ORIGINAL ARTICLE

# Using quantitative pollen-based land-cover estimations and a spatial CA_Markov model to reconstruct the development of cultural landscape at Rõuge, South Estonia

Anneli Poska · Edgar Sepp · Siim Veski · Kalev Koppel

**Abstract** Quantitative pollen-based land-cover reconstruction covering the last 4,000 years was performed using transformation coefficients derived from a modern pollen land-cover database and a palynological record from an annually laminated sequence in Lake Rõuge Tõugjärv. Proportions of four land-cover classes characteristic of cultural landscape were reconstructed: habitation area, arable land, grassland and woodland. A land-use change model using CA_Markov analysis was applied for spatial reconstructions for seven periods: 600 B.C., A.D. 300, 800, 1200, 1700, 1870 and 1940. Historical maps from A.D. 1684, 1870–1899 and 1935 were used for calibration of quantitative estimates and to validate spatial reconstructions. The accuracy of the estimates depends on the availability of modern analogues and differs among land-cover classes, being highest for classes with directly connectable pollen indicator types (arable land, forest) and lowest for settlement areas. Spatial reconstructions produced by the CA_Markov land-cover change model show moderate accordance with historical data. However, the large uncertainties in land-cover input data must be considered in the evaluation of the KIA results of the spatial model. Permanent low intensity, rural land-use in the Rõuge area started at the beginning of the Bronze Age (c. 1800 B.C.). The major increase in the extent of rural land-use took place at the beginning of the 13th century and culminated during the 19th century when c. 90% of the RSAP of Rõuge Tõugjärv was open. During the last century, rural land-use decreased constantly.

**Keywords** Pollen analysis · Historical data · Pollen land-cover transformation · CA_Markov model · Cultural landscape · Estonia

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## Introduction

Pollen analysis has been used as a tool for the examination and interpretation of qualitative human-induced changes in past land-cover since the publication of Iversen's (1941) *landnam* theory. One of the major goals of modern palaeoecology, however, is the development of quantitative pollen-based spatial reconstructions of past land-cover (e.g. Nielsen 2003; Broström et al. 2004). Since 2001, the NordForsk-financed POLLANDCAL community (http://www.geog.ucl.ac.uk/ecrc/pollandcal) has been addressing issues associated with pollen-landscape calibration. These issues concern the prediction of spatial scales for landscapes represented by pollen for different types of sampling sites (Sugita 1994; Bunting et al. 2004; Broström et al. 2005), pollen production and dispersal of major north European wind pollinated taxa (Broström et al. 2004; Bunting 2003; Nielsen 2003), and the use of modern and historical analogues to generate predictive models and

reconstructions of quantitative pollen/vegetation relationships (Gaillard et al. 1992; Sugita et al. 1999; Odgaard and Rasmussen 2000; Nielsen and Odgaard 2004).

In reconstructing the development of the cultural landscape, the value of combining historical, archaeological and (palaeo)ecological data is very high (e.g. Berglund 1991). Due to large spatial and temporal variations in rural land-use and settlement structure, reconstruction of agrarian landscapes is contingent on high-resolution, multidisciplinary case studies (e.g. Sarmaja-Korjonen 1992; Goslar et al. 1999). The critical requisite for such studies is the availability of relevant and reliable historical documents, archaeological material, ecological data and high-resolution, accurately dated palaeoecological data. The chronological and regional irregularity of historical sources (large-scale cadastral maps, historical census data, taxpayer lists, plough-land revisions, etc.) containing relevant information on historical land-use, settlement structure, demographic and economic parameters dictates the need for the combined application of different records (Joosten 1985; Petit and Lambin 2002; Nielsen and Odgaard 2004; Foster et al. 2002; Fuller et al. 1998; Goslar et al. 1999; Cousins 2001). However, $^{14}$C dates with error margins of ± 50–100 years are inadequate for direct comparison with historical data pinpointed to a certain datum. The use of laminated lake sediments with annual time-resolution is not essential but helps to provide a matching scale and thus a solution to the problem (Zillén et al. 2003; Goslar et al. 1999; Lotter et al. 2002). Another important issue concerning correlation of palaeoecological records with historical data is the complexity of resolving the difficulty of defining the spatial scale of the landscapes represented by pollen. There are several theories on the source area of pollen (SAP) in sediments (e.g. Davis 2000; Sugita 1994). The basic approaches range from attempts to define the SAP as an area from where all pollen grains deposited in a certain point originate, to the concept of the 'relevant source area of pollen' (RSAP), i.e. the distance from the site at which the fit between vegetation and pollen abundance no longer improves (Sugita 1994).

Advances in computer technology over the last decades have considerably improved the ability to analyze data in combination with modelling and the development of maps. Rapid development of GIS (geographical information system) applications since the mid–1980s has allowed integration of ecological, archaeological, sociological databases, etc. with spatial attributes. Recent developments in the POLLANDCAL network have stimulated more direct application of GIS in pollen-landscape modelling (e.g. Fyfe 2006). Land-use and cover change (LUCC) modelling is a rapidly advancing scientific field because land-use change is among the most significant human influences on the environment. LUCC models vary enormously in terms of their assumptions, including requirements for input data, spatial dependencies, and number of categories and transitions (Pontius and Malanson 2005). Spatially explicit models of land-use change generally focus on the rate of change between classes, on the assignment of change to classes, or on the combination of the rate and assignment of change between classes (Irwin and Geoghegan 2001). Models can be calibrated using data from previous periods and/or hypotheses of the driving factors affecting change. Output may be the likelihood of each cell converting to a given class (at an unspecified time) or predicted land-use at one or more (specified) dates. Spatio-temporal Markov Chain models can be used to model changes over time among categories in a landscape, whereby each cell in the landscape is designated as a particular category and each cell has a defined probability of transitioning to another category at each step. The cellular automata (CA) component of the CA_Markov model allows the transition probabilities of one cell to be a function of neighbouring cells (Pontius and Malanson 2005).

This study attempts to generate a quantitative pollen-based spatial reconstruction of land-cover changes at Rõuge, South Estonia from the onset of rural land-use at c. 2000 B.C. until modern times using historical cartographic material for calibration and validation. The CA_Markov model was used to predict spatial distribution of 4 land-cover classes at specific times.

## Study area

The South Estonian upland landscape is of glacial origin. The uplands are characterised by numerous hillocks with generally steep southern and gently sloping northern slopes reflecting the direction of ice movement. The ancient valley systems feature steep slopes and contain several deep and elongated lakes with almost complete sequences of Holocene annually laminated sediments (e.g. Veski et al. 2005; Niinemets and Saarse 2006). Lake Rõuge Tõugjärv (57° 44′ 20″ N, 26° 54′ 20″ E; 114 m a.s.l.) is a small lake (4.2 ha in area and 17 m deep) with 832 cm of annually laminated Holocene sediment, lying in a thermokarst depression of the ancient Rõuge valley (up to 75 m deep) of the Võru-Hargla system. Lake Tõugjärv is the lowest in a chain of six lakes connected by small streams (Fig. 1).

The present-day cultural land-cover is patchy and consists of an intricate mixture of forests, cultivated fields and grasslands with a small amount of woodland. The steepest slopes around the lake are covered by mixed forest and the more gentle slopes and plateaus by fields and grassland. Three deciduous (*Alnus* spp., *Betula* spp. and *Populus tremula*) and two coniferous (*Picea abies* and *Pinus sylvestris*) tree taxa comprise most of the woodlands. Various
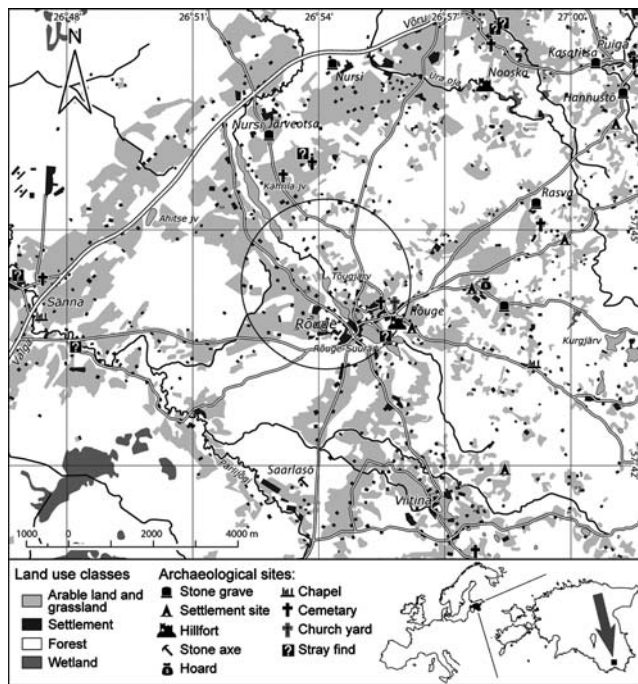
**Fig. 1** Location of the study area. Modern land-cover and antiquities in the Rõuge area. The *circle marks* the RSAP (*sensu* Sugita 1994) of Lake Rõuge Tõugjärv

cereals (*Secale cereale*, *Avena*, *Triticum* and *Hordeum*), potatoes (*Solanum tuberosum*), rape (*Brassica napus*) and clover (*Trifolium* spp.) are the main crops grown in the fields. Grasses (Poaceae) are abundant in both natural and cultural grasslands. The village of Rõuge is the centre of the historic Rõuge parish in south-east Estonia. The study area—with a total area of 30 km² —embraces two medieval manors: Rõuge manor, first mentioned in records from A.D. 1544, and Rõuge pastorate. The area forms a part of the densely populated prehistoric Ugandi County with a village and major stronghold dating back to the eighth to eleventh centuries A.D. (Fig. 1).

The extent of the investigation area is defined by the pre-calculated RSAP (*sensu* Sugita 1994) of Lake Rõuge Tõugjärv (Fig. 1). The RSAP of 100–200 m wide lakes in the South Estonian patchy cultural landscape extends c. 2,000 m from the centre of the lake (Veski et al 2005). The estimated size of the RSAP for Lake Rõuge Tõugjärv is similar to comparably sized basins in Denmark (Nielsen 2003).

## Materials and methods

### Fieldwork

Six parallel overlapping sets of 1 m cores were extracted from the 832 cm lake sediment sequence in March 2000.

Additionally, a frozen core was taken from the topmost unconsolidated sediment in 2001, yielding four 1 m long, 10 cm wide frozen sediment slabs.

### Chronology

The varve chronology extends from A.D. 1339 to 2000, with a cumulative ±9 year estimated error for the 661 year period. The chronology of the Lake Rõuge Tõugjärv sediments older than A.D. 1339 was extrapolated by combining an AMS ^{14}C date [wood from 358 cm below sediment surface 3230 ± 60 ^{14}C year B.P. (1420–1600 cal B.C.), Ua–19532] and varve age-depth estimations (see Veski et al. 2005).

### Pollen analysis

Samples of known volume were taken every ten varves from 0 to 124 cm (A.D. 1620–2000) and every 20 varves below that point. The pollen samples contained on average 3.4 annual laminations from A.D. 1300 to 2000. Older samples contained on average 7.2 annual laminations. Pollen sample preparation followed a standard acetolysis method combined with cold concentrated HF treatment to remove inorganic matter (Berglund and Ralska-Jasiewicz-owa 1986). At least 1,000 arboreal pollen grains were counted in each sample. Pollen data were calculated as percentages of the total terrestrial pollen. Charcoal particles were counted from pollen slides and measured along the longest axis. The diagrams were constructed using TILIA and TGView (Grimm 1991).

### Quantitative land-cover reconstruction

Quantitative land-cover reconstruction was performed using (1) a modern pollen/land-cover analogue database (MPLAD; unpublished) comprising pollen data from surface sediments from 30 small lakes in southern Estonia and detailed digital geobotanical maps (1:2,000 scale) within a radius of 2 km from the centre of each lake and (2) a palaeoecological record from Lake Rõuge Tõugjärv spanning the last 4,000 years. The pollen percentage and land-cover data from MPLAD were used to determine pollen/land-cover conversion coefficients (Table 1). The pollen of apophytes and antropochores in the pollen spectra were classified as suggested by Behre (1981) and adjusted to Estonian conditions by Poska (2001) into three groups:

1.  minor ruderal community indicators. *Rumex* was excluded from the sum because it is common both on meadows and on ruderal land in South Estonia;
2.  arable land indicators:
3.  meadow and pasture indicators.

**Table 1** Pollen land-cover transformation coefficients

| Settlement areas | | Arable land | | Grassland | | Forest | |
|---|---|---|---|---|---|---|---|
| Pollen (%) | Land-cover (%) | Pollen (%) | Land-cover (%) | Pollen (%) | Land-cover (%) | Pollen (%) | Land-cover (%) |
| 0–3 | 0–1 | 0–1 | 0–2 | 0–1 | 0–5 | 50–60 | 20–40 |
| 3–9 | 1–5 | 1–2 | 2–12 | 1–6 | 5–30 | 60–70 | 40–55 |
| | | 2–5 | 12–32 | 6–9 | 30–60 | 70–80 | 55–85 |
| | | 5–15 | 32–42 | | | 80–100 | 85–100 |

The percentage abundance of pollen determined the proportions of four land-cover classes representative of the cultural landscape:

1. settlement area, based on minor ruderal communities indicators;
2. arable land, based on sum of arable land indicators;
3. grassland, based on sum of meadows and pastures indicators;
4. forest, based on sum of *Alnus*, *Betula*, *Pinus* and *Picea* pollen percentages.

Changes in the pollen abundances in each group were plotted against changes in corresponding land-cover. The relationships depicted in these plots were then divided into intervals with linear regression. Due to the absence of analogues for more than 60% open agrarian landscape, conversion of tree pollen values below 70% found in palaeoecological record relied on coefficients derived from the Danish pollen–land-cover analogue database (Odgaard and Rasmussen 2000).

The pollen percentages from the palaeoecological record from Lake Rõuge Tõugjärv were combined into the previously described pollen groups and transferred to land-cover units using the transformation coefficients in Table 1. These percentages were adjusted to total 100%.

GIS modelling

GIS modelling was undertaken using Idrisi32. The spatial land-cover reconstruction was performed using a CA_Markov land-use change model. The spatial extent of the GIS analysis was limited to the RSAP of Lake Rõuge Tõugjärv with a cell size of 15 m. Four land-cover classes characteristic of rural landscape were modelled: settlement, arable land, grassland and forest. The hydrological network was assumed to remain static through the modelled period. The spatial distribution of land-cover was reconstructed for seven points in time (600 B.C., A.D. 300, 800, 1200, 1700, 1870 and 1940). The CA_Markov land-use change model parameters were as follows:

1. The input map (starting point of model) was set to represent only forested landscape to eliminate any influence of pre-determined emplacement of other land-cover types. The input map was masked by the water layer derived from the modern digital cadastral map. Changes in water layer are slight and slower compared to changes in other land-cover classes with different driving forces. As a compromise we assumed no changes in water layer and used the most recent situation on the digital cadastral map. For subsequent time scenarios, the output of the previous modelling session was used as input.
2. The factors for suitability maps—slope, soil class, distance from settlements, roads and water and their influence on the distribution of land-cover classes—were defined on the basis of research by Konsa (1999), Koppel (2005) and Remm (1999). These factors were converted into a relative scale to correspond to values from 0 to 255 for each land-cover class separately (Fig. 2). The higher the value of a factor on the relative scale, the more suitable that factor is for a specific land-cover class. Each modelled land-cover class has 3–5 factors that were unified and quantified into one suitability map per one land-cover class with the help of Saaty's Analytical Hierarchy Process (Saaty 2003, Table 2).
3. A neighbourhood filter (von Neumann (1966) with radius of two cells) was used for every modelled land-cover class to emphasize the impact of corresponding suitability maps in the areas where that land-cover class already exists. The filter was used to predispose the aggregation of pixels of each land-cover class reducing the so-called "salt and pepper pattern" effect. A neighbourhood filter radius determines the impact of the filter; a longer radius results in a greater aggregation effect. Empirical tests with different radii indicated that the best results were achieved with a radius of two cells.
4. Transition matrixes describing changes between different land-cover classes were created for all reconstructed time periods, since the degree of change and balance between different land-cover classes change over time.
5. The number of iterations, determined for every section independently, varied between one to five, depending

**Fig. 2** Suitability maps: **a** arable land, **b** – grassland, **c** – woodland, **d** settlement areas. The values from 0 to 255 correspond to increasing suitability
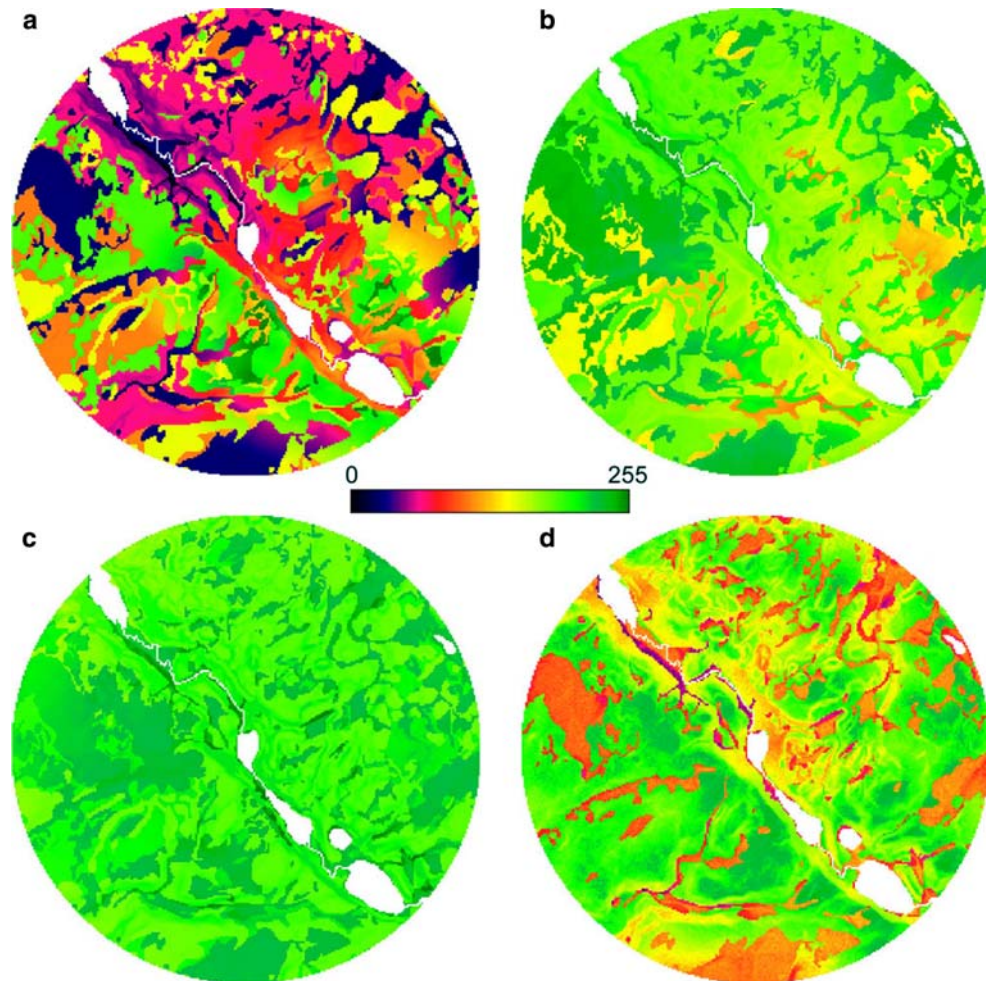


**Table 2** Factors and their weights used for construction of suitability maps

| Factor | Settlement areas | Arable land | Grassland | Forest |
|---|---|---|---|---|
| Soil | 0.45 | 0.64 | 0.64 | 0.70 |
| Slope | 0.25 | 0.10 | 0.13 | 0.10 |
| Distance from settlement | | 0.26 | 0.23 | 0.10 |
| Distance from roads | 0.10 | | | 0.10 |
| Distance from water | 0.10 | | | |
| Random map | 0.10 | | | |

on the length of the modelled section and the degree of change described by the transition matrix.

Thematic GIS layers

1. *Hydrology, settlement and road structure.* These were derived from the 1995 digital cadastral map and the soil map of the Estonian Land Board (both 1:10000) and were used to construct suitability maps. The soil map was reclassified into five rural land-value classes based on the agro-scheme by "Eesti Põllumajandus-projekt" (Kask 1996).

2. *Topographic model.* The topographic model was a 5 m raster derived from a TIN model (produced in MGE Terrain Analyst) based on 2 m interval contours. The topographic model contributed to the production of suitability maps.

3. *Historical maps.* A 1684 and 1870–1899 historic map (Eesti Ajaloo Arhiiv (EAA), 308-2-178; EAA, 2486-3-272, EAA, 3724-4-1917, EAA, 3724-5-2867) and a cadastral map (1:10,000) from 1935 were digitized within a radius of 2 km (the RSAP) from the centre of Lake Rõuge Tõugjärv (using Ocad and MapInfo). Land-cover categories on the maps were reclassified into five categories: settlement, arable land, grassland, woodland and water. The areas with transitional land-cover (arable land–forest), so called "brushwood" areas, were marked separately on historical maps.
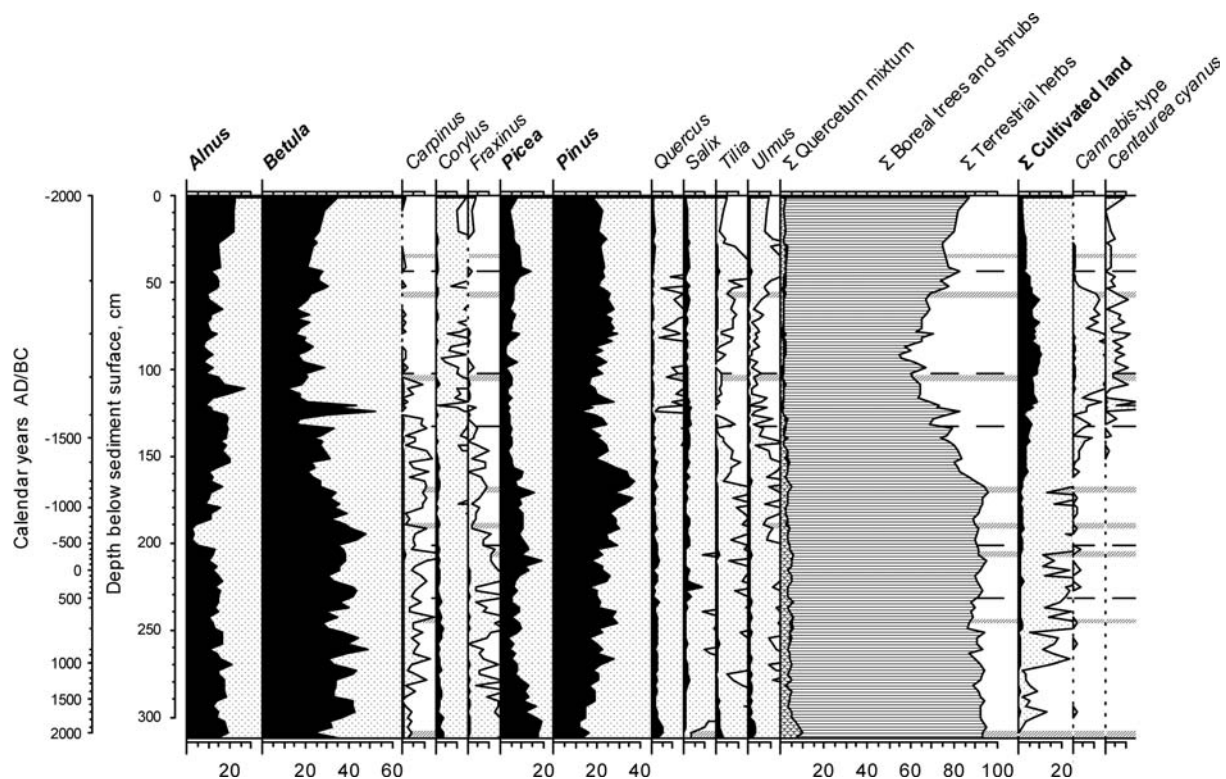
**Fig. 3** Pollen diagram of selected tree and herb pollen percentages. Grouping of pollen types into different land-use categories after Poska et al. (2004). The quantitative land-cover reconstruction is based on taxa marked in *bold*. *Dashed lines* mark the levels of spatial

reconstructions. Archaeological periods are according to Lang and Kriiska (2001). Historical periods show the periods of different regimes

## Results

### Pollen analysis

Evidence of permanent rural land-use in the RSAP of Lake Rõuge Tõugjärv appears from the start of the Bronze Age, around 1800 B.C. (Fig. 3), marked by the appearance of *Hordeum* and *Triticum* contemporary with a decline in *Picea*. At the same time ruderal plants (*Plantago lanceolata*, *Urtica*) suggest the establishment of habitation. Human impact (HI) indicators remain modest until the end of the Bronze Age, although the persistent presence of crop taxa combined with the continuous decline in *Picea* testifies to continuous agrarian activity in the area. During the Iron Age (500 B.C.–A.D. 1200/1250), the percentage of cultivation indicators increases, but remains less than 3%, with the total HI indicators not exceeding 5%. *Hordeum* and *Triticum* dominate the cultivation indicators. *Secale cereale* appears at 1000 B.C. and its presence becomes stable from the Middle Iron Age (A.D. 450). *Picea* abundance increases through the Iron Age to the end of the early Iron Age, then declines rapidly (from 15 to 5%), at which time an *Alnus* regression occurs. The amount of *Betula* and *Picea* pollen decreases from the beginning of the later Iron Age. *Pinus* reaches its maximum (35%) at the end of the Iron Age.

All HI indicators increase from the Middle Ages (c. A.D. 1200/1250), culminating in the 18th century at around 25%. *Secale* (up to 7%) dominates the cultivation indicators. Pollen of weed taxa (e.g. *Centaurea cyanus*, *Convolvulus arvensis*) associated with permanent fields persists from the 16th century. Regression in most HI indicators, accompanied by sharp changes in tree pollen (alternation of short-term regression and transgression phases in *Betula*, *Pinus* and *Alnus*), is evident at A.D. 1550–1600. The proportions of HI indicators decrease from the 18th century to present values comparable to those occurring during the Middle Ages. With respect to arboreal pollen, deciduous taxa (*Alnus* and *Betula*) increase, whilst coniferous taxa (*Pinus* and *Picea*) remain stable.

### Quantitative land-cover reconstruction

*Rumex acetosa/acetosella* type is a major component of the ruderals group, which drives the changes in the reconstructed area of settlement (Fig. 4). The reconstruction shows that the area occupied by settlement up to the Middle Ages was less than 1%, whilst the highest values (around 5%) occurred during the 18th and 19th centuries. A maximum of 10% at A.D. 1700 is the result of extraordinarily high *Urtica* values in one sample. Comparison with
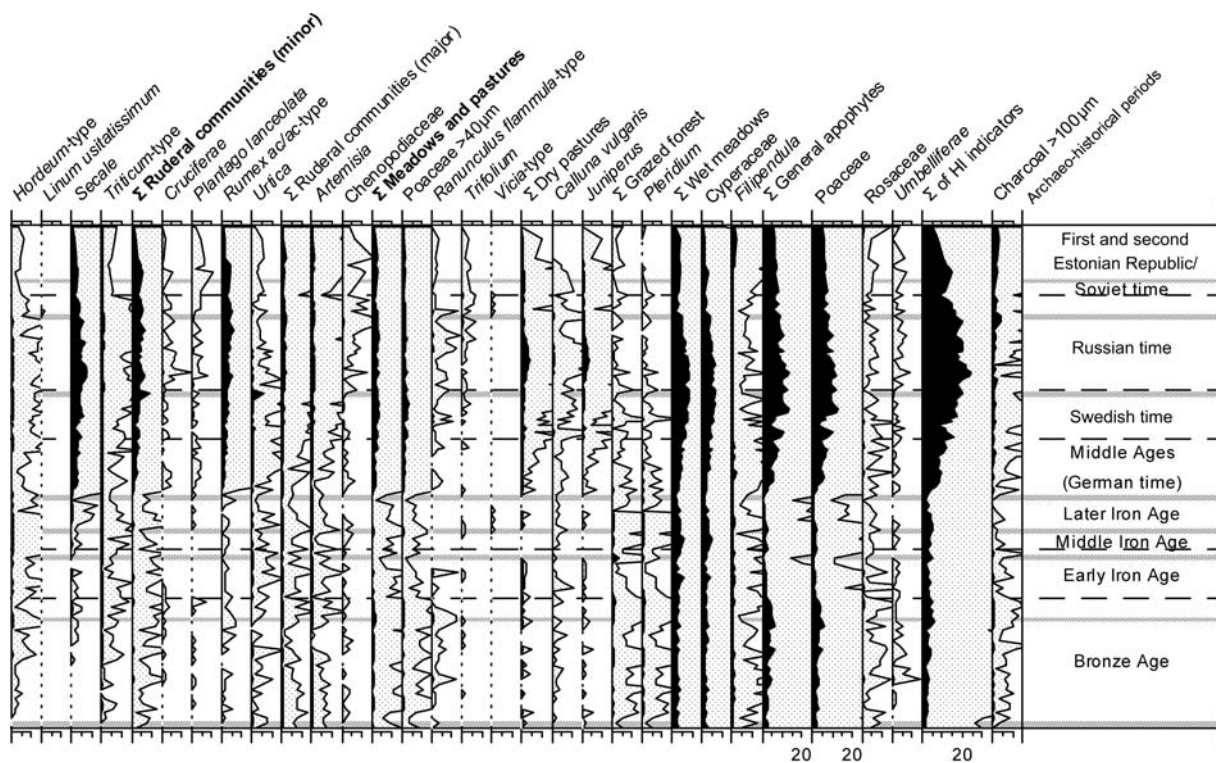
**Fig. 3** continued

historical data (Table 3) shows big discrepancies (error up to ±90%) between the reconstructed and real extent of the settlement area in this time period.

The proportion of arable land remains generally under 5% during the Bronze Age and early Iron Age. During the middle and later Iron Age the amount of cultivated land increased considerably, achieving stable values around 10%. The extent of arable land rises from 5 to 50% from the beginning of the Middle Ages up to the second half of the 18th century, followed by a continuous regression during the 19th and 20th centuries. Comparison with historical data (Table 3) reveals that from the 19th century onwards the reconstruction underestimates the extent of arable land over twofold.

The proportion of grassland is generally less than 5% during prehistoric times and varies between 5 and 15% during historic times. Comparison with historical data (Table 3) shows reasonable agreement between reconstructed and recorded values (error <20%). However, the comparison with the earliest historical map from 1684 shows a large discrepancy (error >75%).

Reconstructed woodland generally forms more than 90% of the land-cover during prehistory. The lowest values (<40%) of forest cover are recorded during the 17th century. Comparison with historical data (Table 3) shows discrepancies between the reconstructed and real extent of forest area leading to overestimation (up to 70%) of forest

cover during the 19th and 20th centuries and underestimation (c. 40%) at the end of the 17th century.

Spatial land-cover reconstruction

Spatial land-cover reconstruction was performed for seven time slices: 600 B.C. (end of the Bronze Age) and A.D. 300 (early Iron Age), 800 (end of the middle Iron Age), 1200 (end of the later Iron Age), 1680 (Swedish time), 1870 (Russian time) and 1935 (First Estonian Republic, Figs. 3, 4). During the prehistoric period, the reconstructions are placed at key break points in land-cover change. Reconstructions of historical period landscapes are placed at times with available cartographic material to facilitate validation of the approach.

All the prehistoric reconstructions place arable land-cover in the south-eastern part of the area (Fig. 5). Grasslands migrate from naturally open moist areas to upland rural areas, although this is an artefact of the transition rules defined by transition matrixes, which demand transformation of certain parts of arable fields into grassland. The placement of the settlement areas correlates well with the placement of arable land. The aggregation of settlement cells into relatively large groups was unavoidable for several reasons: the scarcity of land-cover involved, the small variation in total settlement area between the

**Fig. 4** Proportions of land-cover indicator pollen (see also Fig. 3) and reconstructed land-cover proportions. *Dashed lines* mark levels of spatial reconstructions. Archaeological periods are according Lang and Kriiska (2001). Historical periods show the periods of different regimes
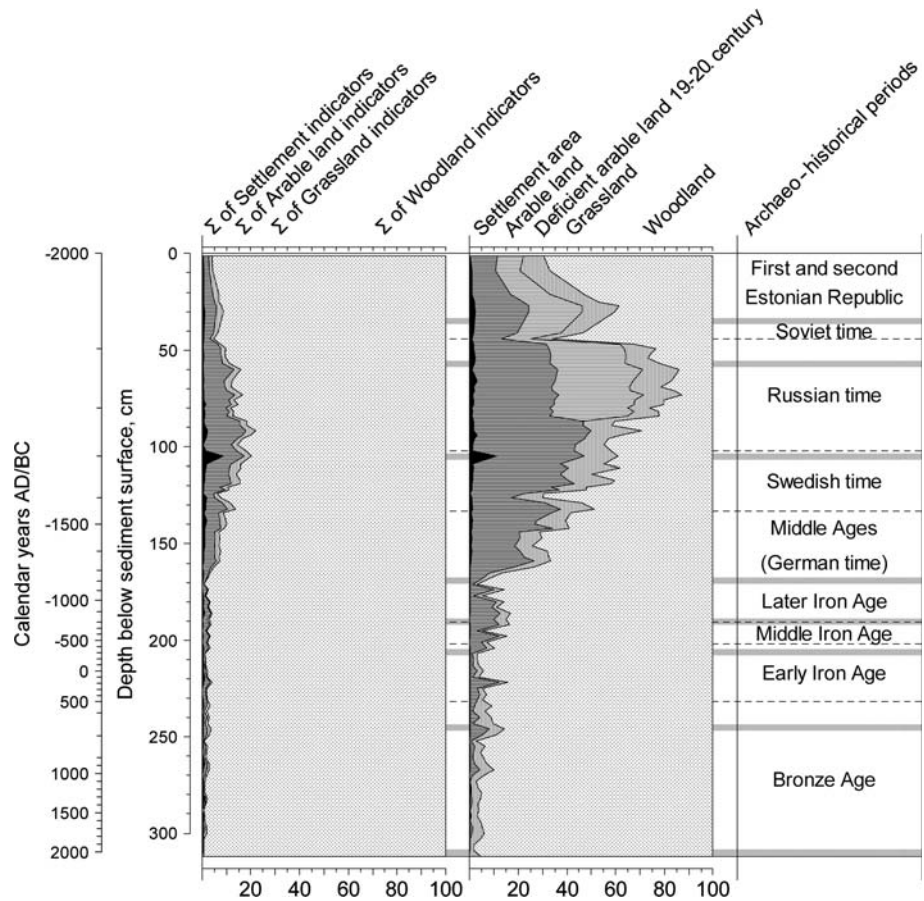


**Table 3** Comparison of pollen % and reconstructed land-cover proportions (three sample average closest to mapping time) with land-cover data on historical maps within the RSAP of Lake Rõuge Tõugjärv

| Years A.D. | Settlement areas | | | Arable land | | | Grassland | | | Forest | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | p (%) | lc (%) | hm (%)[1] | p (%) | lc (%) | hm (%) | p (%) | lc (%) | hm (%) | p (%) | lc (%) | hm (%) |
| 1684 | 3.8 | 1.2 | 0.2 | 7.3 | 36 | 24.1 | 2.5 | 16 | 3.6 | 57.3 | 41.9 | 68.6 |
| 1870–99 | 4.8 | 2.0 | 1 | 7.0 | 32.4 | 64.8 | 1.8 | 12.7 | 12.3 | 65.9 | 52.8 | 11.7 |
| 1935 | 4.7 | 1.8 | 2.2 | 3.5 | 21.2 | 54.8 | 1.6 | 12.3 | 15.7 | 69.2 | 63.1 | 24.8 |
| 1995 | 1.7 | 0.6 | 5.5 | 1.8 | 10.5 | 30.0 | 1.2 | 10.0 | 10.0 | 80.2 | 88.7 | 50.8 |

p (%) Percentage pollen data; lc (%) estimated land-cover proportions; hm (%) land-cover proportions derived from historical maps

reconstructions and the application of similar neighbourhood filters to all reconstructed land-cover classes.

The different land-cover classes form more scattered patterns during historic period reconstructions owing to large changes in land-cover. This also led to further "salt-and-pepper" (Fig. 6), exemplified at A.D. 1680 by the amount of arable land c. ten times greater than that of the previous reconstruction. The amount of arable land predicted by quantitative reconstruction since A.D. 1800 was doubled prior to spatial modelling to overcome the discrepancies between modelled and empirical values (Table 3) and to achieve more realistic spatial reconstructions. This value was calculated based on agrarian

land-cover in Rõuge county in 1926 (Rumma et al. 1926) and at Rõuge manor between 1880 and 1886 (EAA, 1400-1-184). According to these sources up to 50% of arable land was used for potato (*Solanum tuberosum*), flax (*Linum usitatissimum*) and clover (*Trifolium* spp.) cultivation, a widespread phenomenon in South Estonia during the 19th and 20th centuries. The reconstructions place most of the arable land in the southern, south-eastern and western parts of the area, leaving the north and north-east wooded. Historical maps show generally similar trends with the exception of the northern part of the area, where arable land-cover is greatly underestimated between A.D. 1870 and 1940. The historical maps and reconstructions were
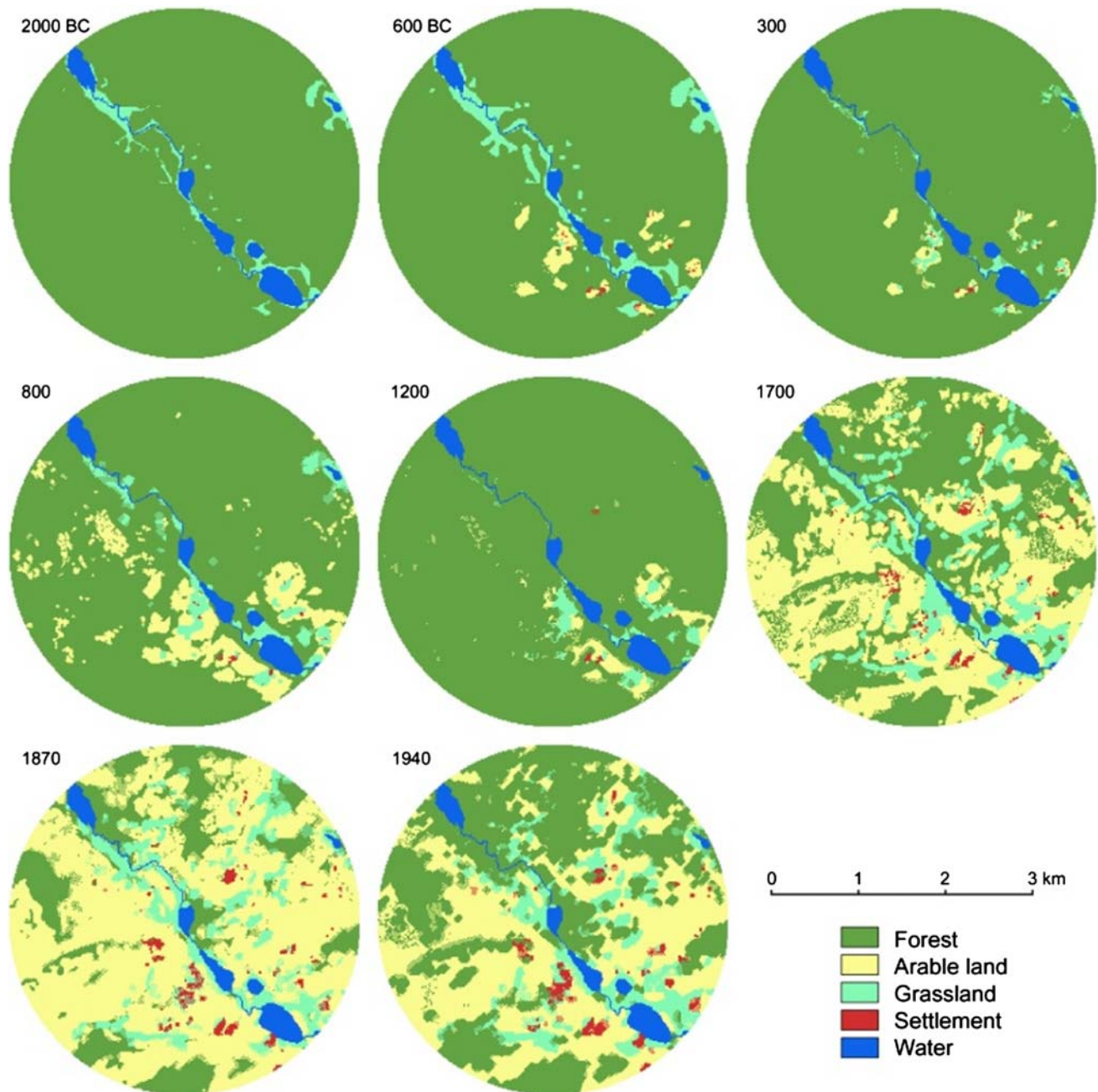
**Fig. 5** Spatial reconstructions of land-cover in RSAP of Lake Rõuge Tõugjärv

compared via cross-tabulation and a Kappa Index of Agreement (KIA) (Table 4). The KIA ranges between –1 (negative correlation) to +1 (positive correlation); values around 0 indicate no correlation between compared maps. The comparison of modelled land-cover with historical maps reveals that the overall agreement is positive but poor. The placement of arable land corresponds best to the real situation, whereas no agreement was found for settlement (Table 4). The reconstructed land-cover corresponds most closely to the historical reference maps in the south–south-

eastern part of the area (Fig. 6), with the lowest correspondence in the northern and north-eastern part.

## Discussion

Quantitative pollen-based spatial reconstructions

Quantitative pollen-based land-cover reconstructions are affected by several limitations including impact of regional vegetation cover, size of representative area, distance
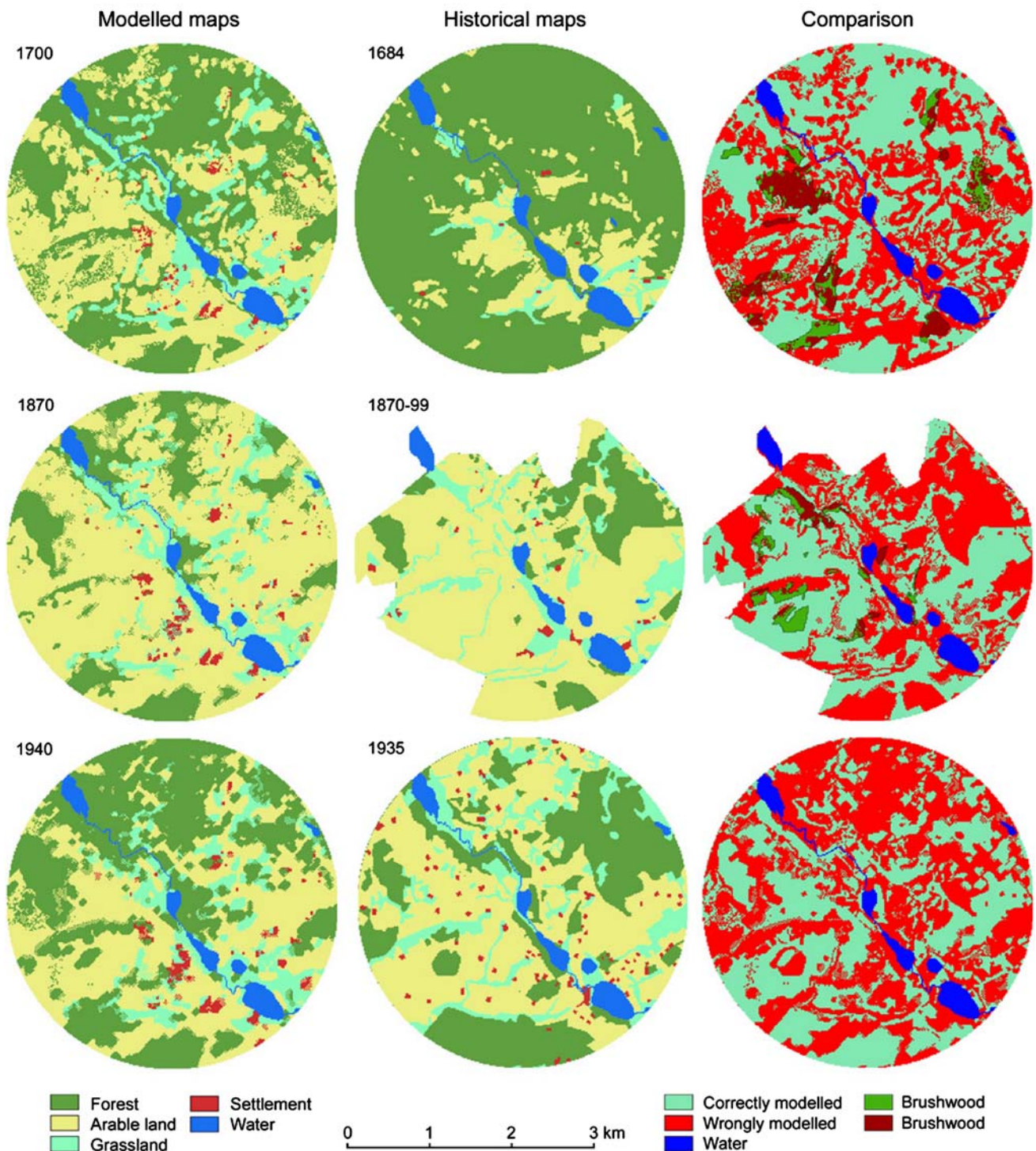
Fig. 6 Spatial reconstructions of land-cover, historical maps and results of cross-tabulation in RSAP of Lake Rõuge Tõugjärv

dependence of pollen-land-cover relations, selection of pollen types to represent land-cover categories, and an inability to reproduce the extent of non-pollen producing areas. Furthermore, the modern pollen-land-cover analogue approach is affected by a lack of suitable modern analogues

to past land-cover arrangements. A possible solution to this lack is the use of historical data to derive analogues for those landscapes presently unavailable (Nielsen 2003).

The CA_Markov model is based on an assumption that land-use at time $t + 1$ is based on land-use at time $t$ and on

**Table 4** KIA (Kappa index of agreement) test results: historical versus reconstructed maps

|                 | 1684   | 1870   | 1935   |
|-----------------|--------|--------|--------|
| Settlement areas | 0.0265 | 0.0235 | 0.0149 |
| Arable land      | 0.3909 | 0.5331 | 0.3173 |
| Grassland        | 0.3100 | 0.1951 | 0.0944 |
| Forest           | 0.2554 | 0.1574 | 0.2996 |
| Overall Kappa    | 0.2175 | 0.3648 | 0.2137 |

a set of rules that take into account changes in and between land-use classes, the suitability of cells and land-use in neighbouring cells. In this regard, it is a simple and straightforward approach. However, it does not consider changes to driving factors, does not sufficiently differentiate between suitable locations and does not allow differentiation of neighbourhood filter rules. The extent of settlement area is difficult to reconstruct based solely on pollen data, because no definite palynological indicators are associated with habitation areas. Although ruderals offer the best indicators (e.g. Behre 1981), they are typically associated with nitrogen-rich environments and/or disturbed biotopes connected rather by fallow and wasteland than by settled area. However, because the aim of this approach was to reconstruct a rural landscape with isolated farmsteads (with their relatively high nitrogen-rich on site waste production per unit compared to villages or towns), ruderals can be used—with caution—to determine the portion of settlement area. Nevertheless, this approach tends to overestimate the extent of early agrarian settlement and fails to represent changes in the settlement area of non-agrarian landscape that includes recreational areas and nucleated settlement (Tables 3, 4; Fig. 6).

The spatial reconstruction of the location and structure of the settlement area within rural landscapes over long periods is difficult due to its negligible size compared to other land-cover classes and its variation in site selection preferences through time. This study focussed on natural factors and excluded other drivers (e.g. socio-economic forces, culture and religion); consequently, the results of the reconstruction of settlement areas are unsatisfactory.

The arable land-cover reconstruction was based on the pollen sum of cultivated taxa, dominated by cereals (*Avena*, *Hordeum*, *Triticum* and *Secale cereale*). Other cultivated crops (e.g. *Linum usitatissimum*, *Solanum tuberosum*, Fabaceae, *Fagopyrum*, forage roots, etc.) are low pollen producers and/or distributors or are harvested prior to blossoming, and therefore are poorly represented in the pollen record. Comparison of the reconstructed scale of arable land-cover with historical maps suggests transformation coefficients for arable land underestimate the portion of arable land since A.D. 1800 by approximately half (Table 3). This is likely to be a combination of numerous factors including:

1. Changes in crop plants. Potato (*Solanum tuberosum*) cultivation gained popularity in the 19th century, a period also characterised by widespread flax (*Linum usitatissimum*) cultivation. Rape (*Brassica napus*) is now common in South Estonia.

2. Changes in the human diet and economy. Potatoes partially replaced cereals in the human diet leading to reductions in *Secale cereale* cultivation. A shift to cattle breeding began in the 17th century and by the beginning of the 20th century, milk and meat production were widespread. This resulted in changes in the proportion of draught animals to cattle (Koppel 2005), which led to a need for an increase and intensification of forage production. For example, clover (*Trifolium* spp.) occupied 20% of the cultivated land at Rõuge manor between 1880–1885 (EAA, 1400-1-184. L 1).

3. Change in agrarian technology. The steep topography of the local landscape resulted in a shift of arable land-use to the margins of the RSAP of the lake, and the local topography favours cattle breeding over crop cultivation in a mechanised agrarian system.

Regardless of the complexity of the quantification of arable land, the best fit in comparison with historical maps was achieved for this land-cover class both by visual inspection and statistical analysis (Table 4). The quality of this fit appears to be related to soil quality: the best soils (south to south-west) fit well; poorer soils fit less well (Fig. 6). It is probable that other factors were more important than natural conditions on more marginal soils.

The existence of at least partially open natural meadows could be expected to predate the expansion of agrarian land-use owing to the presence of low wet areas around and between the lakes in the area. A consequence of using the meadow and pasture indicator (excluding wet meadow indicators) as a basis for the pollen/land-cover transformation is that the extent of (natural) meadows is probably underestimated. Furthermore, the expansion of agrarian economic activities, such as mowing and grazing, would effectively decrease the production and spread of pasture taxa, leading to under-representation of this land-cover type. The historical data on cattle rearing at Rõuge manor, based on Land revisions and Wackenbücher from A.D. 1627, 1638, 1688, 1721, 1744, 1750, 1758, 1805 and 1814 (Rebane 1941; Roslavlev 1965; RA Ö J 1589-1682; EAA, MF 37-1-17, 85; EAA, MF 2-1-35; EAA, 567-1-275; EAA, 567-1-801) show that the extent of grassland must have been underestimated on the historical maps from the end of the 17th century. The portrayed grassland area (Fig. 6) would have been insufficient to produce enough fodder for the registered livestock, even if supplemented by woodland as an additional grazing area, a widespread practice in South Estonia up to the beginning of the last century.

Accordingly, the largest discrepancy between the pollen-based reconstructions and the documentary evidence for the extent of grasslands is registered at the end of the 17th century (Table 3), in which the reconstructed grassland area is about four times greater than that indicated by the historical data.

The use of cultivated grassland may explain the relatively low amount of grassland registered during the agrarian boom period during the 19th century. Clover (*Trifolium* spp.) was one of the major crops in South Estonia from at least the 19th century. Historical data shows that in A.D. 1880–1885 at least 20% of arable land in Rõuge manor was under clover cultivation (EAA, 1400-1-184. L 1) and in 1925 at least 20% of arable land was used for hay production (Rumma et al. 1926). The spatial reconstructions show that natural grasslands, placed on the initial map in the swampy areas surrounding water bodies, tend to migrate to higher ground during modelling. Historical data shows that both types of grasslands existed in the Rõuge area throughout history. The reasons for this discrepancy may lie in the defined suitability factors (Table 2), especially in the relatively high importance placed on distance to the nearest settlement area. However, visual inspection of the reproduced landscape pattern shows some agreement between the reconstructions and historical data (Fig. 6), and KIA, although lower than that achieved for arable land, shows a positive correlation.

Estimation of the extent of woodland based on pollen percentage data is complicated in the boreal forest zone. The fact that the quantitative reconstruction of woodland area based on transformation coefficients fits well (mean error ±5%, maximum 20%) with values derived from the formula woodland area = 100–Σ (settlement, arable land and grassland) is encouraging. The largest discrepancies appear during the last 200 years. However, the part of the pollen rain contributed by wind-pollinated tree species is influenced heavily by the regional (background) pollen component. Modern pollen/land-cover analogues from South Estonia demonstrate the complexity of the problem. Landscapes which are locally >70% open but regionally <50% open still feature total arboreal pollen >80%. Interdependence of percentage-based data further complicates the problem (Fyfe 2006); for example, real decline in herbaceous pollen influx will lead to an artificial inflation of arboreal percentages. The observed discrepancy between the estimated and measured woodland area during the last 200 years could be to some extent a consequence of a reduction in open land pollen production due to intensification of agrarian land-use and the introduction of new species (see above). In addition, changes in forest management and rural land-use practices may have led to changes in spatial distribution of land-cover types.

Comparison of reconstructed woodland cover with historical maps reveals several discrepancies, particularly in the north-eastern part of the reconstructed area, where woodland persists through the historic period (Fig. 6). This probably reflects the complex relationship between natural conditions and socio-economic factors and/or a "bad" model. During the initial stage of arable farming in the Rõuge area, soil type controls the distribution of woodland. However, historical data show that during the expansion phase of arable land-use during the 18th–20th centuries, the area could have been used for crop cultivation in the same manner as the rest of the region. Historical documents show that at least from the 17th century up to the beginning of the 20th century this forest, known as *church forest*, belonged to the Church and was kept untouched. Thus, socio-economic factors became the primary driver in this area during this period.

Development of cultural landscape

The relatively slow paced introduction of cultivation during the Bronze Age is in good agreement with the available archaeological data from the area. Small areas of light and fertile soils in the south and south-eastern part of the investigation area were cleared for wheat and barley cultivation within a broadly forested landscape. These small clearings were created through slash-and-burn methods with long regeneration periods. The Late Bronze Age intensification of rural land-use known from other parts of Estonia (Veski and Lang 1996; Poska and Saarse 1999) is also clearly recognisable at Rõuge. The increase in the presence of charcoal and varying presence of cultivated taxa (now including sporadic appearances of *Secale cereale*) suggest that slash-and-burn agriculture remained the major cultivation method in the area. The short-term expansions of the reconstructed agrarian land-cover during this time are more likely to reflect spatial patterning of cultivation plots than the intensification of agrarian land-use in general, i.e. cultivation began closer to the lake and is thus represented better within the RSAP of the lake. During the Iron Age landscape clearance continued, culminating between A.D. 700 and 1000, a relatively stable period when about 10% of the investigation area was occupied by arable land. The spatial reconstruction places most of the arable land in the southern part of the area. This intensification phase, clearly visible in quantitative land-cover reconstruction despite being hardly detectable on the pollen diagram, is in perfect agreement with the known archaeological evidence of land-use, coinciding with the habitation of the Rõuge settlement and stronghold (Jaanits et al. 1982). The clear regressions in the quantitative reconstruction during

the initial and terminal phase of the stronghold period are probably indications of repeated attacks leading to social contraction at the end of the Iron Age. The period around A.D. 1200 was exceptionally rich in armed conflicts and depredations by Russians, Latvians and Germans, concluding with the German conquest and the Christianisation of the Estonians. This restless period led to a decline in arable land-use to the levels of the Early Bronze Age. With the establishment of serfdom and development of a manor-based economy at the beginning of the Middle Ages, agrarian land-use expanded rapidly. However, the magnitude of the apparent change in quantitative reconstruction of land-cover may be exaggerated due to the start of extensive rye cultivation. Pollen production of self-pollinating plants, such as wheat, has been demonstrated to be much less than open-pollinated crops, such as rye. Wheat plants only produce one-tenth of the pollen of rye plants (D'Souza 1970). The expansion of agrarian land-use continues with some short-term regressions up to the beginning of the 19th century, culminating in an arable-dominated (c. 60%) landscape, which is nearly 90% open. Archaeological finds of the remains of permanent field structures in northern Estonia date back to the end of Bronze Age (Lang 1999). Similar structures are lacking in South Estonia and the timing of appearance of permanent fields is difficult to pinpoint, although increasing proportions of weed taxa suggest that the fieldscape was established within the Middle Ages. The high charcoal input indicates increasing usage of slash-and-burn agriculture. The parallel use of both cultivation types was common in South Estonia up to the beginning of the 20th century with both long (c. 50–100 year cycling) and short (15 year) slash-and-burn methods (Pille Tomson, personal communication). A separate land-cover class (bushland) is denoted on historical maps from the 18th and 19th centuries (forming c. 1/4 of total arable land area) and correspond to a reserve of arable land not continuously cultivated but available for short interval slash-and burn practice (Koppel 2005). Slash-and-burn cultivation was used in South Estonia up to the end of the Second World War. Large-scale decline during 19th and 20th century in arable land-use intensity is apparent in all new detailed pollen records from this region (e.g. Niinemets and Saarse 2006, 2007). This general decrease in arable land cover was caused by a transition from extensive land-use to intensive use of fertilisers and is also noted in historical data. The magnitude of change, however, is not comparable with that suggested by the pollen record. This discrepancy may result from a combination of factors, influencing the pollen signal of arable land-cover already discussed.

Cataclysms, such as war, famine and disease, have interrupted the general increase in population, resulting in short term variations within the cultural landscape. Several pronounced regressions visible in quantitative land-cover reconstruction from the Rõuge area could be correlated with known historical events: the destruction of the Rõuge stronghold (c. A.D. 1000), the German conquest (1227), the Livonian war (1558–1583) and the Estonian War of Independence (1918–1920). However, several known events (e.g the Great Northern War between 1700–1721 and the Second World War) left no traces of similar magnitude.

## Conclusions

1. It is possible to estimate changes in proportions of past cultural land-cover based on the results from fossil pollen data and modern pollen—land-cover analogues. However, there are great differences in the quality of estimations between land-cover classes. The method works best for classes with clear pollen indicator types (arable land, forest) but has little application for non-pollen producing surfaces and classes without clear pollen indicator types (settlement areas). The reliability of past land-cover reconstruction is also highly dependent on the availability and representativeness of modern analogues.

2. The CA_Markov land-cover change model can be applicable for spatial land-cover reconstructions of past land-use. However, some of its characteristics (fixed driving factors, neighbourhood filter rules, etc.) may complicate its application and lower the quality of reconstructions. The best results were achieved when moderate changes were considered. The quality of reconstructions was poorest when periods or classes with exceptionally high or low variability of land-use were considered. In such cases the appearance of a "salt-and-pepper" effect and/or lumping up was inevitable.

3. The application of historical and archeological data for calibration and validation of reconstructions is desirable if realistic reconstructions of the development of the cultural landscape are expected.

4. Permanent low intensity rural land-use began in the Rõuge area at the beginning of the Bronze Age (c. 1800 B.C.). A major increase in the extent of rural land-use started at the beginning of the 13th century A.D. and culminated during the 19th century A.D. with c. 90% of the RSAP of Rõuge Tõugjärv being open. During the last century, arable land-use has been constantly decreasing. Currently the open land represents c. 30–40% of the land-cover.

5. Even short duration cataclysms, such as wars, are detectable on past land-cover reconstructions based on high resolution pollen data with good time control.

# References

Behre KE (1981) The interpretation of anthropogenic indicators in pollen diagrams. Pollen Spores 23:225–245

Berglund BE (ed) (1991) The cultural landscape during 6,000 years in southern Sweden—the Ystad project. Ecological Bulletins 41, Munksgaard, Copenhagen

Berglund BE, Ralska-Jasiewiczowa M (1986) Pollenanalysis and pollendiagrams. In: Berglund BE (ed) Handbook of Holocene palaeoecology and palaeohydrololology. Wiley, Chichester, pp 455–484

Broström A, Sugita S, Gaillard M-J (2004) Pollen productivity estimates for reconstruction of past vegetation cover in the cultural landscape of Southern Sweden. Holocene 14:371–384

Broström A, Sugita S, Gaillard M-J, Pilesjö P (2005) Estimating spatial scale of pollen dispersal in the cultural landscape of southern Sweden. Holocene 15:1–14

Bunting MJ (2003) Pollen-based reconstruction of cultural landscapes: an investigation of pollen source area for non-arboreal taxa. Rev Palaeobot Palynol 125:285–298

Bunting MJ, Gaillard MJ, Sugita S, Middleton R, Broström A (2004) Vegetation structure and pollen source area. Holocene 14:651–660

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

Davis MB (2000) Palynology after Y2K—understanding the source area of pollen in sediments. Ann Rev Earth Planet Sci 28:1–18

D'Souza VL (1970) Investigations concerning the suitability of wheat as pollen-donor for cross-pollination by wind compared to rye, Triticale, and Secalotricum. Z Pflanzenzücht. 63:246–269

Foster DR, Hall B, Barry S, Clayden S, Parshall T (2002) Cultural, environmental and historical controls of vegetation patterns and the modern conservation setting on the island of Martha's Vineyard, USA. J Biogeogr 29:1381–1400

Fuller JL, Foster DR, McLachlan JS, Drake N (1998) Impact of human activity on regional forest composition and dynamics in central New England. Ecosystems 1:76–95

Fyfe RM (2006) GIS and the application of a model of pollen deposition and dispersal: a new approach to testing landscape hypotheses using the POLLANDCAL models. J Archaeol Sci 33:483–493

Gaillard M-J, Birks HJB, Emanuelsson U, Berglund BE (1992) Modern pollen/land-use relationships as an aid in reconstruction of past land-uses and cultural landscapes: Example from south Sweden. Veget Hist Archaeobot 1:3–17

Goslar T, Ralska-Jasiewiczowa M, Geel B van, Łacka B, Szeroczynska K, Chrost L, Walanus A (1999) Anthropogenic changes in the sediment composition of Lake Gosciaz (central Poland), during the last 330 yrs. J Paleolimnol 22:171–185

Grimm EC (1991) TILIA and Tilia graph. Illinois State Museum, Springfield

Irwin EG, Geoghegan J (2001) Theory, data, methods: developing spatially explicit economic models of land use change. Agric Ecosyst Environ 85:7–23

Iversen J (1941) Land occupation in Denmark's Stone Age. Danmarks Geol Unders, Ser 2. 66:1–65

Jaanits L, Laul S, Lõugas V, Tõnisson E (1982) Eesti esiajalugu (Estonian prehistory). Valgus, Tallinn

Joosten JHJ (1985) A 130 year micro- and macrofossil record from regeneration peat in the Peel, The Netherlands: a palaeoecological study with agricultural and climatological implications. Palaeogeogr Palaeoclimatol Palaeoecol 49:277–312

Kask R (1996) Eesti mullad (Estonian soils). Mats, Tallinn

Konsa M (1999) Geograafilise infosüsteemi kasutamine arheoloogias Rõuge kihelkonna näitel (The application of geographic information systems in archaeology on the example of Rõuge parish). Peaseminaritöö, Tartu University, Tartu

Koppel K (2005) Maakasutuse uurimise metoodika Kasaritsa uurimisala (Rõuge kihelkond) 17–19. sajandi külamaastike kujunemise näitel [The research methods of historical land use as exemplified by the formation of rural landscapes on Kasaritsa study area (Rõuge parish) in 17th–19th centuries. Msc thesis, Tartu University, Tartu

Lang V (1999) The introduction and early history of farming in Estonia, as revealed by archaeological material. In: Miller U, Hackens T, Lang V, Raukas A, Hicks S (eds) Environmental and cultural history of the Eastern Baltic Region, vol 57. PACT, Rixensart, pp 325–338

Lang V, Kriiska A (2001) Eesti esiaja periodiseering ja kronoloogia (Periodisation and chronology of Estonian prehistory). Eesti Arheoloogia Ajakiri 5(2):83–109

Lotter AF, Appleby PG, Bindler R, Dearing JA, Grytnes JA, Hofmann W, Kamenik C, Lami A, Livingstone DM, Ohlendorf C, Rose N, Sturm M (2002). The sediment record of the past 200 years in a Swiss high-alpine lake: Hagelseewli (2339 m a.s.l.). J Paleolimnol 28:111–127

Nielsen AB (2003) Pollen based quantitative estimation of land cover—relationships between pollen sedimentation in lakes and land cover as seen on historical maps in Denmark AD 1800. Ph.D. thesis, Univ Copenhagen and Geol Surv Denm Greenl. Danmarks og Grønlands geologiske undersøgelse rapport 57

Nielsen AB, Odgaard BV (2004) The use of historical analogues for interpreting fossil pollen records. Veget Hist Archaeobot 13:33–43

Niinemets E, Saarse L (2006) Holocene forest dynamics and human impact in southeastern Estonia. Veget Hist Archaeobot 16:1–13

Niinemets E, Saarse L (2007) Fine-resolution pollen-based evidences of farming and forest development, southeastern Estonia. Pol J Ecol (in press)

Odgaard BV, Rasmussen P (2000) Origin and temporal development of macro-scale vegetation patterns in the cultural landscape of Denmark. J Ecol 88:733–748

Petit CC, Lambin EF (2002) Impact of data integration technique on historical land-use/land-cover change: comparing historical maps with remote sensing data in the Belgian Ardennes. Landsc Ecol 17:117–132

Pontius GR, Malanson J (2005) Comparison of the structure and accuracy of two land change models. Int J Geogr Inf Sci 19:243–265

Poska A (2001) Human impact on vegetation of Coastal Estonia during the Stone Age. Acta Universitatis Upsaliensis, Uppsala, pp 1–48

Poska A, Saarse L (1999) Holocene vegetation and land-use history in the environs of Lake Kahala, northern Estonia. Veget Hist Archaeobot 8:185–197

Poska A, Saarse L, Veski S (2004) Reflections of pre- and early-agrarian human impact in the pollen diagrams of Estonia. Palaeogeogr Palaeoclimatol Palaeoecol 209:37–50

Rebane H (1941) Liivimaa 1638. a. maarevisjon Eesti asustusalaI. Kaguosa [Land revision of Livland in 1638]. ENSV Riigi Keskarhiivi Tartu osakonna toimetused 1:195–200

Remm K (1999) Reeglipärasusi Otepää kõrgustiku maastikumustris Eesti põhikaardi lehe 5434 näitel [Regular patterns in landscape of Otepää Heights, example from page 5434 of the Estonian cadastrial map. Msc thesis, Tartu University, Tartu

Roslavlev O (1965) Das Dorpater Land 1624/27. Hefte zur Landeskunde Estlands. Wolfratshausen-Waldram, München

Rumma J, Tammekann A, Veski JV (1926) Võrumaa. Maateaduslik, tulunduslik ja ajalooline kirjeldus, Eesti 2. Eesti Kirjanduse Selts, Tartu

Saaty TL (2003) Decision-making with AHP: Why is the principal eigenvector necessary. Eur J Oper Res 145:85–91

Sarmaja-Korjonen K (1992) Fine-interval pollen and charcoal analyses as tracers of early clearance periods in S Finland. Acta Bot Fenn 146:1–75

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

Sugita S, Gaillard M-J, Broström A (1999) Landscape openness and pollen records: a simulation approach. Holocene 9:409–421

Veski S, Lang V (1996) Prehistoric human impact in the vicinity of Lake Maardu, Northern Estona. A synthesis of pollen analytical and archaeological results. In: Hackens T, Hicks S, Lang V, Miller U, Saarse L (eds) Coastal Estonia. Recent advances in environmental and cultural history, vol 51. PACT, Rixensart, pp 189–204

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, S Estonia. J Biogeogr 32:1473–1488

von Neumann J (1966) Theory of self-reproducing automata. University of Illinois Press, Urbana, IL

Zillén L, Snowball I, Sandgren P, Stanton T (2003) Occurrence of varved lake sediment sequences in Värmland, west central Sweden: lake characteristics, varve chronology and AMS radiocarbon dating. Boreas 32:612–626