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Recent advances in long-term climate and moisture reconstructions from the Baltic region: Exploring the potential for a new multi-millennial tree-ring chronology

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A B S T R A C T

This study presents the first results from an ongoing initiative to develop a multi-millennial Baltic tree-ring width (TRW) chronology consisting of 12 floating records from subfossil Scots pines (*Pinus sylvestris* L.) extracted from three Lithuanian peat-mining areas. The floating series have been complemented with absolutely dated TRW chronologies which were obtained from living trees growing in unmanaged and unexploited peatland areas adjacent to each of the above study sites. The subfossil material has been dated by radiocarbon and shows a temporal spread over the last 6000 years, with assemblages of trees during the Holocene Thermal Maximum (HTM; 8000-4000 BP) and the onset of the Medieval Warm Period (MWP, AD 900–1350). Annual tree growth and sample replication of peatland pines reflect moisture variations and long-term climate variability. The importance of extending the TRW chronologies should not therefore be underestimated as (1) climate records of comparable length and resolution do not exist for the Baltic region, but also as (2) a result of a widespread lack of detailed moisture proxies spanning several millennia. Our data clearly show that a 6000-yr, continuous pine chronology from the Baltic region is a realistic objective, and would doubtlessly fill a major geographic gap in an ecologically sensitive region located at the interface between the temperate and boreal vegetation zones.

1. Introduction

Proxy records with a high temporal resolution and a wide geographical distribution are required to increase our understanding of past climate dynamics and to evaluate climate models predicting future climate scenarios (Bradley, 2008). Over the last decades, numerous palaeoclimatic records have been produced for Western Europe and Fennoscandia (e.g., Wanner et al., 2008; Marcott et al., 2013), but comparably few annually resolved records have documented Holocene climate dynamics over the Baltic region as well as in other European areas further to the East. In the Baltic region, long-term climate reconstructions have been derived from pollen (Seppä and Poska, 2003; Gaigalas et al., 2008; Heikkilä and Seppä, 2010) and peat records (Sillasoo et al., 2007; Kalnina et al., 2015), as well as from various proxies contained in lake sediments (Sohar and Kalm, 2008; Stančikaitė et al., 2009). However, apart from studies of Veski et al. (2004, 2005) using laminated lake sediments to reconstruct annual mean temperatures and ecological changes, long and annually resolved proxy records have been clearly lacking in the region. The development of detailed and multi-millennial palaeoclimatic records for the Baltic area should therefore be a priority.

More than 12% of the Baltic region is covered by peatlands (Montanarella et al., 2006). Peatlands provide important global (e.g., carbon storage) and regional ecosystem services (e.g., water storage, biodiversity). They are generally considered as crucial actors in the global carbon cycle (Limpens et al., 2011), but a holistic

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understanding of interactions between climate variations, moisture variability, vegetation dynamics and carbon balance in peatlands still does not exist (Heijmans et al., 2008; Waddington et al., 2014). The Baltic region is located on the Northern rim of the mid latitudes (54–59°N), at the interface between the continental climate of the Eurasian mainland and the more oceanic western European climate (Heikkilä and Seppä, 2010; BACC Author Team, 2014). For these reasons, development of a new network of multi-millennial and highly-resolved proxy records in the Baltic region would allow (i) assessment of peatland hydrology in an environment which is typically characterized by complex lag and feedback effects (Heijmans et al., 2008; Waddington et al., 2014), and (ii) documentation of Holocene climate variability in a key ecologically sensitive region of Europe (Draveniece, 2006; Heikkilä and Seppä, 2010; BACC Author Team, 2014). In that sense, living and subfossil peatland trees from the Baltic region may offer a unique opportunity to fill an important spatial gap within the existing network of moisture-sensitive tree-ring chronologies in Europe.

In north-western Europe, subfossil peatland trees have yielded valuable, annually-resolved data on peatland moisture – and hence indirectly climate – for much of the Holocene (Pilcher et al., 1984; Leuschner et al., 2002; Eckstein et al., 2009; Edvardsson et al., 2012a) as their annual growth reflects moisture variability in the unsaturated zone around the root systems of trees (Boggie, 1972; Linderholm et al., 2002). In the Baltic region, studies by Pukienė (1997, 2003) and Vitas (2009) showed that several phases of tree establishment have occurred in Lithuanian peatlands. Despite first promising results, few attempts have, however, been undertaken to develop extensive tree-ring chronologies comparable to those from Ireland (Pilcher et al., 1984), Great Britain (Lageard et al., 2000; Moir et al., 2010), Germany (Leuschner et al., 2002; Eckstein et al., 2009) and Sweden (Edvardsson et al., 2012a).

In the framework of the ongoing Lithuanian-Swiss CLIMPEAT project (Climate change in peatlands: Holocene record, recent trends and related impacts on biodiversity and sequestered carbon; www.climpeat.lt), a series of dendrochronological field missions have been realized at Lithuanian peatlands to construct new tree-ring width (TRW) chronologies. This paper therefore aims at (i) evaluating the potential of Baltic peatland trees for the development of continuous, absolutely dated and annually resolved multi-millennial TRW chronologies and at (2) investigating possibilities to use TRW and tree replication data as proxies for moisture variability and climate dynamics over the Holocene.

2. Study sites

Three Lithuanian peatland complexes representing different geographic contexts and distances from the Baltic Sea have been selected for this study, namely Aukštumala, Rėkyva, and Rieznyčia (Fig. 1). At present, the peatlands consist both of natural raised bog environments with varying degrees of pine coverage and limited anthropogenic influences (Edvardsson et al., 2015a, b), as well as drained peat-mining areas (Fig. 2). Excavated tree remains from the peat-mining areas show that the peatlands previously have been colonized by Scots pine (*Pinus sylvestris* L.), a species that has shown to have good potential for dendroclimatic studies even in moist environments (Smiljanić et al., 2014; Edvardsson et al., 2015a). The Aukštumala peatland complex is 3018 ha in size and located in Southwest Lithuania (55°23′ N, 21°22′ E, c. 1 m a.s.l., 19 km from the Baltic Sea). The natural raised bog area is sparsely covered by small water ponds as well as scattered groups of pine and birch trees (Fig. 2a). The currently ongoing pine colonization started during the late 1800s, but increasing establishment rates have been recorded over recent decades (Edvardsson et al., 2015a,b). Subfossil trees can be detected in the eastern parts of the peatland where peat-mining

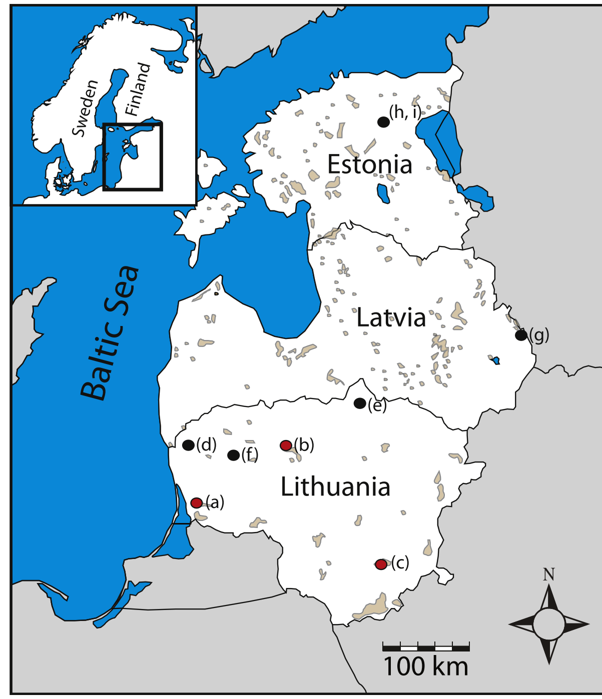

Fig. 1. Overview of the sites described in this study: Red dots show location of the study sites (a) Aukštumala, (b) Rėkyva and (c) Rieznyčia/Kerėplis, whereas black dots show sites discussed in the text, namely (d) Užpelkių Tyrelis bog (Pukienė, 1997), (e) Biržai peatland (Pukienė, 2003), (f) Kegai mire (Vitas, 2009), (g) Lake Kurjanovas (Heikkilä and Seppä, 2010), (h) Männikjärve bog (Sillasoo et al., 2007), and (i) Lake Sinijärv (Sohar and Kalm, 2008). Large peatland complexes are shown in brown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and drainage activities have been conducted since the early 1900s (Fig. 2b). The Rėkyva peatland complex is 2608 ha in size and located in North Lithuania (55°51′ N, 23°15′ E, 130 m a.s.l., 138 km from the Baltic Sea). The peatland complex contains six raised bogs, of which only the western bog area is under a strict reserve status whereas the south-eastern part has been heavily exploited (Fig. 2c). Since the 1850s, continuous tree establishment has been recorded in the natural parts of the peatland complex (Edvardsson et al., 2015b). The Rieznyčia raised bog, as well as the adjacent Kerėplis bog, are both located in a 144-ha peatland complex in Southeast Lithuania (54°27′ N, 24°32′ E, 140 m a.s.l., 269 km from the Baltic Sea). The Rieznyčia peatland has been subject to extensive peat mining, whereas the natural part of the Kerėplis peatland is characterized by relatively dense and homogenous pine coverage. The current pine population started to colonize the natural bog areas during the early 1800s (Edvardsson et al., 2015b). Peat mining activities or drainage projects have been conducted at Aukštumala since the early 20th, and at the other sites since the mid-20th century (Edvardsson et al., 2015b). It can thus be excluded that annual tree growth and tree stand dynamics of subfossil trees have been influenced by anthropogenic activities.

3. Materials and methods

3.1. Fieldwork and development of tree-ring width chronologies

To facilitate continuous peat mining, remains of subfossil tree trunks and stumps are often transported to deposits surrounding the peat-mining areas. Both trees from such deposits and *in situ* trunks preserved in the peat were sampled during fieldwork

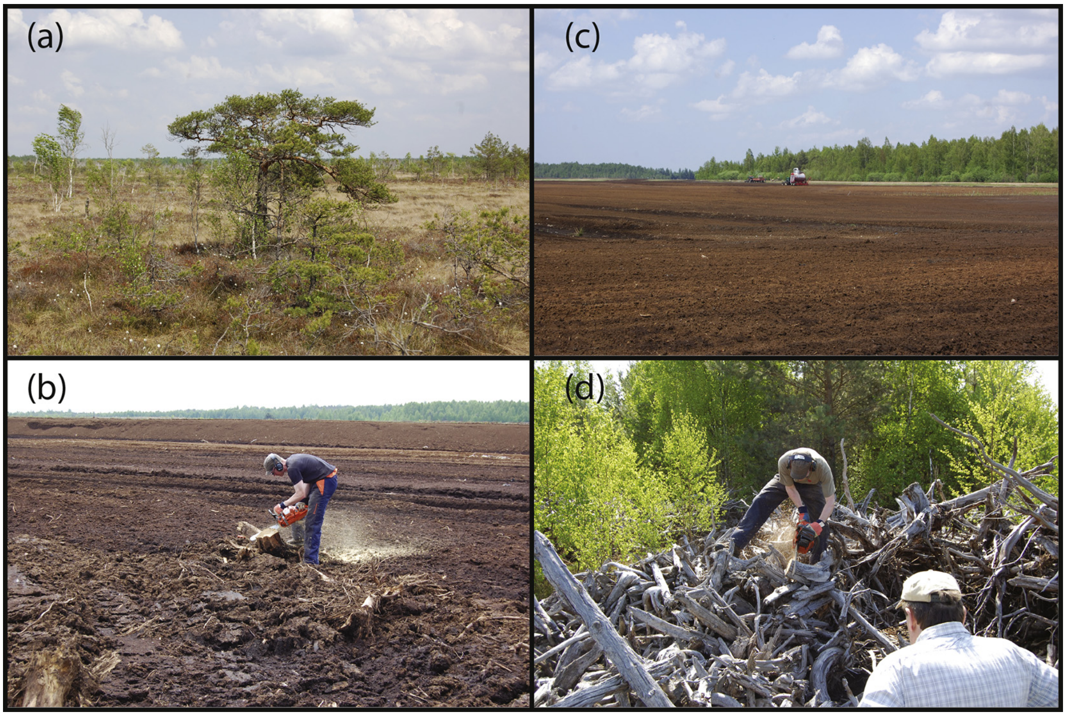

Fig. 2. (a) Natural part of the Aukštumala peatland complex. (b) Aukštumala peat mining area. (c) Sampling of *in situ* tree at Rėkyva. (d) Sampling of trees at a stumps deposit at Rieznyčia.

campaigns in 2013 and 2014 (Fig. 2; Table 1). In total, cross-sections from 335 subfossil pine trees were collected with a chainsaw. Trees with less than 50 annual rings were considered to be unsuitable for cross-dating and hence for the development of TRW chronologies; these young samples were thus excluded from further analysis. Moreover, living pine trees growing at natural raised bogs were sampled at each study site (Table 1) for comparisons to meteorological data (Edvardsson et al., 2015a) and to study ongoing tree-population dynamics (Edvardsson et al., 2015b).

To enhance the appearance of ring borders and cell structures, the wood samples were first air-dried and then sanded with gradually finer sandpapers. TRW series of individual radii were created based on the measurement of annual rings using a LINTAB measuring device connected to a stereomicroscope and a computer using the TSAPWin software (Rinn, 2003). To detect missing and wedging rings as well as possible measuring errors, at least two radii, preferably separated from each other by 90–180°, were measured for each tree. Conventional cross-dating techniques based on statistical and visual comparisons between TRW series were used for a comparison and the development of TRW chronologies (Fritts, 1976; Cook and Kairiukstis, 1990). The quality of measurements and TRW chronologies were thereafter evaluated with COFECHA (Holmes, 1983). To assess the reliability of each TRW chronology, the expressed population signal (EPS) was calculated and the limit at which TRW chronologies were considered as reliable and well replicated was set to the commonly accepted threshold of EPS $\geq$ 0.85 (Wigley et al., 1984). To minimize the influence of non-climatic variations and trends, for example related to tree age, size and geometry, the TRW series were standardized and transformed into dimensionless TRW indices (Fritts, 1976; Cook and Kairiukstis, 1990) using a flexible Friedman's variable span smoother (Friedman, 1984). Both the standardization and calculations of EPS values was performed with ARSTAN_44h2 (Cook and Krusic, 2006). In a last step, tree replication records (based on the counting of overlapping trees) were developed so as to detect tree population changes in the series such as germination and die-off events.

3.2. *Radiocarbon dating*

To approximate calendar ages of the floating TRW chronologies, we applied radiocarbon (^{14}C) dating to some of the trees. Wood samples were analysed at the Laboratory of Nuclear Geophysics and Radioecology at the Nature Research Centre in Lithuania and radiocarbon ages calibrated with the IntCal13 radiocarbon calibration dataset (Reimer et al., 2013) and the OxCal v.4.2 software (Bronk Ramsey, 2001). Wiggle matching (Bronk Ramsey et al., 2001) was then used to narrow down the probable age ranges of radiocarbon dates against the calibration curve. This method is based on the non-linear relationship between radiocarbon and calendar ages, and was applied by fitting sequences of radiocarbon dates with known intervals between on the radiocarbon calibration curve. At least two wood samples with known number of annual growth rings in between were therefore extracted from each TRW

Table 1
Collected wood samples from peatland trees site total trees subfossil trees living trees (total/deposits/in situ).

Site	Living trees	Total trees (total/deposits/in situ)	Subfossil trees
Aukštumala	124	68/68/0	56
Rėkyva	215	163/155/8	52
Rieznyčia/Kerėplis	167	104/76/28	63

chronology, and 26 samples from 15 trees were consequently analysed. Ages given for the floating TRW chronologies represent calculated mean values (m) from the defined sequence probability curves. Error margins indicate uncertainties at the 95.4% probability level.

4. Results and discussion

From the 335 subfossil *P. sylvestris* samples collected at the three study sites in Lithuania, a total of 26 wood specimens was dated by radiocarbon (Table 2); they show a rather even temporal distribution over a period covering 6000–1000 cal BP (calibrated years before AD 1950, Fig. 3). The wood samples dated by radiocarbon allowed age attribution to all of the 12 TRW chronologies as well as to the 176 trees included in these series (Table 3). Five of these TRW chronologies were compiled from trees sampled at the Aukštumala and Rėkyva peatlands, respectively, whereas two were built from material collected at Rieznyčia peatland. When combined these TRW chronologies cover 2885 calendar yr., but as a result of some possible overlapping their length is reduced to approximately 2600 yr (Fig. 4). In addition to these composite TRW chronologies, we also dated a long-lived tree (age >391 yrs) from Rieznyčia with radiocarbon. This tree, proved to be of contemporary age as nine other trees sampled from the same site, but interpreted as a tree growing on mineral soil due to the relatively even annual growth and the lack of correlation with the other material from the same site. We also attempted absolute dating of the TRW chronologies, but no reliable cross-dating statistics (*t*-value > 4, Glk > 60 and $p < 0.01$) were obtained when the Lithuanian material was compared to Swedish (Edvardsson et al., 2012a,b; 2014a) and German (Eckstein et al., 2009) TRW chronologies. Noteworthy, reliable statistics between the German and Swedish peatland TRW chronologies were not obtained until the overlapping sequences exceeded 500 years (Edvardsson et al., 2012a), which may explain

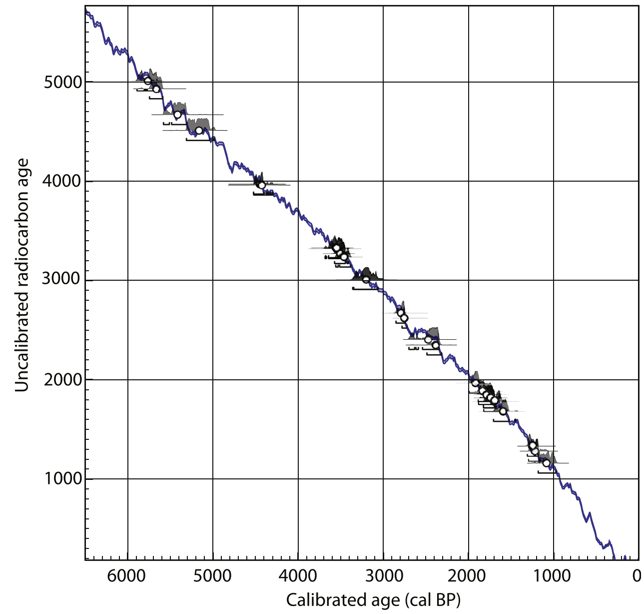

Fig. 3. Fit of the 25 radiocarbon dates of wood samples implemented in OxCal v.4.2 (Bronk Ramsey, 2001) with the IntCal13 ^{14}C calibration curve (blue; Reimer et al., 2013). The calibrated age distributions are shown in grey and the mean ages (m) are indicated by white circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the lack of significant cross-correlation statistics in the relatively short TRW chronologies developed in this study from the Lithuanian material. Differences in climatic behaviour during the overlapping periods between the Baltic area, Scandinavia and/or Western Europe might be another possible reason for the lack of significant correlation. If true, the importance of the new data

Table 2
Radiocarbon dating of wood samples from tree-ring chronologies.

Tree id. No. (used rings)	Yrs. between the samples	TRW chronology	^{14}C-age	Cal BP (Un-modelled)	Cal BP (modelled)
Aukštumala					
Auk061 (25 ± 5)		AuBC01	3970 ± 30	4412 ± 113	4467 ± 53
Auk061 (150 ± 5)	125	AuBC01	3960 ± 35	4409 ± 114	4342 ± 53
Auk009 (20 ± 5)		AuBC02	2620 ± 30	2752 ± 28	2798 ± 72[a]
Auk009 (130 ± 5)	110	AuBC02	2670 ± 40	2798 ± 73	2688 ± 72[a]
Auk033 (15 ± 5)		AuBC03	2405 ± 40	2523 ± 177	2480 ± 58
Auk033 (135 ± 5)	120	AuBC03	2350 ± 35	2401 ± 86	2370 ± 58
Auk020 (50 ± 5)		AuBC04	1815 ± 30	1725 ± 98	1787 ± 72
Auk028 (205 ± 5)	155	AuBC04	1780 ± 40	1695 ± 123	1637 ± 72
Auk062 (50 ± 5)		AuBC05	1850 ± 40	1789 ± 92	1765 ± 67
Auk062 (190 ± 5)	140	AuBC05	1680 ± 40	1573 ± 131	1625 ± 67
Rėkyva					
Rek087 (35 ± 5)		ReBC01	5010 ± 35	5773 ± 119	5758 ± 78
Rek087 (125 ± 5)	90	ReBC01	4930 ± 45	5667 ± 78	5668 ± 78
Rek059 (95 ± 5)		ReBC02	4670 ± 55	5443 ± 138	5361 ± 55
Rek059 (195 ± 5)	100	ReBC02	4510 ± 45	5147 ± 164	5261 ± 55
Rek041 (95 ± 5)		ReBC03	3320 ± 45	3567 ± 116	3597 ± 80
Rek041 (155 ± 5)	60	ReBC03	3300 ± 35	3572 ± 106	3537 ± 80
Rek015 (95 ± 5)		ReBC04	3270 ± 30	3491 ± 82	3515 ± 46
Rek015 (175 ± 5)	80	ReBC04	3235 ± 30	3472 ± 87	3435 ± 46
Rek089 (85 ± 5)		ReBC05	3010 ± 50	3209 ± 150	3244 ± 98
Rek089 (165 ± 5)	80	ReBC05	3010 ± 45	3207 ± 140	3164 ± 98
Rieznyčia					
RILS020 (50 ± 5)		RiBC01	1280 ± 40	1189 ± 104	1253 ± 36
RILS033 (70 ± 5)	39	RiBC01	1330 ± 35	1242 ± 64	1214 ± 36
RILS033 (195 ± 5)	125	RiBC01	1160 ± 35	1074 ± 104	1089 ± 36
RILS109 (20 ± 5)		RiBC02	1880 ± 30	1805 ± 78	1845 ± 72
RILS109 (160 ± 5)	140	RiBC02	1820 ± 25	1730 ± 92	1705 ± 72
RILS111		RiBC03	1965 ± 30	1912 ± 78	–

[a] Poor agreement between the modelled ages.

Table 3
Basic information about the tree-ring chronologies.

Site/code	Nr. trees/length (yrs.)	Covered period (cal BP)	Inter-series corr. (r)/mean TRW (mm)
Aukštumala/AuBC01	8/175	4499–4325 ± 53	0.582/0.86
Aukštumala/AuBC02	9/169	2819–2651 ± 72	0.494/0.81
Aukštumala/AuBC03	6/146	2496–2351 ± 58	0.505/0.61
Aukštumala/AuBC04	4/229	1859–1631 ± 72	0.478/0.41
Aukštumala/AuBC05	3/211	1815–1605 ± 67	0.275/0.46
Rėkyva/ReBC01	29/290	5866–5577 ± 78	0.539/0.93
Rėkyva/ReBC02	30/324	5559–5236 ± 55	0.612/0.58
Rėkyva/ReBC03	7/287	3699–3413 ± 80	0.538/0.42
Rėkyva/ReBC04	6/216	3609–3394 ± 46	0.457/0.56
Rėkyva/ReBC05	3/301	3337–3037 ± 98	0.267/0.52
Rieznyčia/RiBC01	62/321	1314–994 ± 36	0.544/0.58
Rieznyčia/RiBC02	9/216	1873–1658 ± 72	0.562/0.51
Rieznyčia/RiBC03	1/391	1984–1594 ± 78	0.000/0.73

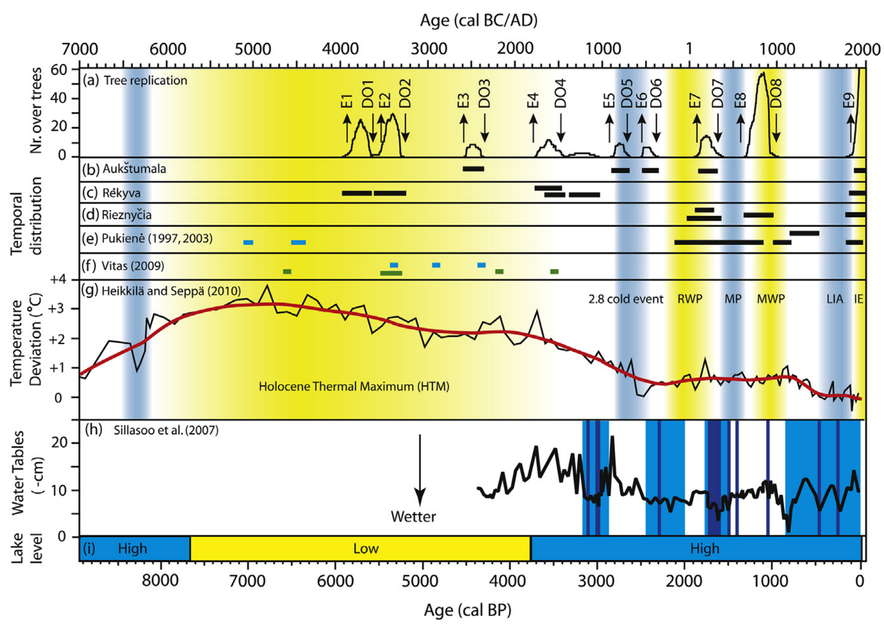

Fig. 4. (a) Total tree replication with arrows showing establishing (E1-9) and dying-off phases (DO1-8). (b–d) Periods covered by different Lithuanian peatland pine chronologies (black lines). (e–f) Previously published subfossil pine (black), oak (blue) and ash (green) material from Lithuania. (g) Long-term pollen based summer temperature deviation (Heikkilä and Seppä, 2010). (h) Water table reconstruction from Männikjärve bog, Estonia, based on testate amoebae assemblages (Sillasoo et al., 2007). Blue fields show moist periods while dark blue lines show wet shifts. (i) Lake-level reconstruction from ostracods (Sohar and Kalm, 2008). Periods associated with relatively warm/dry conditions are highlighted in yellow whereas cold/moist periods are shown in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

series would be even greater, but this would need a substantially larger number of trees covering longer periods of the past.

From the tree replication records, assemblages of peatland pines were primarily observed during the periods 6000–5000, 4500–4300, 3800–3400, 2000–1600 and 1300–1000 cal BP (Fig. 4). The two largest assemblages of trees were clustered around 5800–5200 and 1200–1000 cal BP Furthermore, the tree replication records reveals eight dying-off phases (DO1–8, Fig. 4) and nine establishment phases (E1–9, Fig. 4).

At present, 53% of all trees sampled from these three Lithuanian peatlands (i.e. 176 cross-sections) have been included in the TRW chronologies. The relatively high rejection rate of subfossil tree material is likely a result from (i) the large age distribution of samples with several temporal outliers and (ii) missing and/or wedging growth rings, resulting from harsh growth conditions (e.g., high water table, the substantial acidity of the water, and the deficiency of nutrients) that are known to significantly impact tree growth on peat soils (Boggie, 1972; Linderholm et al., 2002; Edvardsson et al., 2015a). We observe that many trees were also of relatively young age when they died (age <70 years), which first of all results in fairly short time series that renders cross-dating more difficult. Despite this limitation, we obtained three TRW chronologies containing 29, 30, and 62 samples respectively, with EPS values above 0.85 for more than 100 consecutive years (Fig. 5). These TRW chronologies reveal 20 periods of extended (3 yrs or longer) growth depression (−1 SD) and 14 periods with comparably strong growth conditions (+1 SD).

Studies based on living peatland pines from the same sites have revealed that annual growth of living pine trees presumably reflects a multiannual synthesis of moisture variability and changing hydrology (Fig. 6, Edvardsson et al., 2015a). The fact that these variations seem to occur synchronously over large parts of the Baltics indicates a possible regional hydrological forcing of tree growth variations. At the same time, evidence exists for an ongoing

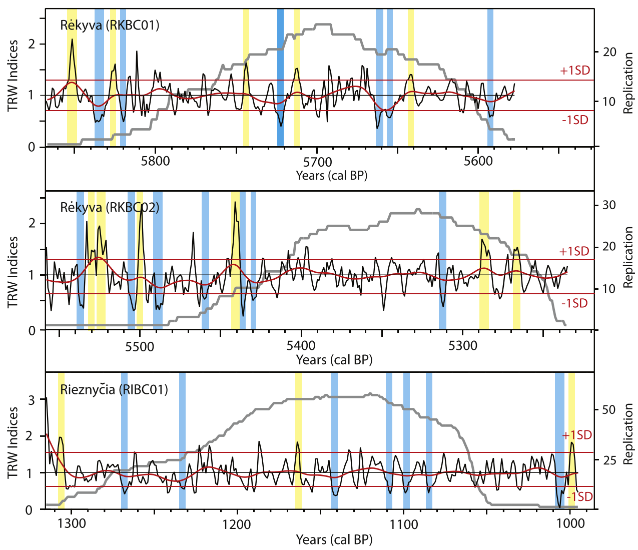

Fig. 5. Representation of the three main tree-ring width (TRW) chronologies from Lithuania. The black curves show standardized and averaged TRW chronologies (dimensionless indices) and the smooth red curves are 20-year low-pass filter splines highlighting the low-frequency patterns of variability. The blue fields are periods of 3 years in a row or longer with depressed growth (TRW indices below −1 SD), and the yellow fields represent periods of elevated growth (TRW above +1 SD). The grey curves show tree replication. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

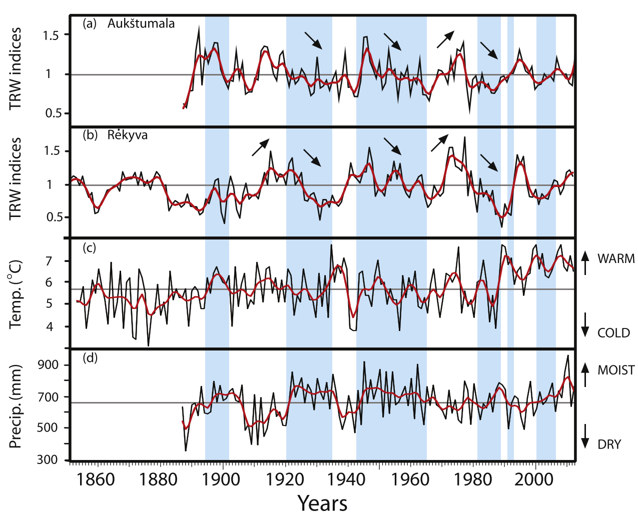

Fig. 6. (a–b) Examples of tree-ring width (TRW) chronologies from living trees growing at Aukštumala and Rėkyva (Edvardsson et al., 2015a). (c–d) Temperature and precipitation data from the meteorological station in Vilnius. The blue bars emphasize moist periods associated with positive precipitation anomalies, grey lines represent average values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tree establishment in the region, sometimes even at accelerating rates, an in particular in unmanaged peatlands (Edvardsson et al., 2015b).

4.1. Trees and water levels in Baltic peatlands

As a rule of thumb, rising water levels in peatlands are associated with unfavourable growth conditions for trees as a result of several physical, chemical, and biological processes, as well as reduced availability of nutrients in the water unsaturated zone (Boggie, 1972; Mannerkoski, 1991). Local studies using living peatland pines confirm these interpretations and prove that, despite the complexity of response, moisture availability (or peatland hydrology in other words) is the most relevant growth-limiting factor at the study sites (Fig. 6; Edvardsson et al., 2015a,b). The eight DO phases observed in the replication records (Fig. 4) and the 20 prolonged periods of depressed annual growth recorded in the TRW chronologies (Fig. 5) can therefore be attributed to wet phases, which is consistent with interpretations from studies combining dendrochronology with information on stratigraphic position and root morphology (Eckstein et al., 2009) as well as analyses of stable isotopes from subfossil peatland trees (Edvardsson et al., 2014b). In addition, studies by Leuschner et al. (2002) show that widespread and synchronous DO phases have occurred during several periods with severely wet conditions recorded during the Holocene. In our series, such events may have taken place at about 5600, 5250, 2700, 1600, and 1050 cal BP (Figs. 4 and 5). Phases dominated by dry and/or warm conditions, on the other hand, are usually associated with enhanced yearly increment rates and widespread tree colonization at peatlands. The periods of tree establishments at about 5800, 5500, 4500, 3600, 1800, and 1200 cal BP (Fig. 4) as well as the 14 periods with strong annual growth (Fig. 5) are therefore likely representing prolonged, dry phases in the Baltic region.

4.2. Moisture and climate dynamics over the last 6000 years

During the onset of the Holocene (about 11,500 cal BP), a rapid transition from generally cold to warm conditions (Marcott et al., 2013) has likely caused an increase of vegetation and peatland formation in the depressions of the Baltic region (Kalnina et al., 2015). In our record, we cannot find evidence for pine establishment for periods prior to the Holocene Thermal Maximum (HTM; c. 8000–4000 cal BP; Fig. 4), and are not therefore in a position to confirm this finding. At Rėkyva, the first recorded tree establishments (E1-2, Fig. 4) occurred during the mid HTM, and at Aukštumala towards the end of that period (E3, Fig. 4). Radiocarbon dated oak trunks (*Quercus* spp.) presented in studies by Pukienė (2003) and Vitas (2009), by contrast, indicate possible presence of trees at the Kegai and the Biržai peatlands (Fig. 1) as early as 7000–6000 cal BP (Fig. 4). If combined, findings indeed show that trees probably were present in Lithuanian peatlands during the entire HTM.

In comparison to subsequent periods, average annual tree growth (Table 3) and tree replication (Fig. 4) can be considered strong during the HTM, which would indicate relatively dry conditions in the peatlands. Several lines of evidence from Fennoscandia (Hammarlund et al., 2003; Snowball et al., 2004; Helama et al., 2004) and the Baltic region (Sohar and Kalm, 2008; Heikkilä and Seppä, 2010; Kalnina et al., 2015) are pointing to relatively warm and dry climatic conditions during the HTM, and are thus confirming the findings of this study. Pollen-based temperature records (Heikkilä and Seppä, 2010), suggest average summer temperatures would have been 2.5–3.5 °C higher than at present, whereas studies of changes in ostracod assemblages in lake sediments from central Estonia indicate relatively low lake levels (Sohar and Kalm, 2008, Fig. 4). Moreover, a regional increase in the degree of peat decomposition over Latvia can be seen as further evidence for drier conditions in the Baltic region over the corresponding period (Kalnina et al., 2015). Pollen and diatom records published by Gaigalas et al. (2008), however, show that the climate in Lithuania was gradually getting moister already at ca. 5500 cal BP. If so, improved preservation conditions due to increased peat growth may also have contributed to the rising numbers of subfossil trees excavated at Rėkyva from the period of the corresponding DO phase (DO1; Fig. 4).

During the HTM, the common factors seem to have limited peatland tree growth over large geographical areas because similar tree-population dynamics (Leuschner et al., 2002; Eckstein et al., 2009) and significant cross-dating statistics (Pilcher et al., 1984; Edvardsson et al., 2012a) have been reported over large parts of north-western Europe. By contrast, the cross-dating statistics obtained from the Baltic TRW chronologies do not yield satisfactory results when compared to absolutely dated series from Sweden (Edvardsson et al., 2012a, b; 2014a) and Germany (Eckstein et al., 2009). As previously stated, the Lithuanian TRW chronologies might still be too short at present to yield reliable long-distance cross-correlations.

Between 4000 and 3000 cal BP, various palaeorecords report a widespread shift towards moister and colder conditions over Europe (Wanner et al., 2008; Morley et al., 2014). The three youngest pine populations from the Rėkyva site died during this transition phase (DO4; Fig. 4). Similar DO phases associated to moister conditions about 3000 cal BP have been reported in both Swedish and German peatland tree populations, pointing to what could be a more regional shift towards wetter conditions (Eckstein et al., 2011; Edvardsson et al., 2014a). In the same way, the summer temperature reconstructions from Heikkilä and Seppä (2010) show a gradual decrease over this period and a more rapid drop between 3500 and 2800 cal BP, whereas Sillasoo et al. (2007) show relatively moist conditions 3170–2850 cal BP (Fig. 4). Increased peat accumulation associated with this transition phase has locally been recorded over Latvia (Kalnina et al., 2015) and regionally over Fennoscandia (Weckström et al., 2010).

The 4000–3000 cal BP transition phase was followed by relatively unstable conditions around the Baltic Sea basin (Borzenkova et al., 2015). Trees established at the Aukštumala peatland between 3000 and 2000 cal BP, but total tree replication (Fig. 4) and average tree growth (Table 3) suggest generally unfavourable conditions, at least when compared with the preceding HTM or the subsequent Medieval Warm Period (MWP). Yet, these data should be interpreted with care, as the TRW chronologies presented here remain floating. A brief episode of relatively warm and dry conditions has, however, been recorded between 3000 and 2800 cal BP in several Latvian peatlands, and as a consequence woody peat layers consisting of pine remains have been detected in the region (Kalnina et al., 2015). The minor tree establishment phase that has been detected at Aukštumala (E5; Fig. 4) is eventually corresponding to this short episode. About 2800 cal BP, however, intensive peat accumulation in Latvia (Kalnina et al., 2015) and the abrupt deterioration of forest limits in Finland (Helama et al., 2004), point to a rapid change towards colder and more humid conditions. This abrupt shift has been recorded in peat records over large parts of north-western Europe and broadly coincides with an increase of the atmospheric ^{14}C concentration due to reduced solar activity (van Geel et al., 1996; Mauquoy et al., 2008; Mellström et al., 2015). Pollen based temperature reconstructions from Latvia confirm this cold shift (Heikkilä and Seppä, 2010), and the fifth DO phase (DO5; Fig. 4) as well as the absence of peatland trees during following centuries might be attributed to the hydrological changes as followed.

Except for a minor peak during the Roman Warm Period (RWP), the summer temperature reconstruction from Latvia suggests relatively stable conditions between 2000 and 1000 cal BP (Heikkilä and Seppä, 2010), whereas the water-table reconstruction from Estonia shows several wet shifts (Sillasoo et al., 2007). Similarly, multi-decadal changes have repeatedly been detected in the tree population dynamics at the peatlands, which underlines the benefits and need for highly resolved proxy records. Initially, pine establishment at Aukštumala, Rieznyčia, and Užpelkių Tyrelis (Pukienė, 1997) confirms favourable warm and dry conditions at the beginning of the RWP (E7, Fig. 4). About 1600 cal BP, a DO phase, which coincide with the colder episode referred to as the Migration period, has been recorded at both Aukštumala and Rieznyčia (DO7, Fig. 4). By contrast, about 1200 cal BP (E8, Fig. 4), massive tree establishment has been recorded at both Rieznyčia and Užpelkių Tyrelis (Pukienė, 1997). These changes coincide with the onset of the MWP and indicate a change towards drier conditions in Baltic peatland environments. Moreover, they reveal a significant modification in the moisture status of the peatlands despite the absence of significant shifts in the temperature reconstruction by Heikkilä and Seppä (2010). Yet, additional and better replicated chronologies are needed to explain the massive DO phase recorded about 1050 cal BP (DO8, Figs. 4 and 5) more in detail. The water-table reconstruction by Sillasoo et al. (2007), however, shows a minor phase of high peatland surface wetness about 1100 cal BP, which could be contemporary with the 1050 cal BP DO phase recorded in Lithuania.

By contrast, no tree establishment has been recorded during the Little Ice Age (LIA; 1350–1850 AD). During this period, we hypothesize that relatively cold and moist conditions may have generated too harsh growth conditions for peatland trees. Our results are consistent with existing literature in which peatland TRW chronologies extending further back than the early 1800s are scarce (Linderholm et al., 2002; Cedro and Lamentowicz, 2011; Edvardsson et al., 2015a). After the termination of the LIA, however, widespread pine establishment can be found at the Aukštumala, Rėkyva and Kerėplis peatlands (Edvardsson et al., 2015b). This contemporary tree establishment, which appears to have accelerated over the recent decades, has primarily been linked to warmer and/or drier climatic conditions (Edvardsson et al., 2015b). Anthropogenic activities such as drainage or peat mining do, however, also generate drier conditions, which are known to be more favourable for tree growth in peatlands. The present tree colonization might therefore have been influenced by land-use changes as well, but probably only to a minor degree as the investigated peatland areas containing living trees have remained unexploited so far.

5. Conclusions and future prospects

The Baltic region is located at the transitional margin between the temperate and boreal vegetation belts, as well as between the continental climate of the Eurasian mainland and the more oceanic climate of Western Europe (BACC Author Team, 2014). The importance of a multi-millennial TRW chronology developed from moisture sensitive peatland trees from this region can therefore not be underestimated as we lack both (1) highly-resolved proxy records from north-eastern Europe and (2) detailed knowledge about moisture variability during the Holocene. Initial analyses, especially over the HTM and more recently over the last two millennia, show promising potential in finding highly resolved information about climate and moisture variability in the Baltic region. Our results also provide valuable insights into vegetation changes at peatlands with respect to hydrological and climatic changes. Such information will be of importance to predict peatland responses to future climate change in the Baltic region.

The temporal distribution of our 12 radiocarbon dated TRW chronologies demonstrates the real potential for the development of a continuous 6000-yr annually resolved moisture record. Challenges in terms of filling temporal gaps over several periods – such as the LIA – still exist. Yet, in comparison with the material described in studies from Sweden (Edvardsson et al., 2014a) and Germany (Eckstein et al., 2011), significant amounts of trees from the last two millennia have been discovered in Lithuanian peatlands. Furthermore, studies using remotely-sensed approaches also show promising potential in expanding the number of sites to cover the entire Baltic region (Fig. 1). For these reasons, we believe that the use of multiple study sites will permit to bridge several temporal gaps. As peat mining activities continue, detection of material even older than 6000 years will likely become possible, which hopefully will encourage continuation of this kind of work and the development of TRW chronologies.

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