed growth (PY-1) occurred synchronously at all the sites in 1976,

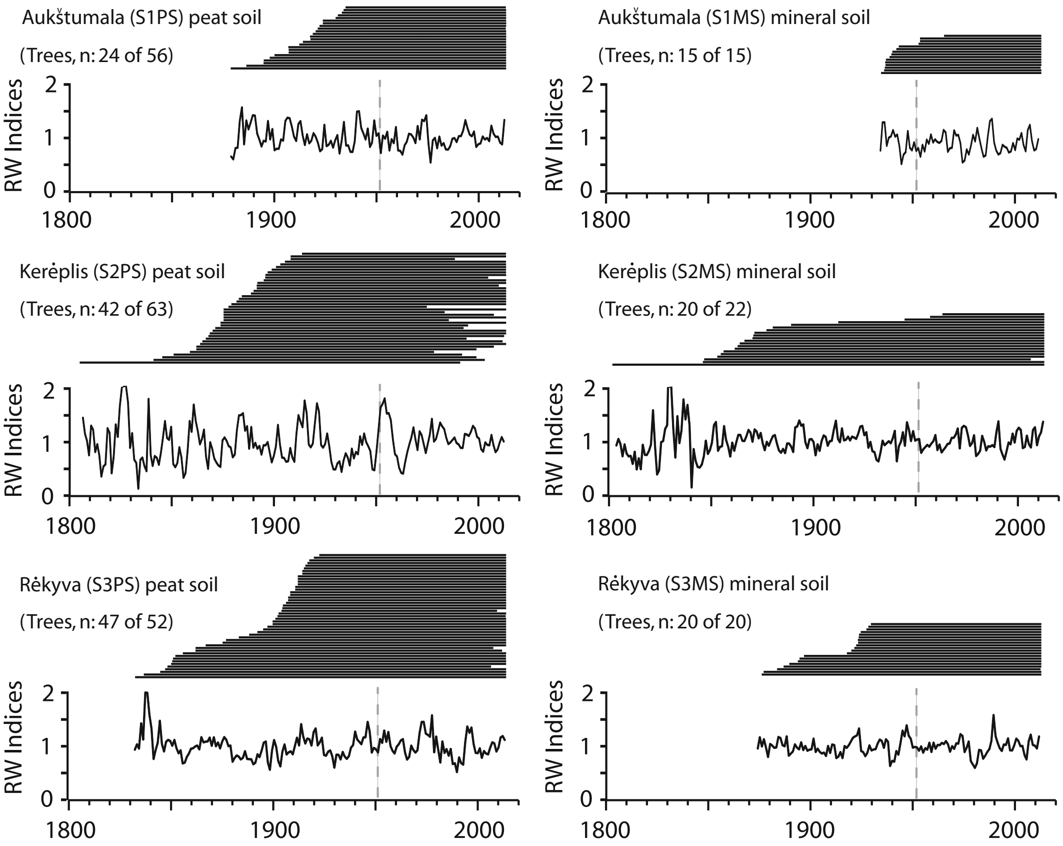


Fig 2 The six ring-width (*RW*) chronologies developed from the three study areas: Peat soil RW chronologies are shown on the *left panel*, chronologies developed from trees growing on mineral soils are shown on the *right panel*. The horizontal *black lines* represent individual trees. *Black curves* correspond to standardized RW (dimensionless indices) chronologies. The *dashed lines* show the onset of the period used for dendroclimatological analyses

Table 1 General information about the RW chronologies

	Aukštumala (S1B / bog)	Kerėplis (S2B / bog)	Rėkyva (S3B / bog)	Aukštumala (S1S / soil)	Kerėplis (S2S / soil)	Rėkyva (S3S / soil)
Trees (n) / length (years)	24 / 127	42 / 207	47 / 180	15 / 76	20 / 212	20 /138
Total period	1887–2013	1807–2013	1834–2013	1937–2012	1801–2012	1875–2012
EPS≥0.85	1940–2013	1865–2013	1905–2013	1960–2012	1890–2012	1930–2012
Series inter-correlation	0.443	0.586	0.516	0.509	0.467	0.467
Average RW (mm)	0.79	0.54	0.48	2.70	1.05	2.17

1979, 1991, and 2009, and in two of the three stands in 1954, 1956, 1960, 1962, 1969, 1980, 1985, 1992, 1993, 2005, and 2006. Strong growth (PY-4) was observed in all stands in 1989, 1990, 2000, 2007, and 2008, and in two of the three stands in 1959, 1961, 1970, 1972, 1983, 1995, 1997, 2004, and 2012.

Dendroclimatological analyses at the inter-annual scale

In the case of the peat-soil trees, the response function analyses yield differing results between the sites (Fig. 4). At S1PS, responses were dominated by precipitation in November (n-1) and August (n). Positive, albeit not statistically significant, responses of the radial growth to temperatures prior the onset of the vegetative period (Jan-Apr t) were also observed at S1PS. Response function profiles evidence the absence of climatic factors controlling significantly tree-ring width at S2PS and S3PS. Site-dependent responses to temperature were observed during extreme years. No statistically significant ($p<0.05$) differences were found in any given month for years with extreme growth deviations at S1PS (Fig. 5). At S2PS, November and December temperatures differ significantly from the mean during extremely positive and negative years. At S3PS, higher temperatures in May characterize negative extreme years. No significant differences were observed for precipitation (not presented here). A negative, yet statistically significant correlation was observed with the length of the growing period at Kerėplis (−0.30, $p<0.05$). No significant r-values (0.21 and −0.02) were obtained in Aukštumala and Rėkyva.

Both the response function (Fig. 4) and pointer year analyses (Fig. 5) revealed a positive influence of pre-growth season temperatures (Feb, Mar) on pine growth at the mineral-soil sites. Significantly different temperatures ($p<0.05$) between PY-I and PY-IV were recorded for (i) March (t) at all three sites, (ii) February (t) at S1MS and S3MS, and (iii) January (t) at S3MS. Statistically significant ($p<0.05$) positive correlations (r) were observed between tree growth and the length of the vegetative period (S1MS=0.43, S2MS=0.39 and S3MS=0.53). Strong growth years (e.g., 1990, 2000, 2007, and 2008) were also frequently associated with long growing seasons. By way of example, meteorological data from Siauliai show that 1990 experienced the longest recorded growing season since 1937 with temperatures above 5 °C for 246 consecutive days.

Table 2 Correlation matrixes between RW chronologies from all study sites with correlation values for the smoothed chronologies given in brackets. Statistically significant correlation coefficients ($p<0.05$) for the annually resolved chronologies are highlighted in bold. Significance levels have not been calculated for the smoothed chronologies

	Aukštumala-bog	Kerėplis-bog	Rėkyva-bog	Aukštumala-soil	Kerėplis-soil	Rėkyva-soil
Aukštumala-bog						
Kerėplis-bog	0.18 (0.45)					
Rėkyva-bog	**0.29** (0.69)	**0.35** (0.30)				
Aukštumala-soil	0.25 (−0.56)	−0.01(−0.61)	0.17 (−0.52)			
Kerėplis-soil	0.14 (0.62)	0.08 (0.16)	0.21 (0.37)	**0.40** (0.20)		
Rėkyva-soil	**0.26** (0.47)	0.01 (−0.02)	0.22 (0.11)	**0.59** (0.01)	**0.62** (0.13)	

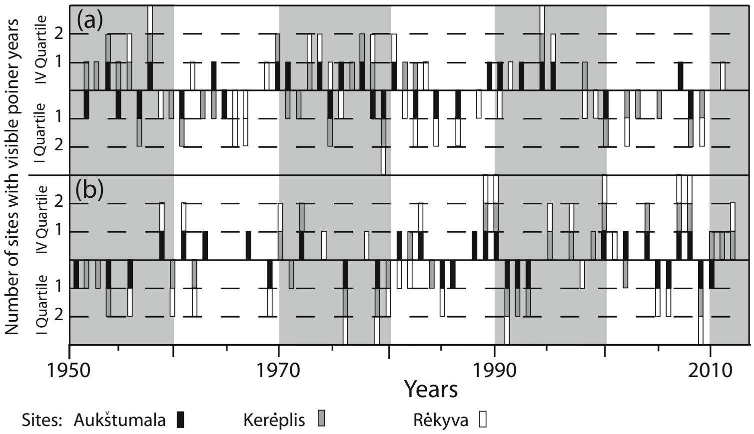


Fig. 3 Number of visible pointer years showing strong (*fourth quartile*) and depressed tree growth (*first quartile*) in the RW chronologies from (**a**) peat soils and (**b**) mineral soils

In addition, the influence of drought was observed during extreme negative years. By way of example, the years 1976 and 1979 show depressed tree growth at all mineral-soil sites (PY-I), which can be associated with unusually cold and dry conditions at the study sites. The year 1976 was, for instance, the driest since 1950 in the Vilnius and Šilutė meteorological records.

Dendroclimatological analyses at the decadal scale

After smoothing, correlations between RW chronologies developed from peat-soil trees increased (Table 2; Fig. 6). Smoothed chronologies showed a common decadal variability in radial tree growth with clear positive trends during the 1910s and the 1970s and synchronous depressions during the late 1920s, 1930s, and the 1960s (Fig. 6a–d). Decadal RW fluctuations properly coincide with rainfall totals at Vilnius (Fig. 6h). Conversely, no common decadal variability was observed in the chronologies from the mineral-soil trees: r-coefficients between mineral-soil chronologies systematically decline in this approach (Table 2) and the visual comparison exhibit no clear synchronicities between the smoothed chronologies (Fig. 6e).

Lagged correlation analyses indicate delayed peat-soil RW responses to annual precipitation measured in Vilnius. For the smoothed series, the correlation coefficient peaked when the time-offset was 5 years in Rėkyva (r=−0.43) and 7 years both in Aukštumala (r=−0.35) and Kerėplis (r=−0.52). Meanwhile, using series with annual resolution, the correlation peaked

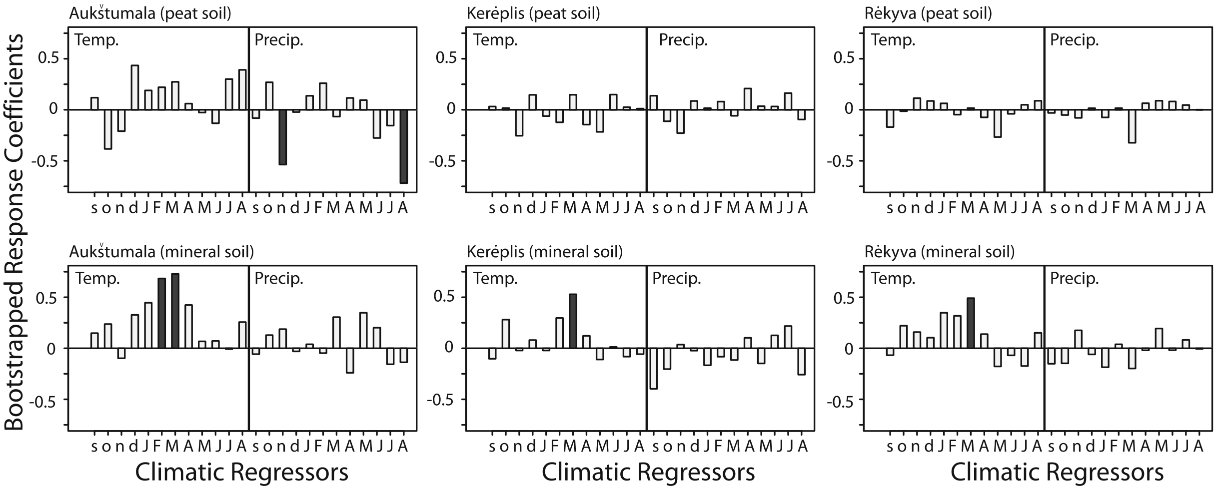


Fig. 4 Response function analyses for the six tree-ring chronologies with temperature (*Temp.*) and precipitation (*Precip.*) data from the nearest meteorological stations. Months for each regressor are indicated below, with months of the considered year (n) in capital letters and those of the previous year (n-1) in small letters. Significant response coefficients are highlighted with *shaded bars*

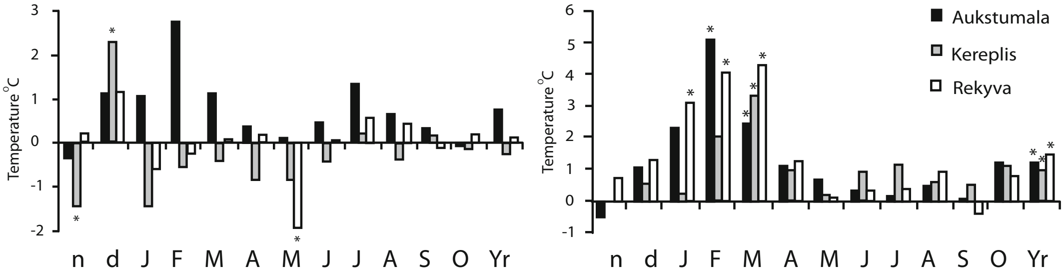


Fig. 5 Air temperature difference between positive (IV quartile) and negative (I quartile) extreme years. Peat soil trees are shown to the left and mineral soil trees to the right. Statistically significant differences ($p<0.05$) according to *t*-test are shown with *stars*

after 2 years in Aukštumala ($r=-0.20$), 3 years in Kerėplis (−0.23), and 4 years in Rėkyva ($r=-0.31$). No similar lag response was observed between long-term temperature variations and peat-soil tree growth for any particular lag, or between long-term precipitation and tree growth records from the mineral-soil trees.

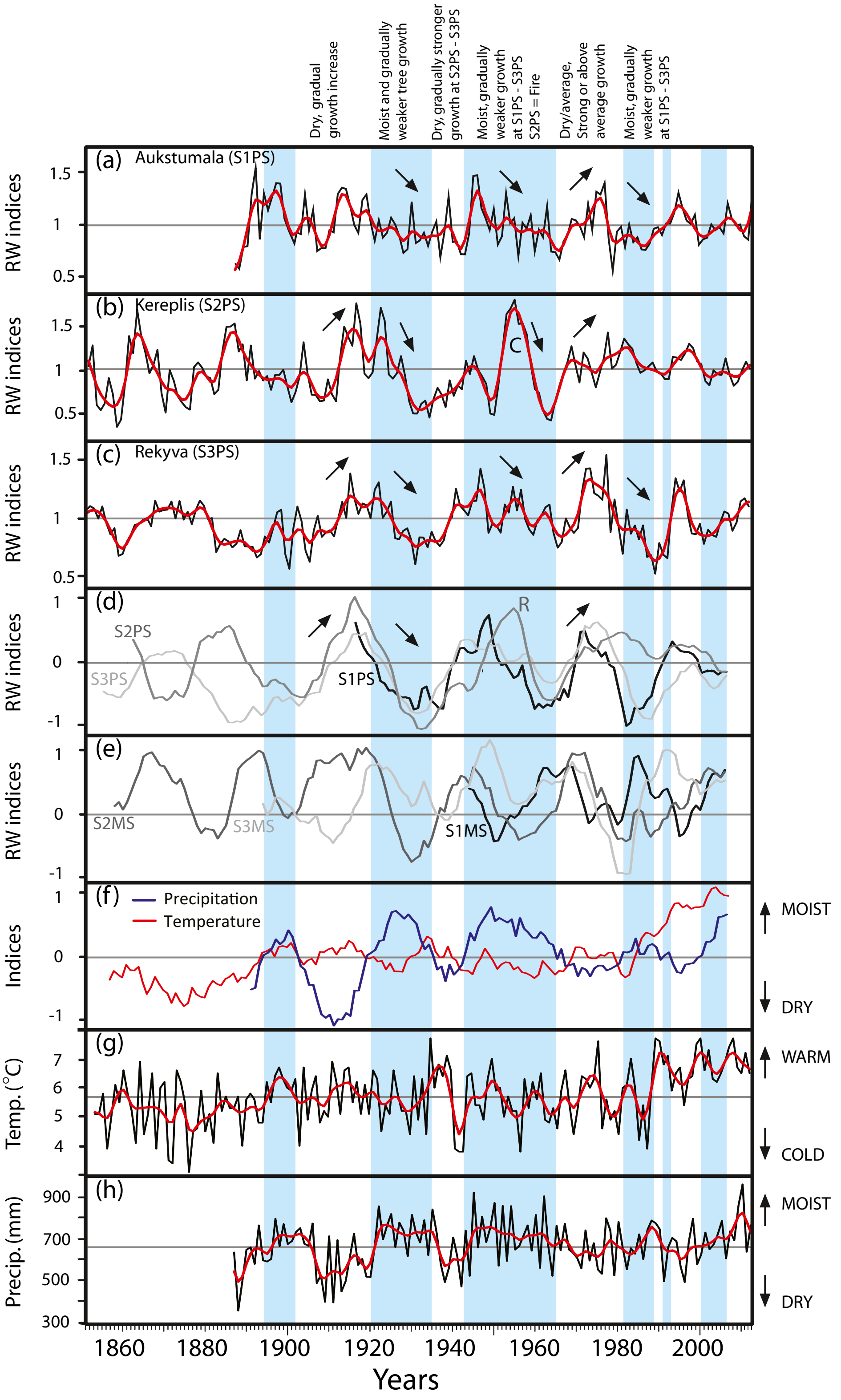
Discussion

Weak inter-annual climatic signal at bog sites

The significant correlations observed between the mineral-soil tree chronologies (Table 2) demonstrate that meteorological conditions prevailing at the regional level control RW formation of trees growing on mineral soils in Lithuania. Both response function and extreme year analyses show that warm winter and early spring temperatures are the primary factors favouring annual tree growth at mineral-soil sites. Remarkable differences in monthly mean temperatures were also detected between years associated with strong (PY-IV) versus depressed (PY-I) tree growth at the mineral-soil sites (Fig. 5). Largest variations were observed for February temperatures in the Aukštumala area, and show that pre-growth season conditions can vary significantly, especially in the coastal regions. Similar observations on tree growth of Baltic pines and winter-spring temperatures have been reported in Lithuania (Vitas 2004), Latvia (Elferts 2007), Estonia (Hordo et al. 2009; Pärn 2009) and in the Polish lowlands (Cedro 2001; Cedro and Lamentowicz 2011). Favourable conditions prevailing in winter and early spring have been described to induce increased cambium activity during the subsequent growth season and to produce larger annual tree rings (Cedro and Lamentowicz 2011). Higher air temperature may also mean less winter damage to roots, less growth limitations (Dauškane et al. 2011) and effective photosynthesis on warm winter days, provided that conifer needles are not frozen (Havranek and Tranquillini 1995).

Conversely, weak correlation coefficients between the peat-soil tree chronologies point to the presence of a complex signal, likely related to local bog hydrology. At the site scale, the lack of significant correlation between chronologies from different soil types corroborates this hypothesis. The peat-soil trees sampled at Kerėplis bog (S2PS) and the adjacent mineral soils (S2MS) are, for instance, only separated by 60 to 400 m. Despite this vicinity, a weak, insignificant correlation ($r=0.08$) is computed between the two respective chronologies. Additionally, the low productivity and the high rates of rejection of peat-soil trees related to missing and wedging growth rings, confirm that harsh growth conditions – e.g., high water table, the substantial acidity of the water, and the deficiency of nutrients – significantly impact tree growth on peat soils (Freléchoux et al. 2000; Vitas and Erlickytė 2007). Given this impact of peatland hydrology on RW a clear response of tree-ring growth to prevailing climatic conditions cannot be found. Interestingly, climatic anomalies during winter sometimes result in opposite extreme tree-growth responses on peat soil and mineral soil environments. By way of example, the strongest and weakest tree growth over the period 1937–2012 is observed in 1990 at the mineral soil (S3MS) and peat-soil sites (S3PS) at Rėkyva, respectively. This opposite re-

Fig. 6 **a**–**d** Peat-soil tree RW chronologies, **e** mineral-soil tree RW chronologies, **f** precipitation and temperature records, **g** average annual temperature and **h** average annual precipitation. *Black curves* (**a**–**c**, **g** and **h**) are annual resolution whereas the *red curves* are smoothed using a 30-year flexible spline. The data series in **d** to **f** are smoothed using a 11-year moving average. The *blue bars* emphasize moist periods associated with positive precipitation anomalies, *grey lines* represent average values and the letter *C* is for callus tissue formed after a fire. All meteorological data is from Vilnius weather station


Dry, gradual growth increase
Moist and gradually weaker tree growth
Dry, gradually stronger growth at S2PS - S3PS
Moist, gradually weaker growth at S1PS - S3PS S2PS = Fire
Dry/average, Strong or above average growth
Moist, gradually weaker growth at S1PS - S3PS
(a) Aukstumala (S1PS)
RW indices
1.5
1
0.5
(b) Kereplis (S2PS)
C
(c) Rekyva (S3PS)
(d)
S2PS
S3PS
S1PS
R
1
0
-1
(e)
S2MS
S3MS
S1MS
(f)
Precipitation
Temperature
Indices
MOIST
DRY
(g)
Temp. (°C)
7
6
5
4
WARM
COLD
(h)
Precip. (mm)
900
700
500
300
MOIST
DRY
1860
1880
1900
1920
1940
1960
1980
2000
Years

sponse is probably generated by positive precipitation anomalies, recorded from January to March 1990, and related to the prevalence of warm and moist air. This constellation may have generated favourable growth conditions at the mineral-soil sites, but wetter peat-soil conditions which in turn limit tree growth in peatlands. Extremely narrow growth rings in 1990 have also been observed in Latvian peatlands (Dauškane et al. 2011). Response function profiles evidence no predominant climatic factors controlling inter-annual RW variability but suggest micro-climatic influences on tree growth.

Regional decadal trends

At the decadal timescale, correlation analyses between smoothed chronologies indicate a regional and multi-annual moisture signal in the peat-soil tree chronologies, which is probably related to regional precipitation fluctuations. A possible explanation for the weak inter-annual, but improved multi-annual responses to climate may be that once a peat soil has been saturated with water, temperature or precipitation changes over single months may not cause any notable hydrological variations affecting the growth conditions for the trees. In fact, various authors (e.g., Ingram and Gore 1983; Almendinger et al. 1986; Charman et al. 2004) indeed suggested that hydrological responses in peatlands tend to be slow and that they depend on persistent climate rather than on short-term variations. In that sense, the depressed tree growth observed in all peat bogs during the 1920s, 1930s, and 1960s coincide with period for which above-average precipitation has been recorded (Fig. 6). The gradual decrease in tree growth on peat soils recorded during the 1920s and early 1930s may thus be associated with the long-term, above average (+ 12 % with ref. to the 1887–2013 period) precipitation recorded at Vilnius meteorological station for the period 1922–1931. Similar depressed growth has been observed in Poland at the Słowinskie Błoto peat bog (Cedro and Lamentowicz 2011) and in Latvian bogs during this same period, especially during the years 1926, 1928, and 1931 (Dauškane et al. 2011). The positive precipitation anomaly observed during the mid-1940s and 1950s also coincides with a gradual growth decrease detected in the Rėkyva and Aukštumala chronologies from peat-soil trees. A similar growth behaviour is observed in Poland (Cedro and Lamentowicz 2011), whereas the strong growth increase during the 1950s at Kerėplis bog was mainly caused by wide growth rings with callus tissues formed after a fire. Conversely, long-term anomalies associated with less than average precipitation generated lower water tables and drier peat-soil conditions. For example, drier conditions (with −18 % of the normal precipitation total) prevailed between 1907 and 1916 and indeed proved to be favourable in terms of RW formation in the peat-soil trees. The relatively dry conditions during the 1970s may also explain the strong growth observed at all peat bogs during this period. Increased annual tree growth since 1971 is also detected at the Männikjärve bog (Estonia; Smiljanić et al. 2014) and associated with low water tables (Charman et al. 2004).

The decadal signal described herein may be attributed to delays or multi-annual hydrological responses to regional climatic fluctuations affecting tree growth on peat soils. This hypothesis is consistent with previous studies (Linderholm et al. 2002; Edvardsson et al. 2014), suggesting that gradual changes in climate may not necessarily affect water tables of peatlands instantly and therefore may not affect tree growth either. In this study, possible multi-annual lags of up to 5 or 7 years have been detected between hydrological parameters and RW in trees. This is compatible with results discussed by Edvardsson et al. (2014), comparing tree-growth responses of subfossil trees to atmospheric moisture variations detected in stable isotope records. The authors of that study report a 1 year integrated climatic response in peat-soil trees. Similar delays in hydrological responses, in the order of a few years and several decades, have been presented by Kilian et al. (1995). Slow hydrological responses may partly be related to precipitation falling as snow and water transport in soils towards the peat bogs, but can also be attributed to the process by which water is replacing air in the relatively large pore spaces of the unsaturated zone of peat (Ingram and Gore 1983; Almendinger et al. 1986). Peat soils are also compressible and changes in water content may result in volumetric fluctuations, which are detectable as variations in surface elevation, which can in turn vary depending on the amount of water that is stored in the bogs (Almendinger et al. 1986; Price and Schlotzhauer 1999).

Conclusions

This study compares growth variability of pine trees growing on peat soils and mineral soils in three separate regions of Lithuania. Growth and climate response patterns differ between trees on peat soils and the neighbouring mineral soils. The annual to inter-annual climatic information in the chronologies from peat-soil trees is much weaker than for pines growing on nearby mineral soils. Results also demonstrate that RW of trees on mineral soils record the positive effects of warm winters and early springs and thus confirm results reported from areas adjacent to the southern Baltic coast and the Polish lowlands. At the same time, however, the annual-growth patterns of the pine trees growing on peat soils are more complex to interpret. At the inter-annual scale, these patterns are loosely associated with the weather conditions due to the hydrology of the bogs, which impact tree growth by generating harsh growth conditions. At the decadal scale, the synchronous growth variations observed in the smoothed chronologies and over large parts of the Baltic area reveal a large-scale climatic control. The complex signal observed in peat-soil trees is thus interpreted as a combination of the direct, primary effect of growth-year climate superimposed to a multi-year integrated response to water-table fluctuations controlled by regional climate. With all factors combined, living and subfossil peat-soil pines in the Baltic area tend to have a limited potential for the reconstruction of inter-annual hydrological variations, but represent valuable proxies for annual to decadal reconstructions, whereas mineral-soil pines preferably reflect the effect of temperatures.

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