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Increased tree establishment in Lithuanian peat bogs — Insights from field and remotely sensed approaches

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HIGHLIGHTS

- Vegetation shifts in peatlands point to environmental and/or climatic changes.
- Scots pine is establishing at accelerating rates in Northern hemisphere peatlands.
- Bog-tree spread is predominantly related to warmer and drier climatic conditions.
- Warm/dry conditions may turn peatlands from carbon sinks to carbon sources.

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ABSTRACT

Over the past century an ongoing establishment of Scots pine (*Pinus sylvestris* L.), sometimes at accelerating rates, is noted at three studied Lithuanian peat bogs, namely Kerėplis, Rėkyva and Aukštumala, all representing different degrees of tree coverage and geographic settings. Present establishment rates seem to depend on tree density on the bog surface and are most significant at sparsely covered sites where about three-fourth of the trees have established since the mid-1990s, whereas the initial establishment in general was during the early to mid-19th century. Three methods were used to detect, compare and describe tree establishment: (1) tree counts in small plots, (2) dendrochronological dating of bog pine trees, and (3) interpretation of aerial photographs and historical maps of the study areas. In combination, the different approaches provide complimentary information but also weigh up each other's drawbacks. Tree counts in plots provided a reasonable overview of age class distributions and enabled capturing of the most recently established trees with ages less than 50 years. The dendrochronological analysis yielded accurate tree ages and a good temporal resolution of long-term changes. Tree establishment and spread interpreted from aerial photographs and historical maps provided a good overview of tree spread and total affected area. It also helped to verify the results obtained with the other methods and an upscaling of findings to the entire peat bogs. The ongoing spread of trees in predominantly undisturbed peat bogs is related to warmer and/or drier climatic conditions, and to a minor degree to land-use changes. Our results therefore provide valuable insights into vegetation changes in peat bogs, also with respect to bog response to ongoing and future climatic changes.

1. Introduction

Vegetation shifts within particular regions and habitats may point to changes in prevailing environmental conditions. Peatlands are globally important landscape components covering approximately 4 million km^2 across the northern hemisphere and are sensitive to environmental changes (MacDonald et al., 2006). Understanding of peatland response to climate change is urgent as peatlands are crucial for the global carbon budget. If conditions are to be changed, terrestrial stored carbon in peatlands can be made available for exchange with the atmosphere (Korhola, 1994; MacDonald et al., 2006; Yu et al., 2010; Limpens et al., 2011; Gažovič et al., 2013). The moisture balance in peatlands may be observed as wetness changes in the acrotelm, the unsaturated zone near the bog surface, and depends on both precipitation and temperature controlled evapotranspiration (Charman et al., 2009). In general, relatively warm and dry periods generate drier conditions in the acrotelm and lowered bog-water tables, which could result in decreased peat growth and carbon net uptake (Gorham, 1991; Lafleur et al., 2003; Gažovič et al., 2013). Increased understanding of past and ongoing

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peatland vegetation changes due to environmental controlled moisture variations in the acrotelm is therefore of crucial importance for the prediction of peatland development and carbon budget, even more so under changing climatic conditions.

During the Holocene, climate driven variations affecting the moisture balance of the acrotelm has simultaneously changed the decomposition of the peat (Aaby, 1976), the bog vegetation and species composition (Barber, 1981; Barber et al., 1994), as well as the degree of peatland tree coverage (Leuschner et al., 2002, 2007; Eckstein et al., 2009, 2010, 2011). More recently, Edvardsson et al. (2012a, 2012b, 2014) have shown that widespread bog-tree establishment phases have occurred during relatively warm and dry periods of the Holocene. It is therefore likely that ongoing environmental changes affecting bog-surface conditions in peatlands will affect species composition and thus result in simultaneous tree establishment or degeneration phases. Such phases of increased bog-tree establishment have been discussed in studies from raised bogs in southern Sweden (Linderholm and Leine, 2004; Edvardsson, 2013). However, the extent, rate, and reasons behind ongoing tree establishment have not been addressed in these studies, nor has the scale of occurrence (local or regional phenomena) been specified.

About 10% of Lithuania is covered by peatlands, of which 44% have been colonized by woody vegetation (Povilaitis et al., 2011). Pukienė (2001) has shown that over the past two millennia several phases of bog-tree establishment have occurred in Lithuania, likely in the absence of human interference. One might thus assume that tree-population dynamics in Lithuanian peatlands reflect natural ecosystem responses to changing environmental conditions. However, many of the tree establishments observed in peatlands during the last century may have been caused by anthropogenic impacts such as groundwater lowering, mire drainage or peat mining activities. In addition, effective precipitation has decreased in the region, resulting in a hydrological regime less favorable for open raised bog habitats (Taminskas et al., 2007; Šimanauskienė et al., 2008), even inside pristine mires. The interaction and connections between peatland development, anthropogenic activity and climatic changes therefore is under heavy debate in Lithuania (Šimanauskienė et al., 2008; Linkevičienė et al., 2008; Taminskas et al., 2012). Despite this ongoing debate and the need for more regional assessments, research on Lithuanian peatlands has remained somewhat scarce (Stravinskienė, 1981; Balevičius, 1984) and was mainly focused on localized phenomena (Pakalnis, 1972, 1987; Bumblauskis, 1983; Pukienė, 1997).

The aims of this study therefore are to (1) test the hypothesis of increased tree establishment in peatlands; (2) compare different approaches to detect tree establishment and spread in selected bogs; and to (3) compare the establishment and spread of trees in peatlands with different initial tree coverage density and geographic settings. Changes in tree coverage, tree age and tree spread were studied in three Lithuanian peatlands using (1) systematic, field-based tree counts in small plots where we defined different age classes, (2) dendrochronological analysis of trees, and (3) remotely sensed interpretation of tree establishment using aerial photography and historical maps.

2. Material and methods

2.1. Study sites

The Lithuanian peatlands selected for this study are Kerėplis, Rėkyva, and Aukštumala (Fig. 1). They represent raised bog environments with varying degrees of tree coverage (Fig. 2) as well as distinct geographic contexts and different distances from the Baltic Sea. The bogs are vegetated by Scots pine (*Pinus sylvestris* L.), but tree density, spread and age distribution were considered to differ significantly between the sites. The Kerėplis peat bog is located in southeastern Lithuania (54°27′ N, 24°32′ E, c. 140 m a.s.l., 269 km from the Baltic Sea) and is part of a peatland complex covering approximately 144 ha. The study site within the Kerėplis bog is characterized by relatively dense and homogenous tree coverage (Fig. 2a). The second study area is the Rėkyva peatland complex, located in northern Lithuania (55°51′ N, 23°15′ E, 130 m a.s.l., 138 km from the Baltic Sea). The peatland complex is 2608 ha in size and contains six bogs of which the Aukštelkė bog is the last remaining natural area and under a strict reserve status. We therefore chose this area as our study site. The bog surface is sparsely covered with pine trees and different generations of trees can be distinguished in the field (Fig. 2b). The third peatland complex is Aukštumala, which is located in southwestern Lithuania (55°23′ N, 21°22′ E, c. 1 m a.s.l., 19 km from the Baltic Sea). It is 3018 ha in size, and the bog area is sparsely covered by scattered groups of trees, often separated by hundreds of meters of open bog surfaces (Fig. 2c).

2.2. Data collection and development

Three different methods were used to study tree age, tree establishment and tree spread across the peat bogs. At first the composition of trees belonging to different age classes was studied by tree counts in 400 m^2 squares (20 × 20 m) representative for the vegetation of the bog. We allocated trees within these plots to five age classes, 0–20, 21–50, 51–80, 81–110, and >111 years. About one-fifth of the trees counted per plot were sampled with an increment borer. Thereafter the total number of annual growth rings in each extracted tree core were counted under a microscope to verify or improve height–diameter–age relations and to reallocate trees to a different age class where needed.

In a second step, 169 pine trees were sampled at the peat bogs using an increment borer. Depending on stand density, the trees were sometimes spread over relatively large areas, at the most separated by 3 km. A total of 62 bog pines were sampled at Kerėplis, 56 at Aukštumala and 51 at Rėkyva. Drill height above bog surface and GPS positions were recorded for all trees sampled. To ensure that as many annual growth rings as possible were to be measured from each sample, the trees were cored close to the ground level at an average height of 0.4 m. After the mounting of cores on woody supports, drying and sanding, tree-ring chronologies were established based on measurements of annual rings using a LINTAB measurement device and the WinTSAP software (Rinn, 2003). The conventional cross-dating techniques (Fritts, 1976; Cook and Kairiukstis, 1990) were used to date individual trees and for the development of tree-ring chronologies. The quality of the cross-dating, measurements and the tree-ring chronologies were evaluated using the COFECHA software (Holmes, 1983). Thereafter, tree germination dates were approached by adding the estimated number of annual growth rings missing due to sampling height above the bog surface. To enable this estimation, five small trees from each site, 0.5 to 1 m in height, were sawed down at root level and their annual height increase assessed by determining their ring age at different heights. The trees from Aukštumala showed an average height growth rate of 2.32 cm yr^{-1}, whereas 2.99 and 3.57 cm yr^{-1} were recorded for the trees growing at Rėkyva and Kerėplis, respectively. Based on these data the year of germination could be approximated for each individual tree. In case that the cores did not contain the pith the estimated number of missing rings was added as well using transparent concentric circles (Bollschweiler et al., 2008).

In a third step, we analyzed tree cover changes and calculated the total size of the tree covered areas using aerial photographs and historical maps in an ArcGis ArcMap 10.2 environment (Johnston et al., 2001). These documents were used to provide further evidence on periods during which trees established, the spatial spread of woody plants across the peat bogs, but also to inform whether the changes observed in approaches 1 and 2 were indeed representative of the entire bogs. Historical maps were obtained from the archives of Nature Research Centre, Institute of Geology and Geography; aerial photographs – covering the years 1945–1955 and 1966–1981 were obtained from the State Land Fund (Archives of the Institute of Land Management, Lithuania) and the

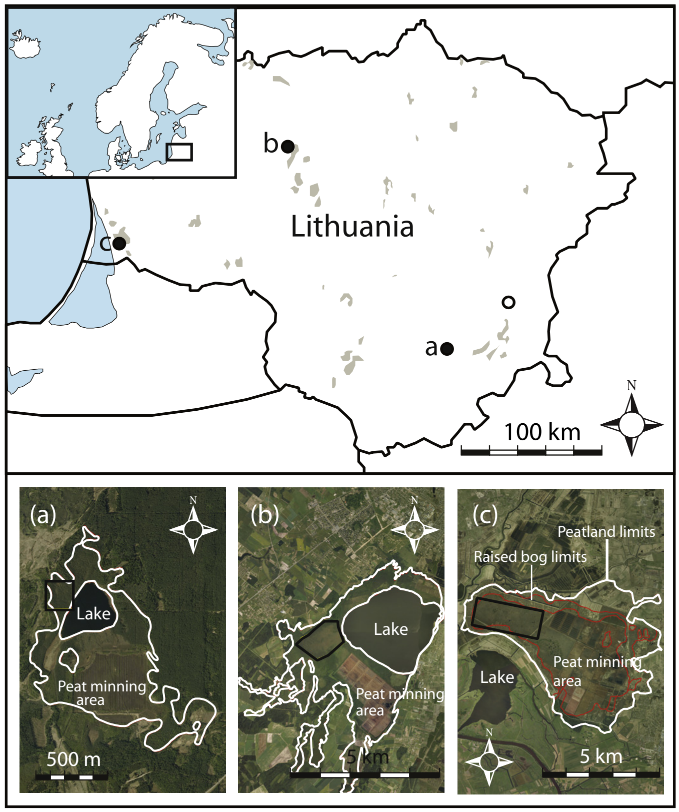

Fig. 1. The black dots show the location of the study sites: (a) Kerėplis, (b) Rėkyva and (c) Aukštumala, all located in Lithuania (inset). The white dot shows the Vilnius meteorological station. Large peatland complexes are shown in grey. Lowermost are overviews of the three study sites. The borders of peatlands are shown in white and the main study areas are indicated in black. Orthophotographs were obtained from the National Land Service under the Ministry of Agriculture, Lithuania.

Vilnius County Archives; orthophotos (1995–2010) were obtained from the National Land Service under the Ministry of Agriculture.

The material from Kerėplis contains historical maps from 1911 to 1914 and 1950 as well as aerial photographs from 1950, 1966, 1981, 1995–1998, 2009–2010, and 2012. In the case of Rėkyva, topographical maps exist from 1911–1914 and 1950, and aerial photographs from 1950, 1974, 1995–1998, and 2009–2010. The data available for Aukštumala include historical maps from 1576 and 1902, a military map from 1860 (Weber, 1902; Couwenberg and Joosten, 2002), topographic maps from 1910 to 1914, 1950 as well as aerial photographs from 1958, 1975, 1995–1998, and 2009–2010.

3. Results

3.1. Approaching tree establishment with tree counts in plots

The 400 m^2 plots at Kerėplis, Rėkyva and Aukštumala contained 80, 136, and 99 bog pine trees, respectively. The tree counts capture

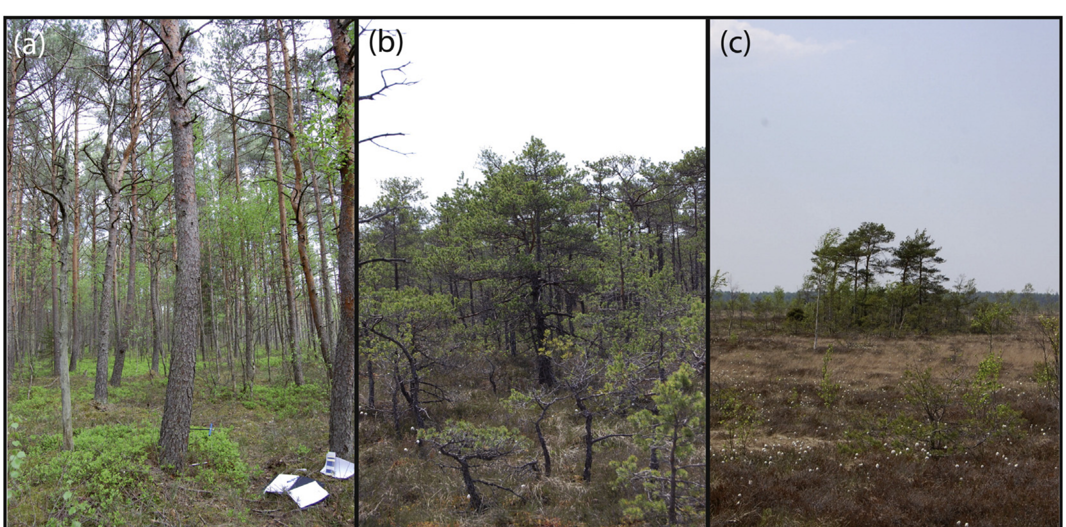

Fig. 2. Varying degree of tree coverage at: Kerėplis (a), Rėkyva (b) and Aukštumala (c) peat bogs.

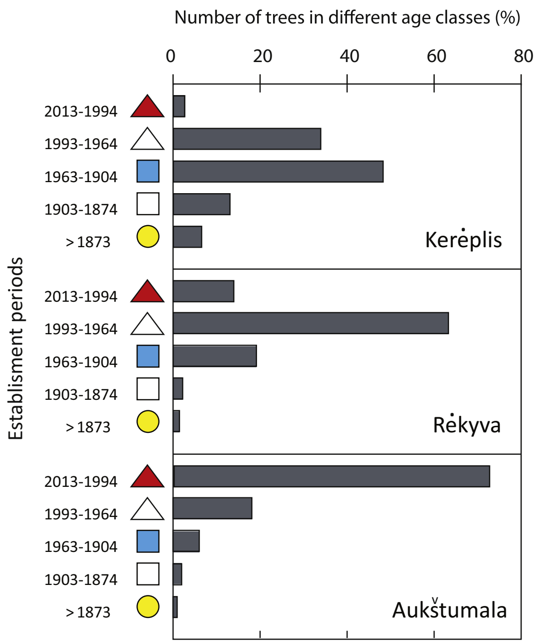

Fig. 3. Tree-age distribution at the three peat bogs analyzed based on tree counts in 400 m^2 plots. Tree age is estimated and trees attributed to specific age classes. Symbols are for comparison and equal to those shown in Figs. 4 and 5. For details see text.

noticeable differences in tree establishment and tree-age distribution between the sites (Fig. 3). At Kerėplis, where tree coverage is relatively homogeneous, tree establishment is scarce after 1994 and amounts to less than 3%, whereas roughly two-thirds of the trees are older than 50 years. At Rėkyva, about 23% of the trees are older than 50 years and a period of increased tree establishment can be observed between 1964 and 1993, representing more than 63% of the current-day tree population. At Aukštumala only 9% of the trees are 50 years or older, whereas 73% of the tree population is less than 20 years in age.

3.2. Dating tree establishment with dendrochronology

Tree establishment data obtained with dendrochronological techniques captures the initial tree establishment at each study site (Fig. 4). At Kerėplis, a gradual increase in tree colonization between 1830 and 1890 can be observed (Fig. 4a). Thereafter, only few trees established, with the exception around the 1930s and 1950s when several bog pines germinated. For the last few decades, by contrast, dendrochronological data points to some tree mortality at Kerėplis. At Rėkyva (Fig. 4b), an initial, yet limited period of tree establishment can be dated to the 1810s through 1830s, followed by more widespread establishment between the 1860s and 1890s. Thereafter, a period of less marked tree establishment becomes visible between the 1910s and 1930s. At Aukštumala (Fig. 4c), dendrochronological records point to a gradual establishment of trees between the 1880s and 1940s, followed by an increased germination of bog pines at about 1950 and from the 1960s to the 1970s.

In addition to the trees presented in Fig. 4, we also analyzed the establishment of young trees at Aukštumala and Rėkyva over the last few decades with dendrochronological techniques. Cross-matches between samples containing less than 40 annual growth rings were in general neither satisfying visually nor statistically, this is why they have been excluded from the site chronologies. However, the annual rings could still be measured and counted to enable estimations of germination years for the relatively young trees.

3.3. Dendrochronological assessment of tree spread

The spatial representation of tree ages within peat bogs allowed analysis of directions and/or patterns of tree establishment (Fig. 4). At Kerėplis, germination patterns of trees appear random with a rather uniform distribution of all age classes throughout the study site. By contrast, the oldest trees are more clustered at Rėkyva whereas young trees are again distributed randomly over the study site. At Aukštumala, we detect isolated groups of trees that are spread over the bog surface. In each of the groups, few trees of relatively high age are surrounded by a larger number of younger trees, pointing to an initial establishment of a few trees which then facilitated a continuous establishment of younger trees in their direct vicinity.

3.4. Age class analyses and tree spread based on historical maps and aerial photographs

Analysis of the aerial photographs shows that, in the case of Kerėplis, the entire study site was covered by trees in the 1950s (Fig. 5a). In total, 85% of the tree coverage was located on biogenic sediments (mostly peat) and present in the form of small scattered groups of trees, whereas the remaining 15% was formed on various types of glacial sediments. The area covered by peatland forest remained fairly unchanged until 1981 when preparation works for peat mining started. Thereafter, more than 60 ha of forest containing scattered trees was felled to facilitate systematic peat mining in 1986. This reduction of peatland forest is visible on the 1995 image (Fig. 5a). However, as soon as peat mining ceased trees started to re-establish at the open surfaces. The general tendency is that tree establishment prevails in both pristine territories surrounding Kerėplis Lake and the parts that were under anthropogenic influence during the late 1980s.

The trees at the Rėkyva and Aukštumala peat bogs were found to grow on biogenic sediments exclusively. Apart from the northern area, much of the Rėkyva peatland has been under anthropogenic influence and two periods of vegetation changes can therefore be distinguished, a natural period prior to 1960 followed by an anthropogenic era since the 1960s. At Rėkyva a gradual increase of trees can be observed since the 1950s (Fig. 5b), especially in the sector investigated in this study (Aukštelkė), which is the most natural part of the peatland complex. In the 1950s about 850 ha (33%) of the bog was covered by trees. Continuous establishment has been recorded over the following decades and in 2009 most of the western parts (about 1640 ha or 63%) was covered by trees (Fig. 5b).

Historical maps from Aukštumala show that the entire peat bog was covered by trees in 1576, whereas tree coverage was almost completely missing between 1796 and 1802 (Couwenberg and Joosten, 2002). Anthropogenic impact is visible in all aerial photographs from Aukštumala as peat mining started prior to 1958. According to the oldest generation of aerial photographs, the Aukštumala peat-bog plateau was open and only sparsely covered by small scattered trees during the late 1950s (Fig. 5c). A slow and gradual tree establishment along the marginal zone can be detected from aerial photographs. The area covered with trees has steadily increased at Aukštumala during the 20th century, from about 362 ha (12%) in 1958 to almost 905 ha (30%) in 2009. Aerial photo interpretation also shows that the central part of the peat bog was almost completely open prior to 1995. At present, however, numerous scattered groups of trees, often in the vicinity to small water ponds, have established in these previously open surfaces.

4. Discussion

4.1. Comparison between different methods

The three different approaches used for the detection of tree establishment and spread were initially analyzed separately and all yielded valuable information on tree dynamics and establishment in Lithuanian

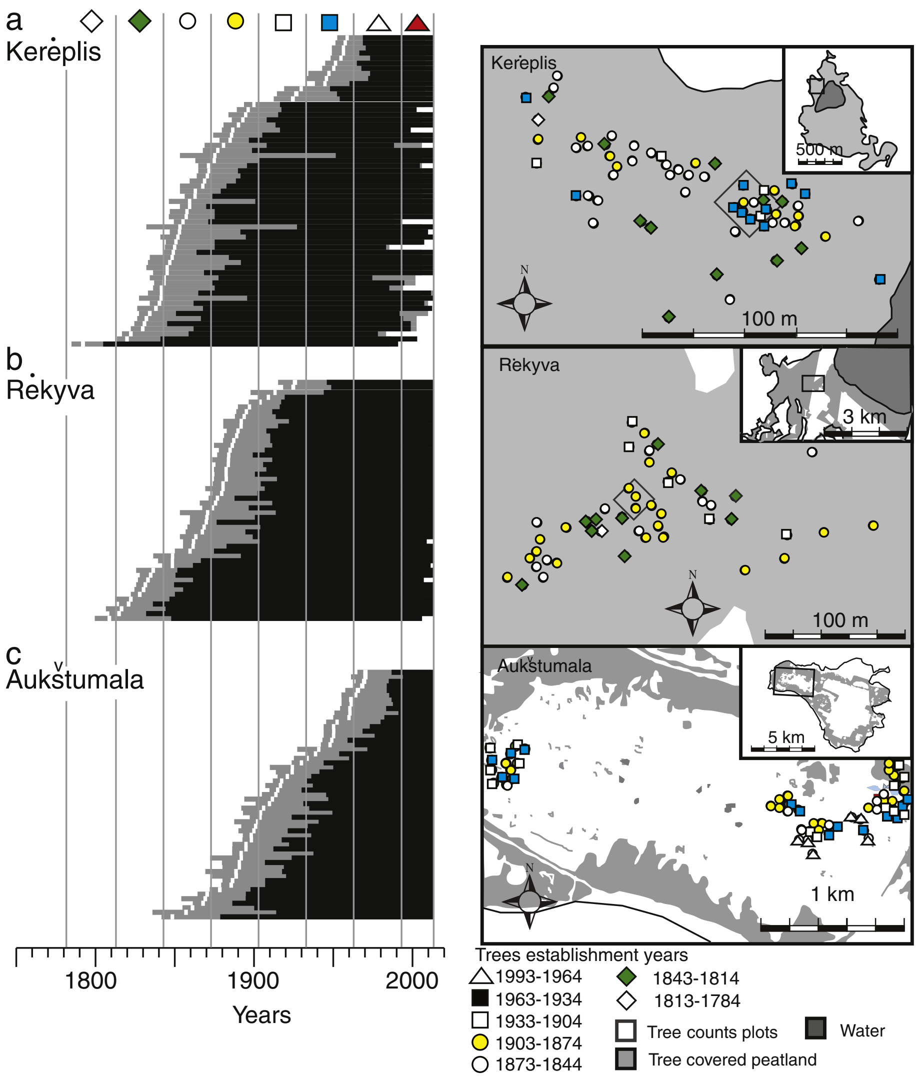

Fig. 4. Germination dates of bog-pine trees as obtained with dendrochronological techniques. The horizontal lines represent individual trees overlapping each other, the black parts show measured annual growth rings, whereas the grey extensions show the range of estimated missing rings due to sampling height (above ground) and the absence of piths on increment cores. The white sections on the grey lines show the estimated germination date for each of the trees. The black and white symbols represent tree ages mapped to the right and are equal to those shown in Figs. 3 and 5.

peat bog environments. The interpretation of data was facilitated greatly through the combination of the different approaches. By way of example, the use of dendrochronology in combination with tree counts in plots allowed to capture both initial and present tree establishment phases, but also yielded data with high temporal resolution and valuable insights on the age distribution among trees. In combination with the information gathered from historical maps and aerial photographs, results enabled a detailed visualization and interpretation of tree establishment patterns and a verification of vegetation spread at the local scale over entire peatlands.

Tree counts in plots provided valuable estimates of tree establishment phases and on the distribution of tree ages across the plot. At the same time, however, while certainly representative of smaller areas, tree ages may differ significantly from those in other sectors. In addition, tree establishment based on dendrochronology also yields much more precise dates. Tree counts also had limited capacity to capture initial establishment as it is difficult to attribute accurate ages to mature trees without ring counting.

Reliable ages were obtained through the dendrochronological dating of tree establishment, but the youngest trees that established during the most recent decades were missed almost completely as juvenile trees respond more to physiological aging processes rather than to environmental changes (Grissino-Mayer, 2001), which result in weak to non-existing cross-matches of young trees with growth patterns of older trees. However, the tree-ring pattern of the young trees could in some cases be visually matched to the tree-ring chronologies and the annual growth rings could be counted to estimate years of tree establishment.

For example, results from the tree counts at Aukštumala show that trees establishing over the last 50-yr period is equivalent to 91% of the total sum of trees. These trees are represented by only 11% of the trees dated with dendrochronological techniques at Aukštumala; they are even totally absent in the Kerėplis and Rėkyva datasets. The composition between different age classes has also been shown to be misleading as relatively old trees are overrepresented among the trees dated with dendrochronology. Although dendrochronological data may fail to detect tree establishment over the most recent decades, it captures the initial establishment much better than the other methods used and also gives more accurate ages. The dendrochronological approach also provides information on a generation shift or dying-off phase at the Kerėplis site, which would not have been captured fully with the other approaches used (Fig. 4a).

Tree establishment analyses based on historical maps and aerial photographs capture widespread vegetation changes, an aspect which

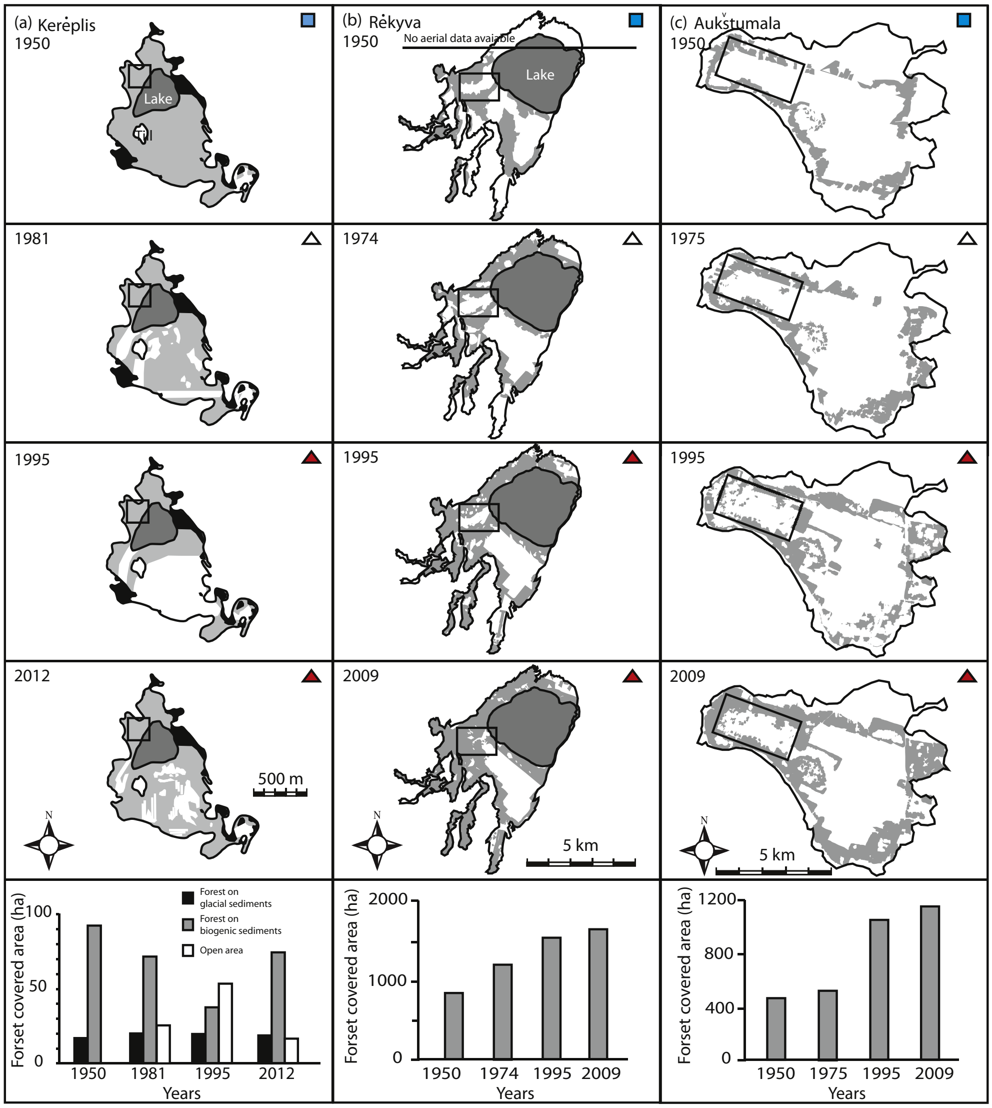

Fig. 5. Tree-cover changes at (a) Kerėplis, (b) Rėkyva and (c) Aukštumala on basis of aerial photographs (M 1: 10 000). The figures show tree cover distribution (in grey) during indicated years and the symbols are for comparison and representing the periods shown in Figs. 3 and 4. The black squares on the maps show the main study areas. The diagrams show forest cover changes in ha at the three peatlands on the basis of the aerial photograph analyzes.

remained undetected in the other two approaches. However, the time resolution depends entirely on how often mapping and aerial photography campaigns have been performed in the past. In the Kerėplis study area, the aerial photographs show scattered trees in the 1950s. According to the results from the tree counting about two-thirds of the tree stand established prior to 1963. Trees were establishing in the study area throughout the entire period covered with aerial photography. The establishment visible between 1964 and 1993 in the tree counts is mainly shown in the form of denser tree coverage in the aerial photographs. The photographs also capture a rapid tree establishment in the southern part of the bog after the termination of peat mining, something the other methods for obvious reasons failed to detect. The aerial photographs and tree count data from Rėkyva agree fairly well between each other, but the increase of trees between 1964 and 1993 is better represented in the ground data from the tree counts. Dendrochronological records also provide a more complete overview of continuous tree establishment, but fails to capture the most recent decades as detailed as the other methods used. It is well adapted, however, to capture the continuous, long-term establishment between 1800 and 1930, something the other datasets were unable to detect. Both aerial photographs and tree count data from Aukštumala capture the increased tree establishment signals over the last couple of decades, especially since the mid-1990s (Figs. 3 and 5). In comparison to the other sites, the dendrochronological data from Aukštumala captures tree establishment changes that occurred only 30 to 50 yrs. ago, but again fails to capture the rapid and ongoing tree establishment that is visible in the tree count data and the aerial photographs.

4.2. Comparison between the study sites

The onset of tree establishment differs significantly between Aukštumala and the other peat bogs. At Kerėplis and Rėkyva, initial tree establishment has been recorded around 1800, whereas the first trees at Aukštumala can be observed about 50 yrs. later. This difference may be related to the distance between the Baltic Sea and the study sites, as the relatively moist conditions in the coastal regions (Aukštumala bog) likely feature less favorable tree growth conditions in peatlands as compared to the continental conditions prevailing e.g., at Kerėplis bog. At Kerėplis, establishment rates have levelled off, likely as a result of limited space for germination. By contrast, the relatively large and open areas present at Aukštumala bog results in less competition between individual trees, allowing for a more widespread and more rapid establishment of trees under present conditions. The study area at Rėkyva peat bog, having a tree density comprised between those of Kerėplis and Aukštumala, also exhibits tree establishment rates at intermediate rates. Noteworthy, tree seedlings were close to absent in the densely forested areas at Rėkyva bog, whereas seedlings frequently were encountered in the more open parts of the bog. The different establishment rates observed at the raised bogs may therefore most likely be related to competition between individual trees. If so, then tree establishment rates due to environmental changes might be shown in a more appropriate way at the Aukštumala peat bog in comparison to Rėkyva and Kerėplis. Tree establishment patterns also differ between the study sites (Fig. 4). At Aukštumala, small groups of trees containing old trees surrounded by younger individuals could be observed both in the field and on aerial photographs (Fig. 5c). At Rėkyva, old trees were found in a relatively small area, indicating a first establishment similar to that in Aukštumala whereas ongoing establishment mainly appears in the areas remaining open for the time being (Fig. 5b). At Kerėplis, germination patterns appear random with a rather uniform distribution of all age classes throughout the study site, which is also confirmed by the aerial photographs showing gradually denser tree coverage in the unmanaged areas.

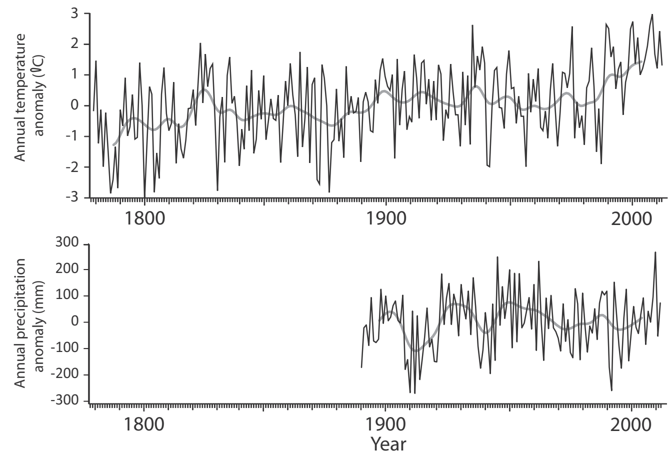

Fig. 6. Uppermost curve show annual temperature anomalies (°C) during the years 1778 to 2012 (black) whereas the lowermost curve show annual precipitations anomalies (mm) from 1887 to 2012 (black). Both data series were obtained from Vilnius meteorological station. To highlight decadal trends both records have been smoothed using a 10-yr Gaussian filter (grey curves).

4.3. Reasons behind the detected tree establishment and future prospects

Peatland vegetation dynamics, as described by e.g., Barber et al. (1994) or Frankl and Schmeidl (2000), and widespread tree establishment and dying-off phases, as described by e.g., Leuschner et al. (2002) Eckstein et al. (2009) and Edvardsson et al. (2012a, 2014), have proved to be valuable proxies for long-term climate controlled palaeoecological and hydrological changes. Decreasing moisture in the acrotelm is commonly described as the main factor enabling tree spread across raised bogs (e.g., Boggie, 1972; Leuschner et al., 2002; Edvardsson et al., 2012b). However, variations in humidity in the upper peat layers can be attributed to a plethora of different causes such as changes in; (1) temperature, (2) precipitation, (3) evaporation and (4) catchment in- and outflows. Over the last centuries different types of land-use changes such as ditching and peat mining has to be added as well. Dendrochronological analysis of trees growing at peatlands has proved that hydrological events due to drainage affect tree growth (Freléchoux et al., 2000). However, the possibility to detect such changes is significantly reduced with distance from the source (Hupp, 1988; Schweingruber, 1996), and the trees used in our study were all growing in areas without visible scars from drainage projects. The tree establishment reconstructed at the three peat bogs is therefore more likely to be a result of environmental changes, related to climate, rather than the result of drainage and peat mining. According to historical maps, climate driven vegetation changes have occurred at the study sites in the past. By way of example and based on historical maps, Aukštumala bog was covered by a forest in 1576, but has been deforested almost completely 200 years later (Weber, 1902; Couwenberg and Joosten, 2002). These tree-cover changes occurred before the onset of any known large-scale local anthropogenic projects and must therefore have been driven by climate. The disappearance of trees might have been related to the Little Ice Age, a cold and humid period (Mann et al., 2009) that most likely caused unfavorable conditions for tree growth in raised bogs.

According to temperature and precipitation records from Vilnius meteorological station (Fig. 1), climatic conditions have changed significantly in the wider study area over the last century (Fig. 6). Annual temperature and precipitation anomalies show that conditions were getting warmer and drier, especially since the 1950s. In case that root systems of peatland trees reach the water saturated zone (i.e., catotelm), moisture surplus in the unsaturated acrotelm can inhibit tree growth as a result of various physical, chemical, and biological processes (Boggie, 1972; Vitas and Erlickytė, 2007). Moist conditions in the acrotelm can for example generate a decrease of oxygen, formation of toxic compounds, and reduced availability of nutrients for the trees (Boggie, 1972; Mannerkoski, 1991; Vitas and Erlickytė, 2007). Positive temperature anomalies would therefore generate favorable growth conditions for bog pines to germinate and enable established bog pines to survive. The positive temperature trend observed in Vilnius, especially over recent decades (Fig. 6), is in concert with the increase in tree coverage in Lithuanian peat bogs, and even more so with the intense tree spread at Aukštumala since the mid-1970s (Fig. 5c). The actual increase of bog trees may in itself generate a positive feedback loop resulting in increased evapotranspiration and improved nutrient conditions at the bog through aeration and increased peat decomposition (Moir et al., 2010). With the ongoing and projected increase in temperatures and evapotranspiration, the observed tree establishment can be expected to continue in the future. At the same time, drier peatland surface conditions are likely to reduce peat growth and decrease the carbon accumulation in the peat, which would then result in decreased ability for the peatlands to act as carbon sinks (Gorham, 1991; Lafleur et al., 2003). Further field and monitoring studies are thus needed to clarify the exact interactions between climate and peatland development, hydrology, and vegetation dynamics. This would enable more accurate predictions of peatlands future role in the global carbon cycle in terms of predicted climate change.

5. Conclusions

Improved understanding of peatland vegetation dynamics and interaction with changing environmental conditions is urgently needed to enable predictions on how peatlands will likely respond to future climatic changes. Our study provides evidence for the ongoing establishment of bog trees, sometimes even at accelerating rates, as for instance at the three Lithuanian peat bogs Kerėplis, Rėkyva, and Aukštumala, investigated in this contribution. It also demonstrates that the combination of multiple approaches including field and remotely sensed techniques should be preferred clearly over individual approaches so as to detect tree establishment and spread in full. Tree establishment is likely to result from a combination of climatic and land-use changes, but changing climatic conditions over the 20th century have been shown to be the most important driver of increasing tree establishment rates, even more so at the sparsely vegetated study sites where tree germination is favored by less competition.

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