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RESEARCH ARTICLE

Reading past landscapes: combining modern and historical records, maps, pollen-based vegetation reconstructions, and the socioeconomic background

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Abstract

Context Anthropogenic and environmental changes are reshaping landscapes across the globe. In this context, understanding the patterns, drivers, and consequences of these changes is one of the central challenges of humankind.

Purpose We aim to test the possibilities of combining modern multidisciplinary approaches to reconstruct the land-cover and linking the changes in land-cover to socioeconomic shifts in southern Estonia over the last 200 years.

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Methods The historical records from five, and maps from six time periods and 79 pollen-based land-cover reconstructions from four lakes are used to determine the land-cover structure and composition and are thereafter combined with the literature based analyses of socioeconomic changes.

Results All information sources recorded similar changes in the land-cover. The anthropogenic deforestation was comparable to today's (approximately 50%) during the nineteenth century. Major political and socioeconomic changes led to the intensification of agriculture and maximal deforestation (60–85%) at the beginning of the twentieth century. The land nationalisation following the Soviet occupation led to the reforestation of the less productive agricultural lands. This trend continued until the implementation of European Union agrarian subsidies at the beginning of the twenty first century.

Conclusions Pollen-based reconstructions provide a trustworthy alternative to historical records and maps. Accounting for source specific biases is essential when dealing with any data source. The landscape's response to socioeconomic changes was considerable in Estonia over the last 200 years. Changes in land ownership and the global agricultural market are major drivers in determining the strength and direction of the land-cover change.

Keywords Past cultural landscape · Land-use change · Historical data · Pollen-based reconstructions · Socioeconomic factors · Estonia

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Introduction

Terrestrial land-cover has a central role in a biocultural system. It provides food, shelter, and a habitat for other organisms, and contributes to a large number of supporting, provisioning, regulating, and cultural ecosystem services essential for the socioeconomic prosperity of people (Maffi 2005; Burkhard and Maes 2017). The present day landscapes of Europe are a result of the millennia long interaction between humans and nature (Kaplan et al. 2009). Socioeconomic and political forces, alongside biophysical ones, have been recognized as important factors in defining agriculture and land-use developments (Rabbinge and Van Diepen 2000). Information on the impact of socioeconomic changes on the development and resilience of land-cover is therefore essential for the successful preservation and maintenance of the biological and cultural legacy of historical landscapes. The landscape history, including long term dynamics of the habitat structure, management regimes, and land-use traditions, has been found to have a considerable impact on the composition and resilience of the ecosystem (e.g. Lindbladh et al. 2013).

Historical maps and records are used as an information source to determine the temporal and spatial aspects of past land-cover changes (e.g. Cousin 2001; Bender et al. 2005; Hamre et al. 2007; Raet et al. 2008; Tomson et al. 2015). The available historical data in Estonia reaches back a few centuries (Veski et al. 2005; Tomson et al. 2015). These datasets are often scarce and heterogeneous in space and time, and influenced by data type and collection purpose. Furthermore, the changes in classification standards, the overall scarcity of data sources when dealing with the past, and/or their fragmentary nature can lead to an erroneous interpretation of the recorded state.

Pollen-analysis based vegetation reconstructions are an alternative means of obtaining information on past land-cover and land-use. Successful studies present the pollen-based land-cover reconstructions using the Landscape Reconstruction Algorithm (LRA) technique developed during the last decade (Sugita 2007a, b) as a good alternative to historical data for long term landscape development reconstructions (Mazier et al. 2015; Trondman et al. 2015). However, only plants producing and dispersing pollen can be reconstructed. Most common temperate and boreal tree species have a medium to high pollen productivity and dispersal capacity, making this method well suited to study the shifts in the forest composition of northern Europe. Cultural landscapes on the other hand contain a large number of units dominated by different herbal assemblages with largely diverging pollination capacities. Many cultivated plants are harvested before flowering (e.g. carrots, cabbages, peat roots), are autogamous (e.g. wheat and barley), or insect pollinated (e.g. flax, potato, different legumes, clover and rape).

There are few studies combining historical data, maps and pollen analysis (e.g. Berglund 1991; Poska et al. 2014). Numerous historical records and maps preserved in archives and abundant sedimentary records from lakes provide a great opportunity to use a multidisciplinary approach to reconstruct past land-cover changes in Estonian.

In this study we present data from six mapping periods, four farmland revisions, and pollen-based land-cover composition reconstructions from the Karula Upland, southern Estonia, covering the last 200 years. The major aims are (1) to compare and evaluate the data sources potential as information providers on past land-cover changes; (2) to discuss the impact of large scale socioeconomic changes on the spatial pattern and composition of land-cover.

Materials and methods

Study area

The study was carried out in the Karula Upland, in southern Estonia (Fig. 1), which has a unique hilly cultural landscape, shaped by natural processes and long-term human activity. The altitudes in the upland are 75–137 m asl. Numerous small lakes and bogs are located in the depressions between the hills.

Situated in temperate climates at the border between the boreal and nemoral forest zone (Metzger et al. 2005), the natural land-cover of Estonia is a mixed hemiboreal forest. The millennia-long anthropogenic deforestation led to the emergence of the present day cultural landscape which has a forested – open land ratio around 50%, where the main tree species are Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* L.), Norway spruce (*Picea abies* L.) and grey alder (*Alnus incana* L.), respectively 37, 29, 22 and 3% (Raudsaar et al. 2014).
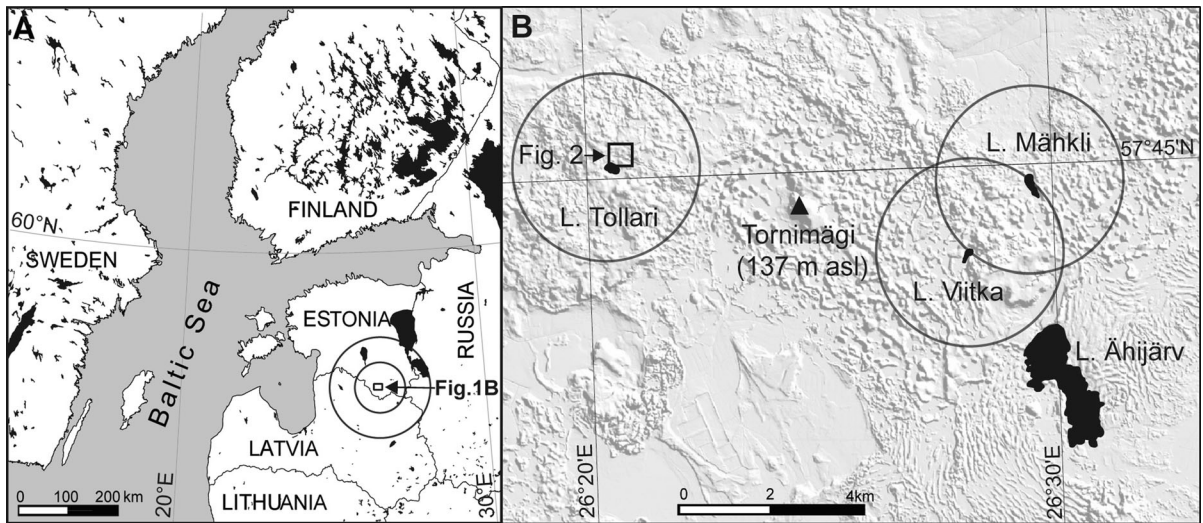
Fig. 1 Location of the study area (**A**) and the investigated lakes on a shaded relief map from the Estonian Land Board (**B**). Black circles mark the extent of reconstructed regional (**A**) and local

(**B**) land-cover. Black rectangles at **A** and **B** mark the extent of the map presented at **b** and Fig. 2 respectively

Estonia has experienced dramatic political and socioeconomic alterations and land ownership changes during the last two centuries. Land belonged to the squires and Crown during the Russian Empire (1710–1917). The emancipation of serfs and the purchase of land by peasants began in the nineteenth century. The Estonian Republic (1918–1940) was formed after the collapse of the Russian Empire, and all manor estates were nationalized. While the forests became state property, the majority of nationalized agricultural land was divided between numerous new

homesteads. Estonia lost over 10% of its population during World War (WW) II and the deportations to Siberia in 1941–1949 (Õispuu 1996). Following the occupation of Estonia by the Soviet Union (1940–1991) all of the farmland was nationalized with the land reform in 1940. Collective (CF) and State (SF) Farms were established during the next decade. After the collapse of the Soviet Union and the restoration of the Estonian Republic in 1991, the CFs and SFs were terminated and the land was returned to
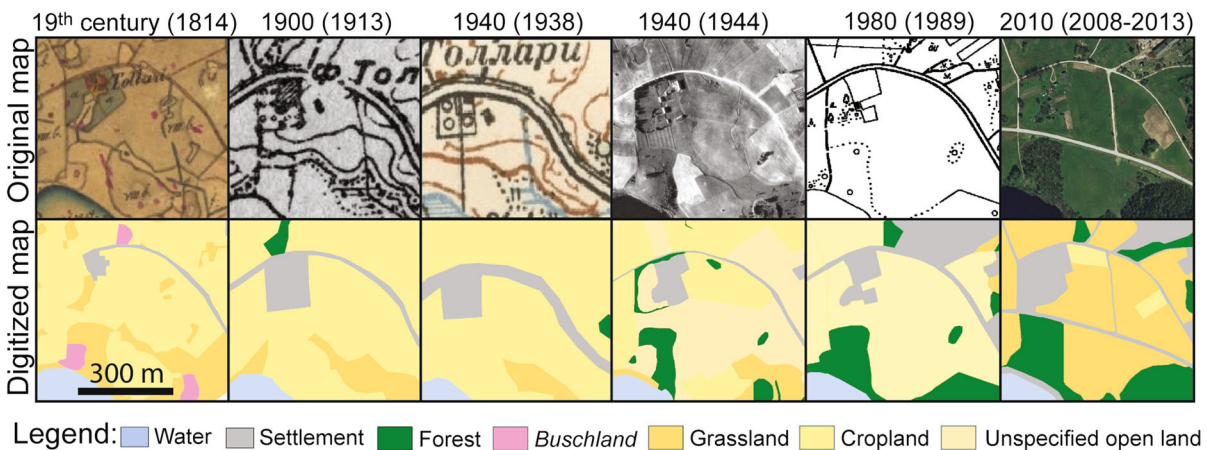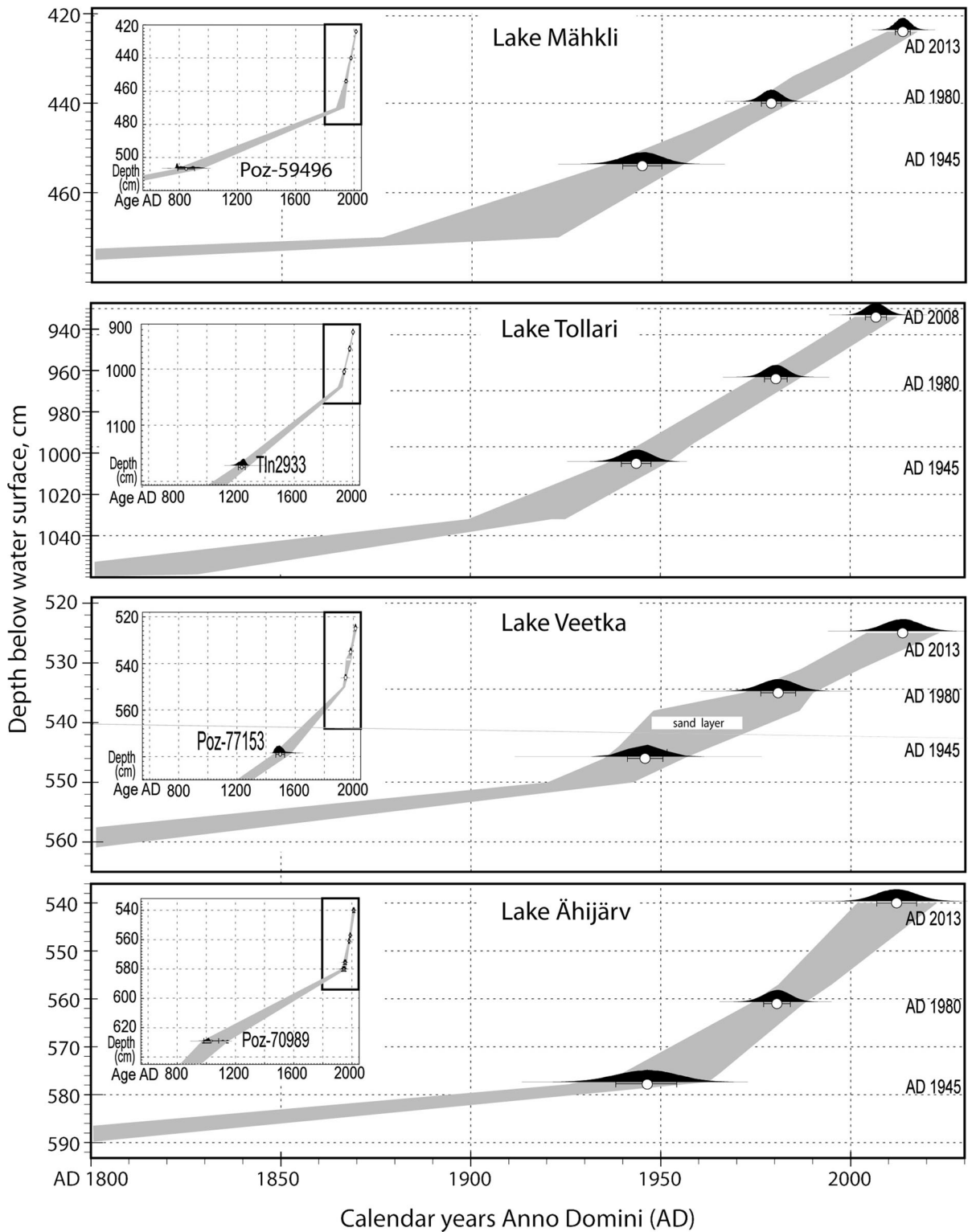

Fig. 2 Examples of original and digitized/classified maps and aerial photos, representing a 600 × 600 m square on the north-eastern shore of Lake Tollari (see Fig. 1B) from different time windows. See Appendix I for map related details

◄ **Fig. 3** The age-depth models for investigated lakes covering the timespan of AD 600-present (small figure) and AD 1800-present (an enlargement of the proportion delimited by a black rectangular outline in the small figure). The light grey area marks the possible modelled age range at a 95.4% probability. The black graphs show the probability distributions of the calibrated radiocarbon dates and spherical fly ash particle analysis determined ages. The weighted average ages are shown by white circles, and associated standard errors by black lines

the previous owners (Sirendi et al. 2009). Estonia joined the European Union in 2004.

Lakes Ähijärv (57°42′41″N, 26°29′52″E), surface area 176 ha; Mähkli (57°44′49″N, 26°29′30″E), surface area 8.4 ha; Tollari (57°45'07"N 26°20'32"E), surface area 4.3 ha; Viitka (57°44′01″N, 26°28′10″E), surface area 3.6 ha, and their surroundings were selected for a detailed long term land-cover change study (Fig. 1). Pollen-based reconstructions from a large lake (Ähijärv) reflect regional land-cover dynamics (Sugita 2007a) in a 50 to 100 km radius around the lake, covering southern Estonia and northern Latvia (Fig. 1A). The natural conditions (climate and geomorphology) and vegetation, both in taxonomic composition and cover proportions, of that area are uniform; the same applies to the political and socioeconomic development. The term "regional" is henceforth used for Lake Ähijärv results. The small lakes (Mähkli, Tollari, Viitka; Fig. 1B) reflect local land-cover dynamics (Sugita 2007b) in up to a 2 km radius (Poska et al. 2011). The 2 km radius was set for the historical records and maps to match the area of land-cover reflected in pollen spectra from small lakes.

Modern and historical maps

Different scale and type historical and modern maps and aerial photos (Fig. 2; Appendix I) were used to retrieve spatially explicit information on the land-cover distribution over the last 200 years. To determine the local land-cover distribution in the surroundings of the small lakes the maps falling into six time windows (generally ± 5 years around the indicated decade): modern (2010), during the twentieth century (1980, 1950, 1940, 1900) and during the nineteenth century (mapping time 1814–1870) were used. All the maps were analysed using MapInfo Professional.

Historical records

The historical data on the land-cover composition and cropland division was available for three time periods (1881/1883, 1939 and 1981/1983) at a regional scale and for two time periods (1929 and 1939) at a local scale (Appendix II).

These published inventories list the proportions of forests and arable land types and the crop specific sowing quantities. The reports from 1929, 1939 and 1981/1983 covered only lands used for agriculture, leaving out the state forests. The Estonian State Forest management database (http://register.metsad.ee/avalik/) and maps of the Karula State Forest District from 1982 were used to determine the proportion of the state forests in the studied area. The distribution of state forests is representative of the entire twentieth century, as the forest borders and taxonomic composition have not changed considerably since 1920s.

Pollen-based land-cover reconstructions

All sediment cores were obtained using a Belarus type peat sampler in the winter of 2013, except for Lake Tollari, which was cored in the winter of 2006. We used an Uwitec sediment sampler to capture the sediment–water interface in 2014.

Age-depth models for all cores were established by the OxCal 4.2.4 deposition model (Bronk Ramsey 2008, 2009) combining spherical fly ash particle analysis derived ages, radiocarbon dates, and lithological data (Fig. 3, Appendix III). The age of the sediment surface was assumed to correspond to the coring time. The modelled weighted average (WA) ages and associated standard errors expressed as years *Anno Domini* (yr AD) were used to determine the ages of the pollen samples.

The sedimentation rate was high (3–10 mm/year) in all studied lakes allowing for a high temporal resolution. The standard errors of the modelled WA ages which are younger than AD 1920 do not exceed 5 years and for earlier period ± 30/20 years (Fig. 3). Accordingly, a decadal resolution (± 5 year) around the decade was adopted for the pollen data for the twentieth and twenty first century. The nineteenth century data was divided into two time windows: AD 1825 (± 25 years) and 1875 (± 25 years).

The sediment samples of 1 cm³, containing pollen deposited over a period of 1–4 years, were used for the

pollen analysis. The samples were prepared with the standard acetolysis method (Erdtman 1969). At least 1000 pollen grains were counted for each level. Pollen identification was carried out according to Faegri and Iversen (1989).

Due to species specific differences in pollen production and dispersal capacities, the pollen abundance does not correspond directly to the plant abundance in the land-cover. The LRA modelling framework (Sugita 2007a, b) was used to overcome this discrepancy. The LRA consists of two parts (Fig. 4): (1) the REVEALS (Regional Estimates of VEgetation Abundance from Large Sites) model (Sugita 2007a) estimates the vegetation proportions at a regional scale (10^4–10^5 km^2) using pollen from a large (> 100 ha) sampling site; (2) the LOVE (LOcal Vegetation Estimates) model (Sugita 2007b) estimates the vegetation proportions on a local scale (< 10^4 ha) using pollen from a small (< 10 ha) sampling site. The resulting taxon-specific cover proportions provide a distance weighted estimate of the relative abundance of a reconstructed taxon, as plants growing near the sampling site are likely to contribute more pollen than plants growing at a greater distance. This approach has been extensively tested in northern Europe (Nielsen and Odgaard 2010; Poska et al. 2014; Hjelle et al. 2015; Mazier et al. 2015) and North America (Sugita et al. 2010) using modern and/or historical pollen and vegetation data.

The REVEALS model version 4.5 and the pollen data of Lake Ähijärv was used to reconstruct the regional vegetation proportions. The LOVE model version 4.6.1, the regional vegetation estimates
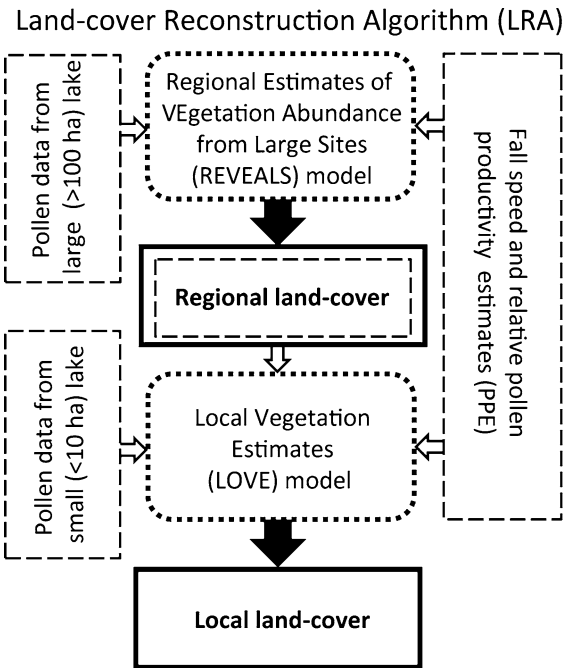

Fig. 4 Conceptual design of the LRA framework based on Sugita (2007a,b), presenting applied models (delimited by dotted lines) with their inputs and outputs (delimited by dashed and continuous lines respectively)

produced by the REVEALS model, and the pollen data from the Lakes Mähkli, Tollari, and Viitka were used to reconstruct the local vegetation compositions in the surroundings of the lakes. The distance weighted proportional cover of twenty major plant taxa (Table 1, Appendix IV) representing on average 97% of the identified pollen grains in every sample was reconstructed. The set of relative Pollen

Table 1 Land-cover class (LCC) transition scheme

Harmonized LCC	Mapped LCC	Pollen-based LCC (taxa)	Recorded LCC
Settlement	Settlement	Wasteland (*Artemisia*)	Settlement
Forest	Forest	Woodland (*Alnus, Betula, Corylus, Fraxinus, Picea, Pinus, Quercus, Tilia, Ulmus*) and Shrub (*Juniperus, Salix*)	Forest
Wetland	Wetland	Wetland (*Calluna*)	
Semi-open	*Buschland*		
Grassland	Grassland	Grassland (Cyperaceae, *Filipendula, Plantago*, Poaceae, *Rumex*)	Grassland
Cropland	Cropland	Cropland (*Cerealia, Secale cereale*)	Cropland
Unspecified open land	Unspecified open land		Other

Productivity Estimates (PPE) and pollen fall speeds used by models is given in Appendix IV.

Harmonisation of the temporal resolution and land-cover classification

The temporal resolution of the datasets ranges from 1 year for the historical records to a number of years for the pollen data and maps. The time windows comparable with the temporal resolution of the LRA reconstructions (± 5 years around a specific decade, e.g. 1940s refers to the time interval from 1935 to 1945) were assigned to the maps and historical records based on the mapping and data collection time (Appendix I). The highest possible land-cover classification level was preserved for all data sources when presented separately.

For comparison purposes (Fig. 8) the land-cover composition was simplified to a level achievable by all data sources (Table 1). The *buschland* was not merged with other categories as its composition is still unclear. The waterbodies and non-vegetated areas were excluded from historical records and map based land-cover proportions calculations, as the LRA reconstructions depict only vegetated parts of the land-cover. In order to enhance the comparability of the pollen-based land-cover reconstruction with the mapped reconstruction (Fig. 8), the mapped land-cover data were distance weighted using d^{-2} (Calcote 1995), where d is distance from the centre of the lake.
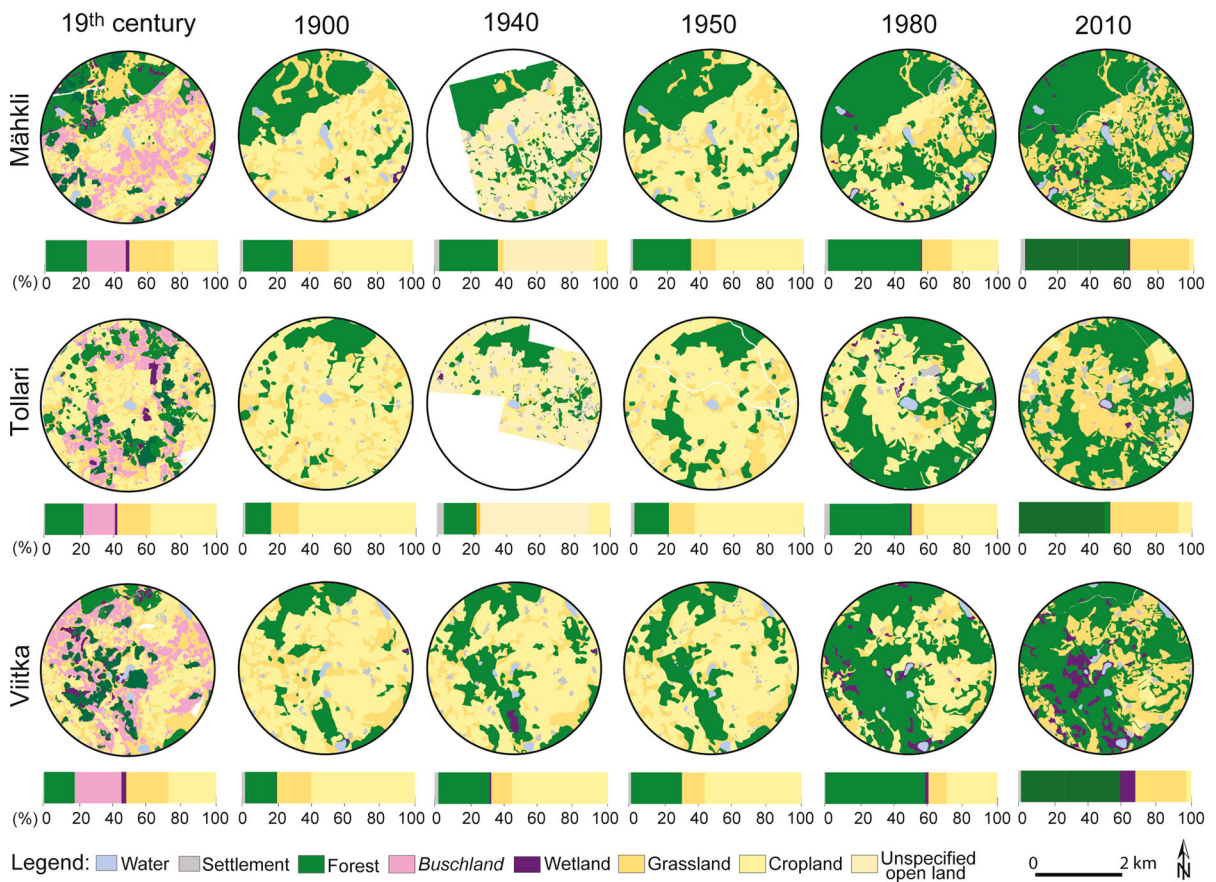

Fig. 5 Maps (circles) and map derived cover percentages (histograms) of the land-cover in 2 km circles surrounding the Lakes Mähkli, Viitka and Tollari
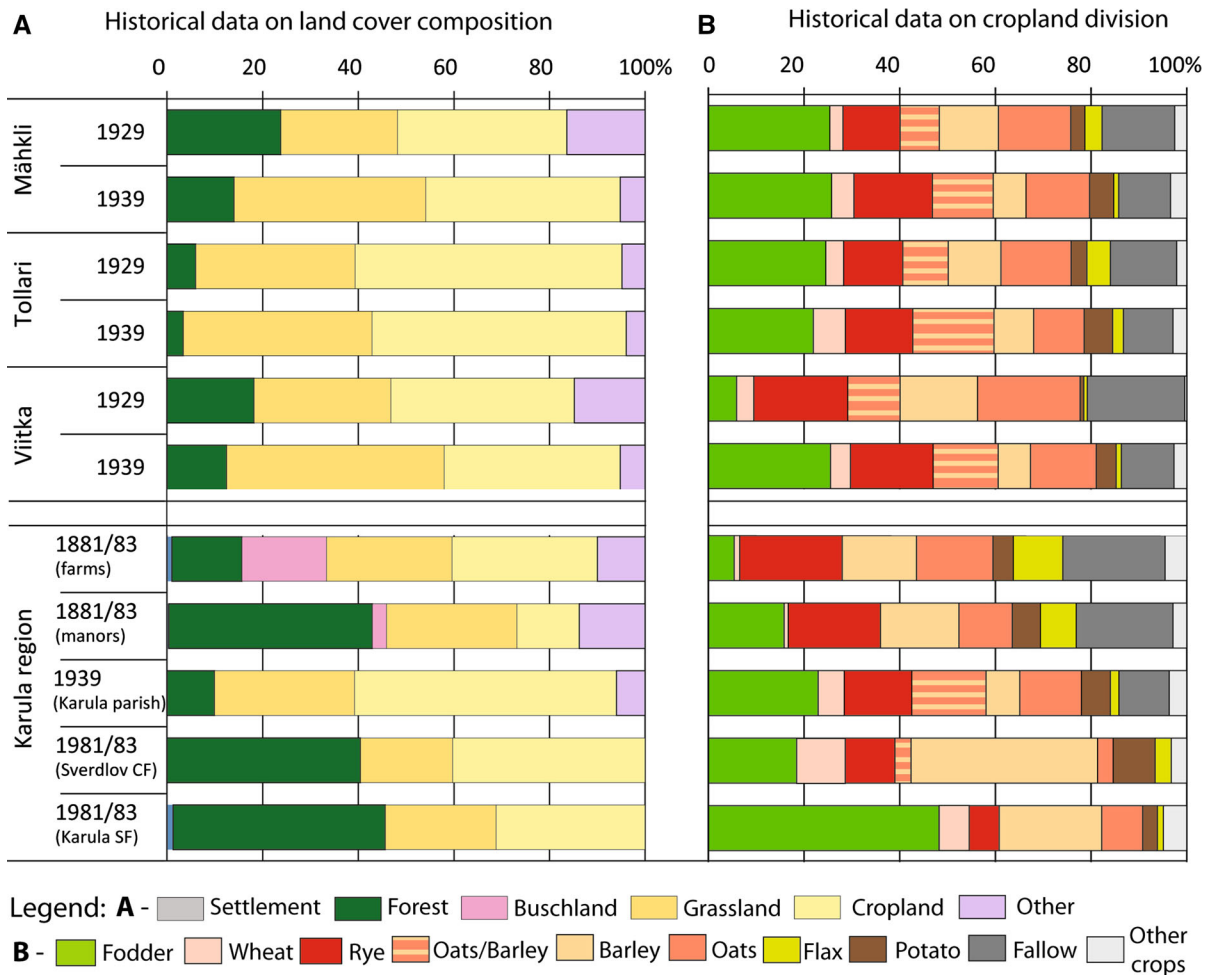
Fig. 6 Land-cover proportions (A) and cropland division (B) based on historical records

Results

Cultural landscape development in the Karula Upland

According to the historical maps the permanent forest cover was 18–21% in the nineteenth century (Fig. 5). A considerable part of land (19–27% of the total analysed local area) was attributed to the *buschland* category in nineteenth century maps and farmland revision records.

The arable fields, hay meadows and pastures were the main components of open (unforested) land in the surroundings of all studied lakes. The historical records show clear differences in the land-use of manors and peasant farms (Fig. 6) in the nineteenth century. While the permanent forest occupied 16% of

the land in farms, 45% of the lands were recorded as permanent forests for the manors. The proportion of *buschland* was considerably higher for farms than for manors (18 and 3% respectively). Crop preferences for both estate types were rather similar, with different cereals (rye, oat, barley and wheat) grown in ca 50% of the cultivated area (Fig. 6B). The largest differences in the cropland division between manors and farm-steads were recorded for fodder (mainly clover and timothy-grass) plants (16 and 5% respectively). The pollen-based reconstructions show that the proportion of open land (grass- and cropland), was 49% at the regional scale in the nineteenth century, and the local forest cover ranges from 22% in Viitka to 50% in Tollari (Fig. 7).

The landscape openness increases on the maps during the first half of the twentieth century (Fig. 5).
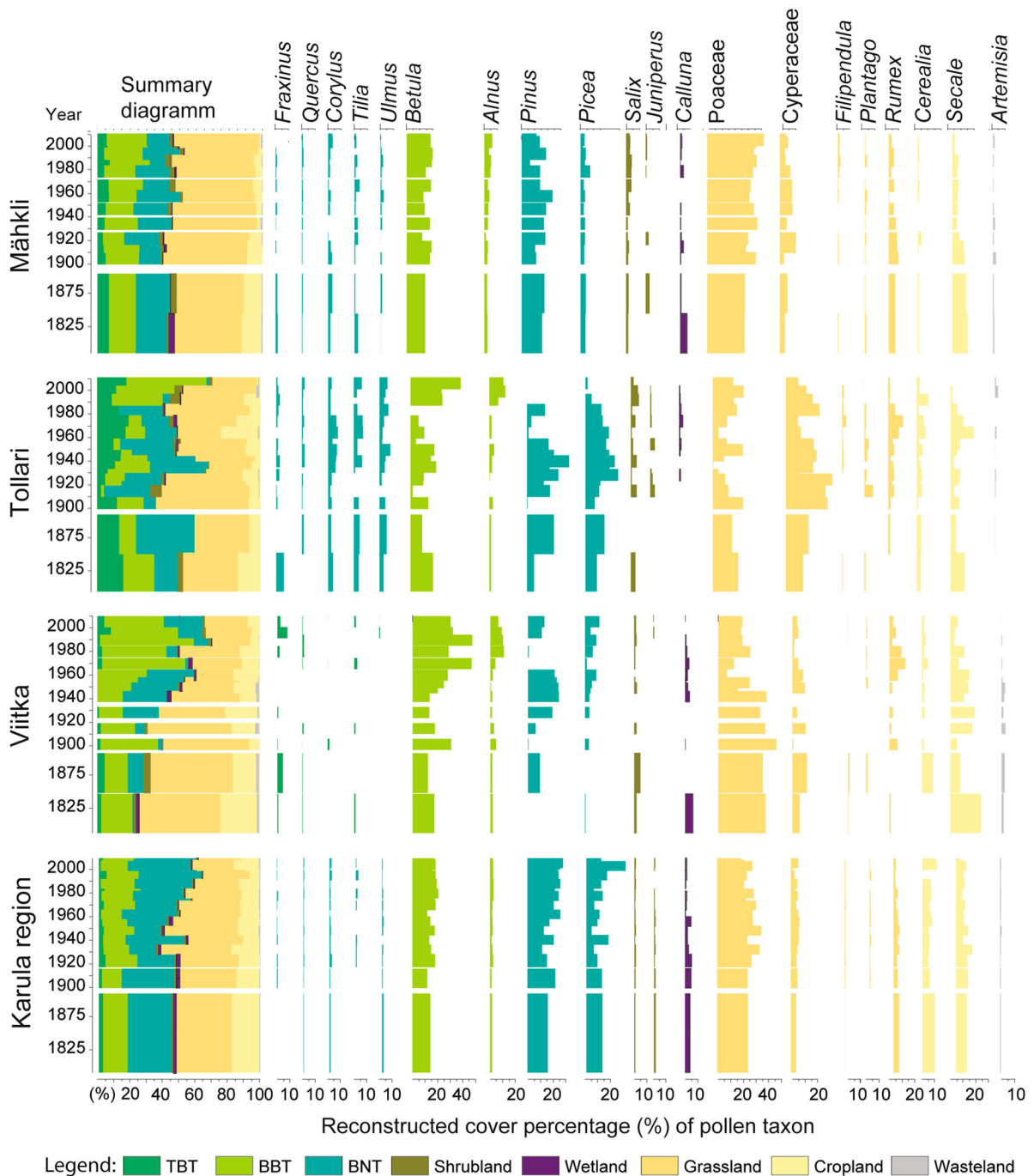
Fig. 7 Pollen-based land-cover reconstructions. *TBT* temperate broadleaved trees, *BBT* boreal broadleaved trees, *BNT* boreal coniferous trees

The previously abundant *buschlands* were mostly converted to grasslands and arable fields. The historical records also suggest maximal openness during the first part of the twentieth century, and a permanent forest cover of 3–14% is recorded before WW II (Fig. 6A). Land inventories from 1929 and 1939 record ca 30% of hay meadows and pastures as areas needing clearing of trees and shrubs (the density of

forest/shrub cover is not known). The land inventories account only for farmland. The state forest proportion in local land cover was 11.7% in Mähkli, 6.8% in Tollari, and 5.4% in Viitka. Taking into consideration the proportion of state forests, the recorded tree cover is increased by 25–65% (Appendix II). The differences in the two inventories do not necessarily indicate landscape changes, as the number of farms included is much smaller in 1929 (Appendix II). In arable fields the fodder plants and different cereals were the major crops cultivated, the sowing quantities of other crops (buckwheat, pea, vetch, root vegetables, fruit and kitchen gardens) are 2–7% of the local croplands around all the studied lakes according to the records (Fig. 6B).

The pollen-based reconstructions show a more or less stable period of land-cover openness (60–65%) in Tollari and Mähkli during the first decades of the twentieth century (Fig. 7). The openness decreased somewhat in comparison to the nineteenth century in Viitka, but remained high (60–68%) until the 1930s. The regional forest cover was similar to the nineteenth century during the first decades of the twentieth century and reached its lowest values (40%) in 1930 and 1940s. The forest composition remained similar to the previous period with pine, spruce, and birch as major forest forming species. Open land-cover was dominated by grass- and croplands.

The proportion of woodland doubled during the second half of the twentieth century (from 20 to 50% in Tollari; from 30 to 60% in Mähkli and from 30 to 60% in Viitka) according to the maps (Fig. 5). The general landscape structure was rather stable during the last decades, as the cadastral maps from the 1980s depict a distribution of wooded and open areas that is similar to that of today. Regardless of the stable land-cover structure the cropland proportion, especially the part of rye, is diminished in all reconstructions at the end of the twentieth century. The open areas are dominated by grasslands (83–93% of the open area) today, but were mostly classified as croplands in the maps from the 1950 and 1980s (Fig. 5). According to the inventories from the 1980s the grasslands occupied 19–23% (Appendix II) and additionally, fodder crops (timothy-grass and clover) were grown at up to 48% of the croplands (Fig. 6B). The pollen-based reconstructions of regional vegetation show that the proportion of woodlands increased throughout the second half of the twentieth century and reached a maximum (67%)

in 1990s (Fig. 7). A major increase is present in coniferous trees: at first pine and later spruce reach their maximal regional occurrence. Considerable differences are seen in local vegetation dynamics. While a clear increase in forest cover is observable elsewhere; only a slight (max 10%) decrease in open land-cover is recorded in Mähkli. A sharp increase (up to 70%) of pollen-based tree-cover in Tollari in 1940s was followed by a quick decrease during the next decade (Fig. 7). In Viitka a continuous decrease (interrupted shortly around 1980s) in the open land-cover from 60% in 1930s to 30% in the last decades of the twentieth century is recorded by pollen-based reconstructions (Fig. 7). Characteristic to Tollari and Viitka is a clear increase in birch and alder representation, during the above described phases of woodland expansion.

In general, the boreal broadleaved (birch and alder) and coniferous (pine and spruce) trees dominate the woodlands both at a regional and local scale in pollen-based reconstructions throughout the investigated period (Fig. 7). The temperate broadleaved trees (mainly elm, lime and hazel) are rare and in total do not exceed 5% of the regional land-cover (Fig. 7). A somewhat higher coverage of these trees is registered locally, with maximal occurrences reaching 20% in Tollari. The most common crops (> 50%) on arable lands are different cereals (mainly rye, barley and oats) according to the historical records. The records show that the proportion of rye was highest (up to 20% of the cultivated land) during the nineteenth century, reduced to ca 6% during the second part of the twentieth century (Fig. 7), and is negligible according to the Estonian Agricultural Registers and Information Board database today.

Comparison of land-cover representation based on different data sources

The past land-cover composition at a source specific spatial, temporal, and taxonomic resolution achievable by the used data sources (Figs. 5, 6 and 7) is not directly comparable. The woodland composition was not distinguished by the historical maps and records (Figs. 5, 6) and it was therefore not possible to explore the differences in tree species representation. Using the harmonized land-cover classification the major types (wooded/open land proportions) derived from
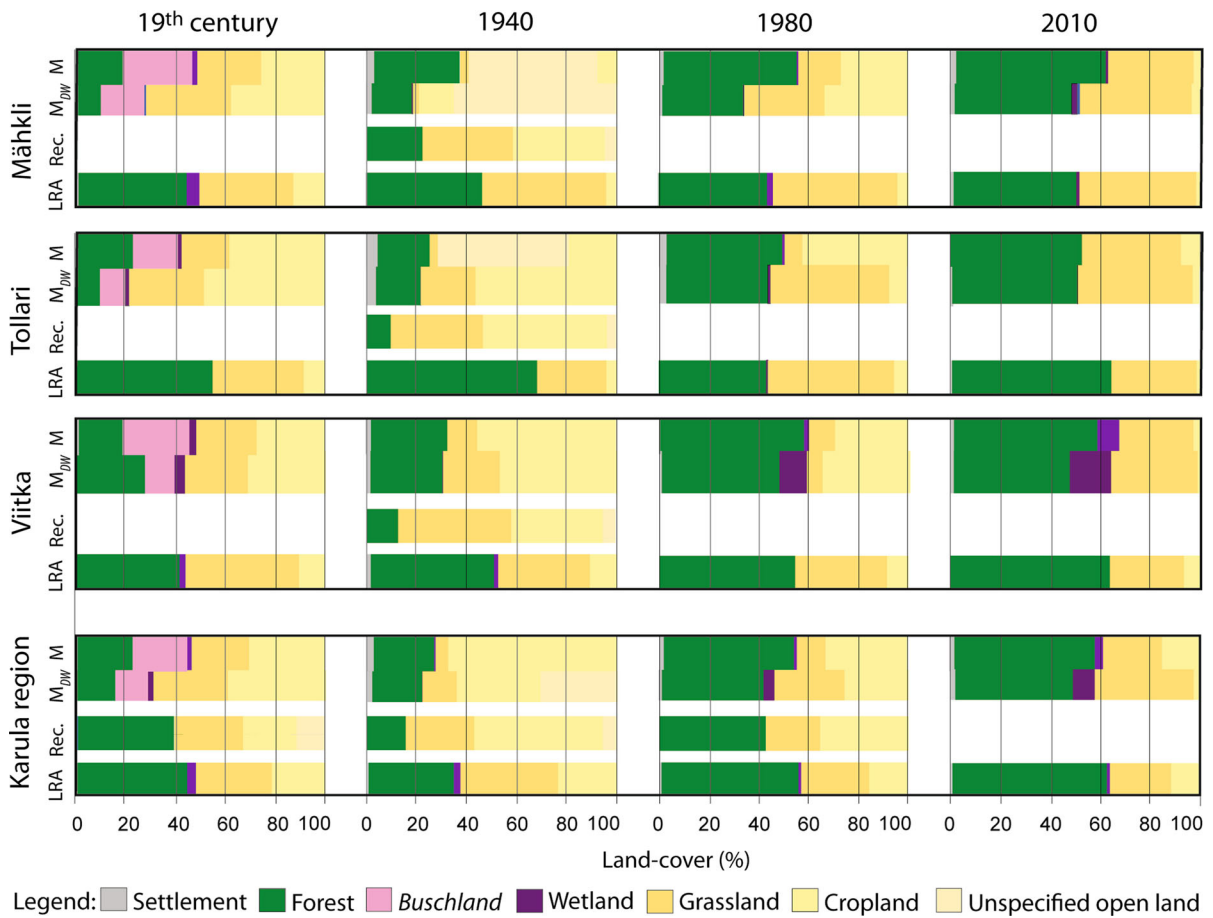
Fig. 8 Comparison of past land-cover proportions derived from different data sources. *LRA* pollen-based reconstructions, *Rec* historical records, *M* historical maps, *M_DW* distance weighted historical maps

different data sources fit together well, with the differences rarely exceeding 10% (Fig. 8).

The only exceptions are the datasets depicting land-use during the 1940s. While historical records register a forest cover of 3–14% both locally and regionally, the one recorded by maps comprising the state forests as well, show 20–35%, and by pollen-based reconstructions 35–68% (Fig. 8). The conformity of wooded/open land division recorded by different data sources for the nineteenth century depends highly on the classification of the *buschland* category. The estimates are fairly similar (40–45%, 39% and 41–55% according to maps, records, and pollen-based reconstructions respectively) when the *buschland* is accounted as a wooded rather than open or semi open land-cover class, but only 18–22% of the woodland-cover is recorded by maps if the *buschland* is classified as an open land-cover type. The distance weighting of

the map-derived land-cover considerably changed the forested/open land ratio in Tollari (nineteenth century) and Mähkli (nineteenth century, 1940 and 1980s), but did not improve the similarity to pollen-based reconstructions.

The open land-cover was divided into two parts: natural grasslands, and cultivated croplands, by all the used data sources (Figs. 5, 6 and 7). The determination of the grass- and cropland proportions derived through different approaches result in the largest discrepancies between the estimates for all (except the modern) time windows (Fig. 8). The croplands, incorporating different cultivated fodder plants, root vegetables, and other crops besides corn fields occupied 3–72% of the land-cover in the historical maps, and 32–61% according the historical records. The pollen-based reconstructions, accounting only for the corn

proportion of the land-cover, do not show a cropland cover higher than 22% for any time window.

Discussion

The level of land-cover reproduction and data inherent biases

A rare combination of information sources on past land-cover changes was utilized. While the historical maps and records have an undisputable place as providers of information on past land-cover, the opportunities brought by recent advances in palaeoecological modelling are considerably less known.

The maps are the best sources of spatially explicit data, but the resolution of the information can vary considerably due to different mapping scales and aims. For the Karula Upland, where the land-cover consists of an intricate mosaic of small patches, the loss of information with smaller scaled maps could be considerable. The loss of wooded patches in a generally open agrarian landscape due to the different mapping scale is clearly visible when comparing the aerial photo from 1944 (scale 1:10,000) with the 5× smaller scale topographic map from the same period (Fig. 2). The determination of the definite spatial extent of land-cover units can also be hampered by the usage of symbols rather than lines to distinguish the land-cover units. Furthermore, the actual plant species content, or even the land-cover type, depicted in maps is sometimes not determinable. The *buschland* category in nineteenth century maps is a good example of such historical land-cover units, not classifiable with certainty even at a land-cover type (wooded/open) level (Raet et al. 2008; Tomson et al. 2015). While traditionally these areas are regarded as generally open land, comprising of sparse arable, fallow, and grass covered patches, and different stages of regenerating young tree cover (Tomson et al. 2015), the pollen-based reconstructions suggest the existence of considerable tree cover, as the map-derived woodland
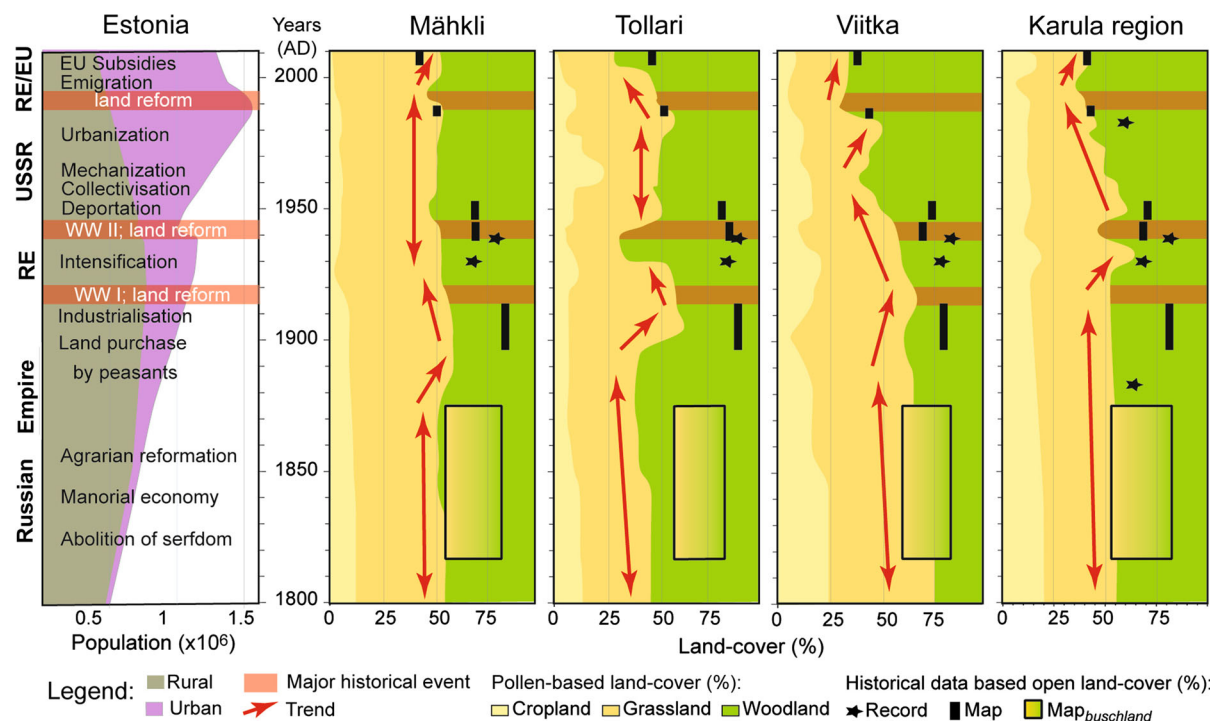

Fig. 9 Major political and socio-economical events and population dynamics in Estonia over the last 200 years. The corresponding pollen-based reconstructed land-cover changes are compared with the open land percentages derived from historical Records and Maps. The map-based openness estimate for the nineteenth century (Maps*buschland*) is given as a range accounting for the ambiguously classifiable *buschland* category. *RE* Republic of Estonia, *EU* European Union, *USSR* Union of Soviet Socialist Republics, *WW* World War

proportion becomes strikingly similar to the reconstructed one when *buschland* is considered a forested rather than open land-cover unit (Figs. 8, 9). The *buschland* disappeared as a separate land-cover unit at the end of the nineteenth century, and were either transformed into arable lands, grasslands, or left to grow into forests (Meikar and Uri 2000; Liitoja-Tarkiainen 2006). The contemporary pastures and hay meadows could also contain patches with woody vegetation. Even areas mapped as croplands are not absolutely unambiguous and could be subject to short or long term fallows. For example, according to historical records, 10–11% of the arable land was under fallow. The pollen-based reconstructions show such land-cover as grassland, instead of arable land.

The historical records carry detailed information on the recorded items (e.g. crops and cattle) and have an excellent (usually annual), but often discontinuous, temporal resolution (Veski et al. 2005; Poska et al. 2014). The spatial resolution of historical vegetation records is very variable ranging from field/plot based records (Walker et al. 2009) to county/country based ones (Laanisto et al. 2015). The traditional, largely self-sufficient farms needed a certain amount of cereals and fodder every year in order to function and could not change the proportion of crops rapidly. Major challenges when using written sources to describe the past land-cover are therefore often connected to the divergence of the temporal and spatial scales of study from the ones in the preserved records. The materials highlight the selective nature of the inventories (data from only a certain property type or branches of land-use are available/used) as a possible source of land-cover depiction biases (Fig. 6). The land-use inventories and land-cover maps do not always record the need for wood clearing from land accounted as pastures and hay meadows. Here, both the need for clearing recorded by land inventories, and the difference between historical data and pollen-based reconstructed forest cover (Figs. 8, 9) suggests that the woody vegetation in pastures and hay meadows had to be notable at the beginning of twentieth century.

The biggest advantage of using pollen as a source of past land-cover information is the method's applicability for depicting the vegetation of the distant past not reachable with historical records, and allowing for a continuous reconstruction of land-cover dynamics over the course of many millennia (Groot et al. 2011;

Marquer et al. 2014). However, the pollen-based reconstructions are point estimates, the spatial resolution of which is determined mainly by the size of the sedimentary basin and the vegetation structure, and can vary from tens of meters to a few hundred kilometres (Sugita 1994). A larger input of pollen from the vegetation located close to the lake is expected to have a considerable impact on the reconstructions when the land-cover nearby is different from the one further away (Figs. 5, 8). The correlation between the pollen-based and the mapped land-cover was not improved by the distance weighting at any of the tested locations and time periods (Fig. 8), probably caused by the homogeneity of pollen rain at spatial scales comparable to the pollen source areas of the investigated lakes.

The temporal resolution of the pollen data depends on the sedimentation rate and type of the sediments used, and can vary from centennial/millennial to annual (Veski et al. 2005; Zhao et al. 2008). The largest biases are connected to the selective capacity of the method to reconstruct the cover of prevalently wind pollinated taxa with a relatively high pollen production and dispersal capacity with sufficient confidence (Broström et al. 2008). While practically all major tree species in the temperate zone are fit well into these criteria, the majority of the herbs and a number of the crops produce little (e.g. flax, rape, clover, potato) to no (root vegetables) pollen (Erdtman 1969). Therefore many of the cultivated taxa are difficult or impossible to detect through pollen analysis. The comparison of data derived from different data sources (Fig. 8) illustrates the consequences of this bias for our study. The pollen-based reconstructions depicting only cereals (mainly rye) show a considerably lower cropland proportion than historical records or maps. The discrepancy between datasets is considerably reduced when considering that according to the historical records only 50% of the agrarian land was used for cereal cultivation, and only ca 10–20% was occupied by rye. The cereal's pollen productivity estimates used by the LRA models are another important source of biases, as the available estimates are highly variable (Broström et al. 2008) and could be enhanced due to historical dissimilarities in cultivated cereal species and/or varieties.

The correct determination of the deposition time has a crucial importance when dealing with high resolution sedimentary records as well. Errors in the

age determination in combination with irregularly paced historical data, should therefore be considered as a possible explanation for the temporal discrepancies in the occurrence of events anticipated by the different methods (Berglund 2003). The slight discord in the timing of the drop in the fraction of open land, well seen at the regional scale and between pollen and historical maps/records from around 1930–1940, can be a result of such a displacement (Fig. 9).

Land-use and land-cover changes in the context of socio-economic shifts

The land-cover of Europe has been affected by anthropogenic deforestation for many millennia (Kaplan et al. 2009). The maximum reduction of forest cover was reached around the seventeenth century in central and western Europe (Nielsen and Odgaard 2010; Marquer et al. 2014). The Industrial Revolution started during the eighteenth century and led to industrialisation, urbanization, agricultural intensification, and food production globalisation and it initiated the reforestation of areas less favourable for agriculture (Lambin and Meyfroidt 2010). The transformation from a rural society to an industrial society with a high degree of urbanization occurred late in Eastern Europe compared to the rest of Europe. The sub-continental scale studies on the agrarian development of Eastern Europe show, that the deforestation culminated at the beginning of the twentieth century, and the reforestation has been observable since 1950 (Kuemmerle et al. 2015). Estonia is situated in the transitional zone between Western and Eastern Europe, therefore the regional differences in land-use intensity are great and both deforestation patterns can be recognized. While several previous studies have recorded land-use dynamics comparable to western European land-cover development (Veski et al. 2005: Poska et al. 2014), Karula Upland resembles the one typical for Eastern Europe with a somewhat delayed deforestation peaking at the beginning of the twentieth century.

All the land-cover data sources are in agreement and show that Karula was similar to or slightly more open than today during the nineteenth century. The proportion of permanent arable fields in the land-cover was small and these were usually located on the flat kames with more fertile soils (Tomson et al. 2015). The permanent hay meadows were traditionally constrained to the wet areas. The three-field system and utilization of short- and long-term fallows accompanied by slash-and-burn cultivation was common during the nineteenth century. The *buschlands* were probably the result of variable cycle length slash-and-burn practices, and were, besides crop farming, used for multiple purposes such as a source of (fire)wood, temporary pastures, or hay meadows. The hay meadows and pastures were sometimes covered by patches of trees or bushes, as on nineteenth century maps the trees' symbols are also drawn in grassland. Maintenance of such semi-open cultural land-cover types contributed to the recorded by pollen preservation of considerable wood-cover up to the end of the nineteenth century.

Due to a considerable socio-economical change associated with the dissolution of the previous manor based agrarian system, land purchase by peasants took place during the second part of the nineteenth century (Kahk 1992). A majority of the areas previously used as temporary croplands for slash-and-burn cultivation (*buschlands*) were turned into permanent arable fields according to the maps. However, a smaller proportion of the former *buschland* area was left for forest regeneration. In pollen diagrams this process is reflected as a locally increasing proportion of tree-cover in the Viitka and Tollari areas at the end of the nineteenth century. The intensification of land-use led to the abandonment of slash-and-burn practices at the end of the nineteenth century in the region (Jääts et al. 2010) and the six-field system was introduced to the Karula region in the 1880s (Sepp 1940). Potato and clover were introduced and cattle breeding expanded in Estonia during the second part of the nineteenth century (Kahk 1992). The sale of the land provided nobles money to introduce animal husbandry, work on dairy cattle and sheep selection, modernize farms, and increase the productivity. The bigger proportion of clover and timothy-grass according to historical records in manor arable fields compared to peasants ones in the Karula area illustrates the increasing importance of cattle breeding in manors. Flax cultivation was uncommonly widespread (increase from < 2% habitual for Estonia to 10% of the cropland) in Karula (Fig. 6B), and was also peaking elsewhere in southern Estonia during the second part of the nineteenth century (Lillak 2003; Liiv et al. 2017), due to the increased linen prices in European markets related to the American Civil War

(1861–1865). All above mentioned taxa are poor pollen producers and therefore these processes were recorded by pollen-based reconstructions as a decrease in cropland (cereals) at the end of the nineteenth century.

The change in political power, the land nationalisation, and the division of the manor estates by the Estonian Republic (1918–1940) did not cause a considerable disruption in land-use in the region. The studied area was occupied by farms that had already been purchased in the nineteenth century, with the exception of the former manor lands in Tollari, where a number of new (smaller) households were established. The dairy products were the most important export article for Estonia during the first part of the twentieth century (Pae et al. 2009; Peters et al. 2009). The short-term fallows were partly replaced with fodder herbs (timothy-grass and clover) and feed grain (mainly oat and barley) cultivation due to the increasing importance of cattle rearing. Pollen analyses and historical records show the culmination of the deforestation in Karula during the first part of the twentieth century. A similar timing in the deforestation maximum has been observed elsewhere in Estonia (Mander and Palang 1999; Poska et al. 2014).

The forest cover in farms was reduced to 3–14% in 1939 according to historical records and the used aerial photos and maps from 1938–1944 show 30–40% forests (Fig. 8). The pollen-based reconstructions show the maximum deforestation from 1900 to 1930s, and generally show a higher forest cover than the maps. The role of trees in the areas used as pastures and hay meadows in Estonia before WW II is described by Meikar and Uri (2000). On the other hand, considering the time determination accuracy of pollen-based reconstructions in the present study ($\pm$ 5 years) the observed sample could represent an adjacent time-window. This time-window coincides with WW II, the deportations of local people, and the demolishment of the former societal and agrarian structure by the Soviet regime. The area most affected by the deportations was Viitka (Merila-Lattik 2005). The rapid afforestation of former agricultural lands in Karula during the decades following WW II was also noted by Tomson et al. (2016). Considering the extent of the above mentioned changes, the differences in land-cover composition by different data/information sources in the 1940s could reflect the instability of the contemporary land-cover, where slightly differing

recording time could result in the documentation of considerably different land-cover composition.

The nationalization of private farmlands, impoverishment of the rural population, and urbanization was greatly intensified during the following decades. While less than 20% of the Estonian population lived in towns at the beginning of the twentieth century, over 70% of the population lives in urban areas today (Fig. 9). The above described societal changes in combination with the mechanization of the agrarian sector led to an abandonment of less fertile fields and areas not reachable by heavy machinery (Tomson et al. 2016), and resulted in a decade long decrease in agrarian activities and an overgrowth of former croplands and grasslands in Karula. The increase in forest cover observable from mid-twentieth century onwards can largely be attributed to these changes. The overgrowth of former agricultural land is particularly well seen in the reconstructions from Viitka and Tollari, as a drop in open land-cover types and an increase in birch and alder (Fig. 7), typical for the early stages of overgrowing fields in southern Estonia, during the second part of the twentieth century. A similar trend, a major increase in the forest area and decrease of agricultural land in active usage, is observable all over Estonia during this period (Mander and Palang 1994). However, the reconstructions of the land-cover surrounding Lake Mähkli show a clearly different development. The proportion of permanent forests owned by manor and state was the largest in the Mähkli area and therefore the changes in agricultural land proportion do not appear so expressively as in the other areas.

The agricultural lands on less productive soils or at steeper slopes were incorporated into state forestry during the second part of the twentieth century and a lot of plantations with coniferous trees were established in former agricultural lands. The share of pine and spruce practically doubled in Karula during the second half of the twentieth century according to the pollen data (Fig. 7).

The reestablishment of the Estonian Republic at the beginning of the 1990s and restoration of the land to the previous owners caused a further fall in agrarian activities (Sirendi et al. 2009). A part of the former croplands were abandoned and gradually overgrown by early successional trees by the end of the last century (Fig. 9). This process is visible when comparing maps from 1980 and 2010s, and seen as a major

increase in birch and alder in pollen-based reconstructions for Tollari and Viitka. An active farm reestablished near Lake Viitka in 1990s led to an increase in open land-cover and a decrease in early successional trees reflected by the pollen-based reconstructions. The land-use in the region intensified after Estonia joined the EU in 2004 and the abandoned land was taken into agrarian use following the implementation of the EU's Common Agricultural Policy during the last decade. A considerable amount of the abandoned land has been turned into agricultural land and is used for cattle and sheep breeding today.

Conclusions

The scarce and disrupted temporal and spatial coverage of preserved historical datasets hampers research on past land-cover changes. The quantitative land-cover reconstructions based on pollen grains accumulated in sedimentary environments are an excellent alternative, capable of providing both a high temporal resolution and continuity of the record. Such reconstructions can provide information on land-cover units the composition of which is unknown (e.g. *buschland*), is unspecified (e.g. forest) by the available historical datasets, and/or are beyond the reach of the historical data.

The combined usage of historical records, maps, and pollen-based reconstructions allows for a reconstruction of a wide spectrum of land-cover related aspects (spatial patterns, taxonomic composition of woodlands, and agrarian land division). The information derived from different sources is comparable, when simplified to a resolution achievable by all records and considering the source specific biases.

The extent of anthropogenic deforestation during the nineteenth century was approximately 50% and is similar to today's. The maximal deforestation (< 30% forest cover) was reached during the first part of the twentieth century. Reforestation took place during the second part of the twentieth century and reached its peak at the beginning of the twenty first century.

The changes in socioeconomic factors (political regime, land ownership, population density, agrarian practices, and mechanization) have diverging impacts on agrarian land-use. The substantial socioeconomic shifts resulted in the stable continuation or increased intensity of agricultural land-use while the agrarian production based economy was preserved during the nineteenth century and during the first decades of the twentieth century. However, similar socioeconomic factors accompanied by the industrialisation, urbanization, and globalisation of agrarian production led to a considerable decrease in agrarian land-use during the second part of the twentieth century. The response of land-cover to the major shifts in agrarian land-use is observable on the decadal scale.

References

Bender O, Boehmenr HJ, Jens D, Schumacher KP (2005) Analysis of land-use change in a sector of Upper Franconia (Bavaria, Germany) since 1850 using land register records. Landscape Ecol 20:149–163

Berglund BE (ed) (1991) The cultural landscape during 6000 years in southern Sweden—the Ystad project. Ecol Bull 41:1–495

Berglund BE (2003) Human impact and climate changes—synchronous events and a causal link? Quat Int 105:7–12

Bronk Ramsey C (2008) Deposition models for chronological records. Quat Sci Rev 27:42–60

Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. Radiocarbon 51:337–360

Broström A, Nielsen AB, Gaillard M-J, Hjelle K, Mazier F, Binney H, Bunting J, Fyfe R, Meltsov V, Poska A, Räsänen S, Soepboer W, von Stedingk H, Suutari H, Sugita S (2008) Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: a review. Veg Hist Archaeobot 17:461–478

Burkhard B, Maes J (eds) (2017) Mapping ecosystem services. Pensoft Publishers, Sofia

Calcote R (1995) Pollen source area and pollen productivity: evidence from forest hollows. J Ecol 83(4):591–602

Cousin SAO (2001) Analysis of land-cover transitions based on 17th and 18th century cadastral maps and aerial photographs. Landscape Ecol 16:41–54

Erdtman G (1969) Handbook of palynology. Morphology–Taxonomy–Ecology. An introduction to the study of pollen grains and spores. Verlag Munksgaard, Copenhagen

Faegri K, Iversen J (1989) Textbook of pollen analysis. 4th Edn. Faegri K, Kaland PE, Krywinski K (eds). Wiley, Chichester

Groot MHM, Bogot RG, Lourens LJ, Hooghiemstra H, Vriend M, Berrio JC, Tuenter E, Van der Plicht J, Van Geel B, Ziegler M, Weber SL, Betancourt A, Contreras L, Gaviria

S, Giraldo C, González N, Jansen JHF, Konert M, Ortega D, Rangel O, Sarmiento G, Vandenberghe J, Van der Hammen T, Van der Linden M, Westerhoff W (2011) Ultra-high resolution pollen record from the northern Andes reveals rapid shifts in montane climates within the last two glacial cycles. Clim Past 7:299–316

Hamre LN, Domaas ST, Austad I, Rydgren K (2007) Land-cover and structural changes in a western Norwegian cultural landscape since 1865, based on an old cadastral map and a field survey. Landscape Ecol 22:1563–1574

Hjelle KL, Mehl IK, Sugita S, Andersen GL (2015) From pollen percentage to vegetation cover: evaluation of the Landscape Reconstruction Algorithm in western Norway. J Quat Sci 30(4):312–324

Jääts L, Kihno K, Tomson P, Konsa M (2010) Tracing fire cultivation in Estonia. For Stud 53:53–65

Kahk J (1992) Uuenduste sissetung 18. sajandi lõpust 19. sajandi keskpaigani. In: Kahk J (ed) Eesti talurahva ajalugu 1. Tallinn, Olion, pp 365–377

Kaplan JO, Krumhardt KM, Zimmermann N (2009) The prehistoric and preindustrial deforestation of Europe. Quat Sci Rev 28:3016–3034

Kuemmerle T, Kaplan JO, Prishchepov AV, Rylsky I, Chaskovskyy O, Tikunov VS, Müller D (2015) Forest transitions in Eastern Europe and their effects on carbon budgets. Glob Change Biol 21:3049–3306

Laanisto L, Sammul M, Kull T, Macek P, Hutchings MJ (2015) Trait-based analysis of decline in plant species ranges during the twentieth century: a regional comparison between the UK and Estonia. Glob Change Biol 21:2726–2738

Lambin EF, Meyfroidt P (2010) Land use transitions: socio-ecological feedback versus socio-economic change. Land Use Policy 27:108–118

Liitoja-Tarkiainen Ü (2006) Talukõlvikud Vooremaal 17.–19. sajandil. In: Tamberg T (ed) Vene aeg Eestis. Uurimusi 16. sajandi keskpaigast kuni 20.sajandi alguseni. Eesti Ajalooarhiivi Toimetised 14(21), Tartu, pp 229–254

Liiv M, Alliksaar T, Freiberg R, Heinsalu A, Ott I, Reitalu T, Tõnno I, Vassiljev J, Veski S (2017) Drastic changes in lake ecosystem development as a consequence of flax retting: a multiproxy palaeolimnological study of Lake Kooraste Linajärv, Estonia. Veget Hist Archaeobot. https://doi.org/10.1007/s00334-017-0650-y

Lillak R (2003) Eesti Põllumajanduse Ajalugu. Eesti Põllumajandusülikooli kirjastus, Tartu

Lindbladh M, Fraver S, Edvardsson J, Felton A (2013) Past forest composition, structures and processes: how paleoecology can contribute to forest conservation. Biol Conserv 168:116–127

Maffi L (2005) Linguistic, cultural, and biological diversity. Annu Rev Anthropol 34:599–617

Mander Ü, Palang H (1994) Changes of landscape structure in Estonia during the Soviet period. GeoJournal 33(1):45–54

Mander Ü, Palang H (1999) Landscape changes in Estonia: reasons, processes, consequences. In: Krönert R, Baudry J, Bowler IR, Reenberg A (eds) Land-use changes and their environmental impact in rural areas in Europe. The Parthenon Publishing Group, Lancs, pp 165–187

Marquer L, Gaillard M-J, Sugita S, Trondman A-K, Mazier F, Nielsen AB, Fyfe RM, Odgaard BV, Alenius T, Birks HJB,

Bjune A, Christiansen J, Dodsonm J, Edwards KJ, Giesecke T, Herzschuh U, Kangur M, Lorenz S, Poska A, Schult M, Seppä H (2014) Holocene changes in vegetation composition in northern Europe: why quantitative pollen-based vegetation reconstructions matter. Quat Sci Rev 90:199–216

Mazier F, Broström A, Bragee P, Fredh D, Stenberg L, Thiere G, Sugita S, Hammarlund D (2015) Two hundred years of land-use change in the South Sweden Uplands: comparison of historical map-based estimates with a pollen-based reconstruction using the landscape reconstruction algorithm. Veg Hist Archaeobot 24:555–570

Meikar T, Uri V (2000) Võsamaade majandamisest Eestis. Eesti metsad ja metsandus aastatuhande vahetusel. In: Meikar T, Etverk, I (Eds) Akadeemilise metsaseltsi toimetised XI. Tartu, pp 103–120

Merila-Lattik H (2005) Karm ja kaunis Karula. Elust, olust ja inimestest muinasajast tänapäevani. Eesti Folkloori Instituut, Tartu

Metzger MJ, Bunce RGH, Jongman RHG, Mucher CA, Watkins JW (2005) A climatic stratification of the environment of Europe. Glob Ecol Biogeogr 14:549–563

Nielsen AB, Odgaard BV (2010) Quantitative landscape dynamics in Denmark through the last three millennia based on the Landscape Reconstruction Algorithm approach. Veg Hist Archaeobot 19:375–387

Õispuu L (ed) (1996) Political arrests in Estonia 1940–1988, vol 1. Estonian Repressed Persons Records Bureau, Tallinn

Pae T, Tammiksaar E, Sooväli-Sepping H (2009) Historical geography of Estonian cattle breeds. Trames J Humanit Soc 13(4):357–373

Peters KJ, Kuipers A, Keane MG, Dimitriadou A (eds) (2009) The cattle sector in Central and Eastern Europe. Developments and opportunities in a time of transition. EAAP Technical Series, 10, Wageningen Academic Publisher, Wageningen

Poska A, Meltsov V, Sugita S, Vassiljev J (2011) Relative pollen productivity estimates of major anemophilous taxa and relevant source area of pollen in cultural landscape of the hemi-boreal forest zone (Estonia). Rev Palaeobot Palynol 167:30–39

Poska A, Saarse L, Koppel K, Nielsen AB, Avel E, Vassiljev J, Väli V (2014) The Verijärv area, South Estonia over the last millennium: a high resolution quantitative land cover reconstruction based on pollen and historical data. Rev Palaeobot Palynol 207:5–17

Rabbinge R, Van Diepen CA (2000) Changes in agriculture and land use in Europe. Eur J Agron 13:85–100

Raet J, Sepp K, Kaasik A (2008) Assessment of changes in forest coverage, based in historical maps. For Stud 48:67–78

Raudsaar M, Pärt E, Adermann V (2014) Forest resources. Distribution of forest land area and growing stock by counties. In: Raudsaar M, Merenäkk M, Valgepea M (Eds) Yearbook 2013. Estonian Environment Agency, p. 4

Sepp H (1940) Lõuna-Eesti põllumajanduse arengu suund 1880-ndais aastais: mit einem Referat: Die Richtung der Entwicklung der Feldwirtschaft in Süd-Estland in den 80-er Jahren des 19. Jahrhunderts. Tartu, pp 341–402

Sirendi A, Kõiv M, Niilo L, Pumbo E, Saar E (2009) Muutused ja reformid siirdeperioodil turumajandusse. In: Eesti

põllumajandus XX sajandil. III, Ülevaade põllumajandus-est siirdeperioodil: aastad 1990–2008. Saku, pp 27–187

Sugita S (1994) Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. J Ecol 82:881–897

Sugita S (2007a) Theory of quantitative reconstruction of vegetation. I. Pollen from large sites REVEALS regional vegetation composition. Holocene 17:229–241

Sugita S (2007b) Theory of quantitative reconstruction of vegetation. II. All you need is LOVE. Holocene 17:243–257

Sugita S, Parshall T, Calcote R, Walker K (2010) Testing the Landscape Reconstruction Algorithm for spatially explicit reconstruction of vegetation in northern Michigan and Wisconsin. Quat Res 74:289–300

Tomson P, Bunce RGH, Sepp K (2015) The role of slash and burn cultivation in the formation of southern Estonian landscapes and implications for nature conservation. Landscape Urban Plan 137:54–63

Tomson P, Bunce RGH, Sepp K (2016) Historical development of forest patterns in former slash and burn sites in Southern Estonia. In: Angoletti M, Emanueli F (eds) Biocultural diversity in Europe. (Environmental History 5), Springer, pp 303−318

Trondman A-K, Gaillard M-J, Mazier F, Sugita S, Fyfe R, Nielsen AB, Twiddle C, Barratt P, Birks HJB, Bjune AE, Björkman L, Broström A, Caseldine C, David R, Dodson J, Dörfler W, Fischer E, van Geel E, Giesecke T, Hultberg T, Kalnina L, Kangur M, van der Knaap P, Koff T, Kuneš P, Lagerås P, Latałowa M, Lechterbeck J, Leroyer C, Leydet M, Lindbladh M, Marquer L, Mitchell FJG, Odgaard BV, Peglar SM, Persson SM, Poska A, Rösch M, Seppä H, Veski S, Wick L (2015) Pollen-based quantitative reconstructions of Holocene regional vegetation cover (plant-functional types and land-cover types) in Europe suitable for climate modelling. Glob Change Biol 21:676–697

Veski S, Koppel K, Poska A (2005) Integrated palaeoecological and historical data in the service of fine-resolution land use and ecological change assessment during the last 1000 years in Rõuge, southern Estonia. J Biogeogr 32:1473–1488

Walker KJ, Preston CD, Boon CR (2009) Fifty years of change in an area of intensive agriculture: plant trait responses to habitat modification and conservation, Bedfordshire, England. Biodivers Conserv 18:3597–3613

Zhao Y, Yu ZC, Chen FH, Liu XJ, Ito E (2008) Sensitive response of desert vegetation to moisture change based on a near-annual resolution pollen record from Gahai Lake in the Qaidam Basin, northwest China. Glob Planet Change 62:107–114