



DISSERTATIONES GEOLOGICAE UNIVERSITATIS TARTUENSIS

22

**VEGETATION AND LAND-USE HISTORY  
OF THE HAANJA HEIGHTS (SE-ESTONIA)  
DURING THE HOLOCENE**

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PRESS

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This dissertation is accepted for the commencement of the degree of Doctor of Philosophy (in Geology) at the University of Tartu on 18.02.2008 by the Council of Faculty of Science and Technology of the University of Tartu.

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This thesis will be defended at the University of Tartu, Vanemuise 46, room 246, on 11.04.2008.

Publication of this thesis is granted by the Institute of Ecology and Earth Sciences, University of Tartu.



The publication of the current thesis was supported by the Doctoral School of Ecology and Environmental Sciences created under the auspices of European Union Social Fund structural funds measure 1.1. Educational System Supporting the Flexibility and Employability of the Labor force and Providing of Lifelong Learning for All.

ISSN 1406–2658

ISBN 978–9949–11–825–0 (trükis)

ISBN 978–9949–11–826–7 (PDF)

Autoriõigus Eve Niinemets, 2008

Tartu Ülikooli Kirjastus

[www.tyk.ee](http://www.tyk.ee)

Tellimus nr 86

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## ABSTRACT

The discovery of laminated lake sediments in southeastern Estonia initiated an extensive high-resolution study of vegetation dynamics, including attention to the human impact in this region (Veski *et al.* 2004, 2005; Niinemets & Saarse 2006, 2007a, b). The aim of the study was to prove the annual character of laminae, precise reconstructing of vegetation history of the upland area, investigation of pollen profiles together with archaeological and historical data to reveal human impact on vegetation since the introduction of agriculture, and to detect from pollen profiles and sedimentological data the major climatic or other events.

The present thesis is a part of this study and focuses on:

- 1) the vegetation history of the upland area of southeastern Estonia,
- 2) the human impact on vegetation,
- 3) the nature of sedimentation in small lakes of the upland mosaic landscapes in southeastern Estonia.

Three sediment profiles in south-eastern Estonia were studied sedimentologically and palynologically: Lake Plaani in the centre of the Haanja Heights, Lake Verijärv on the slope of the Haanja Height, and Lake Lasva in an ancient buried valley at the foot. Time-scales were constructed from conventional and AMS  $^{14}\text{C}$  dates, and varve counting.

The combined results of the varve counts with  $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$  and  $^{241}\text{Am}$  analysis show that the sedimentary sequences of L. Verijärv and Lasva are laminated annually. High sedimentation rates and laminated structures enabled the completion of a high-resolution palaeoecological study and comparison of pollen records with historical data.

An abrupt change in sediment composition in L. Verijärv (a decrease in mineral matter and an increase in carbonates) about 10,000 cal BP obviously reflects the isolation of the lake. In L. Verijärv, the increase of mineral matter content between 1000 cal BP and present is marked as a two-peaked event, which may reflect diminished human activity near the lakeshores. An increase in organic matter content during the last 100 years in all lakes is probably related to increased use of chemical fertilizers, which resulted in increased organic production in the lakes.

The vegetation dynamics in SE Estonian uplands has several distinctive features compared with lowland regions of Estonia, such as the earlier arrival of *Picea*, *Ulmus* and *Quercus*, stable broad-leaved woods due to suitable habitats in the mosaic landscape and later human influence. Haanja Heights seems to have served as an immigration bridge between south and north. Most of the tree taxa that immigrated from south were present earlier than in lowland localities at the same latitude. Comparison of the tree pollen immigration and distribution patterns in L. Plaani and L. Verijärv reveals a clear south-north shift in dynamics of thermophilous taxa (*Ulmus*, *Tilia*, *Quercus* and *Fraxinus*). This spreading

order of tree taxa is coincident with the transition from the highest areas to the lowland but it remains unclear if altitude played any role.

Despite the mosaic landscape, the human impact pattern is rather similar throughout the study area. Neolithic human impact was modest. Evidence of human impact in the pollen record increased at 3500 cal BP in the surroundings of L. Verijärv and at around 2700 cal BP in vicinity of L. Plaani. The main agricultural crop was rye, extensively cultivated from about 1500 cal BP in the L. Plaani area, from 1300 cal BP in the L. Verijärv area and, finally, from about 800 cal BP in the L. Lasva area. Marked declines in *Alnus* coinciding with the start of rye cultivation is probably due to the onset of the Iron Age activity in the region, which brought along clearance of the alder woods, probably as a result of using wood as a fuel for iron work. Cultivation of *Fagopyrum* refers to the contacts with neighboring tribes. Rye cultivation was most extensive 1200–200 cal BP. Since AD 1860–1870 rye cultivation decreased as a result of changes in land ownership and the start of potato cultivation. Several historical and political events, foremost wars, crop failures, plagues and famines, liberation from serfdom, and collectivization affected agrarian activity and are indicated on pollen diagrams as declines in anthropogenic indicators.

All lakes also revealed some distinctive features in the pollen record. The pollen diagram of L. Plaani displays an 8200-year cold event, expressed as a decrease in *Quercetum Mixtum* and an increase in *Betula*. The L. Verijärv sequence displays evidence of a catastrophic forests fire about 3450 cal BP, interpreted from a band of clay within a succession of organic sediments coinciding with a peak in charcoal and a decrease in arboreal pollen. In the L. Lasva sequence, a sharp peak in aquatics (*Nuphar*, *Nymphaea*) at about 5700 cal BP resulted from a change in water level or a pollen aggregate dropped by an insect.

**KEY WORDS:** annually laminated lake sediments, loss-on-ignition, pollen, Holocene vegetation history, human impact, Haanja Heights, 8200 cold event

## PREFACE

This thesis summarizes and synthesizes the following papers, three of which (I, II and III) concern one lake in the area of the Haanja Heights, and paper IV which unites the main results. These papers are referred to in the text by Roman numerals I–IV.

- I. Niinemets, E., Saarse, L. 2006. Holocene forest dynamics and human impact in southeastern Estonia. *Vegetation History and Archeobotany* 16 (1), 1–13.
- II. Niinemets, E., Saarse, L. 2007a. Fine-resolution pollen-based evidences of farming and forest development, south-eastern Estonia. *Polish Journal of Ecology* 55, 283–296.
- III. Niinemets, E., Saarse, L. 2007b. Mid- and late-Holocene land-use change inferred from pollen record, southeastern Estonian upland area. *Review of Palaeobotany and Palynology* 146, 51–73.
- IV. Niinemets, E., Saarse, L. Vegetation and land-use dynamics in south-eastern Estonia. *Quaternary International* (Submitted manuscript).

### **AUTHOR'S CONTRIBUTION IN PAPERS:**

In papers I–IV, the author's contribution involves pollen counting, data processing, diagrams compilation and interpretation, as well as graphics drawing, writing and finalizing the draft manuscript.

Related publications not included in this thesis:

- Saarse, L. and Niinemets E. 2007. Environmental changes in SE Estonia during the last 700 years. *Boreal Environment Research* 12, 611–621.
- Niinemets, E., Saarse, L., Poska, A., 2002. Vegetation history and human impact in the Parika area, Central Estonia. *Proceedings of the Estonian Academy of Sciences. Geology*, 51(4), 241–258.
- Tiljander, M., Saarinen, T., Niinemets, E., Ojala, A.E.K. 2000. Rapid environmental changes in Central and Eastern Finland over the last 2,000 years based on X-ray density variation of varved sediments in four lakes. 8th International Paleolimnology Symposium, PEARL, Queens University, Kingston, Canada, August 20–24, 2000, p. 100.

- Saarse, L., Niinemets, E. 2005. Lake sediment composition changes during the last 700 years. International Field Symposium on Quaternary Geology and Landform Processes. Sept. 4–9, 2005, Apatity.
- Poska, A., Seppä, H., Saarse, L., Veski, S., Niinemets, E. 2006. Late Holocene climate change in Estonia based on pollen and loss-on-ignition data from two annually laminated lakes. In: Jones, V., Jenks, C, Hughes, M., Binney, H., Birks, J. (eds), Natural Climate Variability and Global Warming. Final open science meeting: HOLIVAR 2006, 12–15 juuni 2006, London, p. 122.

## SUMMARIES OF PAPERS INCLUDED IN THE THESIS

### **Paper I. Holocene forest dynamics and human impact in southeastern Estonia**

The discovery of laminated sediments in lakes in southeastern Estonia initiated an extensive litho-, chrono- and biostratigraphical study of lakes in southeastern Estonia. This study examined a 9.9 m-thick sequence of laminated sediments from a core extracted from the deepest part of Lake Verijärv. Methods used in the study included loss-on-ignition analyses, varve counting, radiometric age determinations and pollen analyses. Varve counting combined with  $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$  and  $^{241}\text{Am}$  dating proved the lamina have an annual character.

The vegetation history of this research extended 10,300 years before present (cal BP). Reconstruction of the past vegetation dynamics was based on pollen percentages, accumulation rates and human impact diagrams. Two main shifts in vegetation dynamics occurred during the Holocene. The first occurred about 7700 cal BP when the pine-birch forest was replaced by deciduous mixed forest, and the second at about 3200 cal BP marked by a regeneration of the pine-birch-spruce forest. This major reduction in broad-leaved trees at ca 3200 cal BP occurred later than in other parts of northern Estonia. This was due to delayed human influence in the woodland development and the presence of suitable habitats for QM taxa to survive in the mosaic landscape. A catastrophic forest fire occurred near Verijärv about 3450 cal BP, which opened the landscape, enhanced intensive soil erosion and sedimentation of a thick clayey layer. As crop cultivation was introduced to the Haanja Heights at least ca 3500 cal BP, this raises the possibility that the fire was caused accidentally or on purpose by humans during slash-and-burn practice, although natural causes cannot be dismissed. A sharp decline in *Alnus* between 1500–1650 cal BP coincided with the start of the continuous *Secale* curve and evidence of extensive land-use. The high-resolution pollen record from Verijärv shows vegetation changes that occurred in the study area from the early Holocene to the present and the land-use history since the late Neolithic period. The vegetation dynamics in southeastern Estonia has several specific features, such as the early arrival of *Picea*, *Ulmus*, *Quercus* and *Tilia*, and the late final decline of *Ulmus*.

### **Paper II. Fine-resolution pollen-based evidences of farming and forest development, south-eastern Estonia**

Lake Lasva is a lake with laminated sediments in an agricultural area of southeastern Estonia with dense prehistoric settlement. A 9.85-m long core from the deepest part of the lake — covering about 6300 years — revealed high sedimentation rates and laminated structures. The main core was studied

palaeobotanically at high resolution. Both loss-on-ignition and palynological analyses were used to reconstruct the vegetation and lake history. The time-scale was constructed from five accelerator mass spectrometry (AMS)  $^{14}\text{C}$  dates, which show good linearity and fit with varve counts, indicating that there are no hiatuses in sedimentation within the sediment column. The high-quality time resolution allows comparison of historical events with the palynological record.

*Betula*, *Pinus*, *Picea* and broad-leaved species, later mostly *Betula*, *Pinus* and *Alnus*, grew in the area until ca 3000 cal BP. There is strong correspondence between archaeological and human impact signals in the palynological study. The first weak signs of human impact are evident at 6300 cal BP. The establishment of the Neolithic Kääpa settlement (Fig. 1) at 5400–5100 cal BP coincides with a sharp decline in broad-leaved tree pollen. The reduction in *Picea* between 3800 and 3500 cal BP concurrent with a slight increase in *Artemisia* and Chenopodiaceae pollen and charcoal particles corresponds to the founding of the Villa settlements (Fig. 1). The first attempt at small-scale tillage, indicated by the first occurrence of *Triticum*-type pollen and followed by a long-term gap, dates back to 5100 cal BP. Limited arable farming with *Triticum* and *Hordeum* cultivation appeared at the end of the Roman Iron Age in the study area. After the German crusaders invaded the area about 800 cal BP, arable farming started to develop very quickly. *Secale*, *Triticum*, *Hordeum*, *Fagopyrum*, *Linum*, and *Cannabis* were grown. The high frequency of *Rumex*, *Trifolium*, Poaceae and *Plantago lanceolata* are indicative of the expansion of stock farming. Several historical events, foremost wars, crop failures, plagues and famines, affected agrarian activities and are indicated by declines in the cereal influx curve. Noticeable *Alnus* decline, being characteristic of other profiles of the region, occurred at 1200–1100 cal BP.

As a distinctive feature, a short culmination of aquatics (*Nuphar*, *Nymphaea*) together with an increase in terrestrial NAP (Poaceae, *Filipendula*) and a reduction in tree pollen occurred about 5700 cal BP. This may reflect a water level change or a random aggregate of aquatic pollen collected and dropped by a bee.

### **Paper III. Mid- and late-Holocene land-use change inferred from pollen record, southeastern Estonian upland area**

Lake Plaani is a shallow lake in the centre of the Haanja Heights. A 5.9-m thick sediment sequence from L. Plaani was subjected to pollen and loss-on-ignition analyses and radiocarbon dating in order to reconstruct the vegetation and land-use history in the mosaic upland landscape of southern Estonia.

The L. Plaani area was dominated by a mixed broad-leaved forest between 8430 and 2800 cal BP, followed by a mixed deciduous forest. Forest clearance started at ca 4000 cal BP and became more extensive after 2800 cal BP. Pollen diagrams of the Lake Plaani area, as well as the Haanja Heights as a whole,

have several unique features, such as a great abundance of *Tilia* forest between 8000 and 5500 cal BP, dominance of *Picea* and *Quercus* forest between 5500 and 2800 cal BP and preservation of *Quercus* forest until 1000 cal BP. *Ulmus* was common between 8500 and 2800 cal BP, but exhibits no distinct maximum in the mid-Holocene.

L. Plaani is the second lake in Estonia, after L. Tõugjärv (Veski *et al.*, 2004), in which the so-called 8200 cal BP cold event has been detected. In the Plaani sequence the cold event is dated earlier at ca 8300–8400 cal BP. Changes in pollen spectra, foremost a decline in *Corylus* and *Alnus*, are similar to that in L. Tõugjärv, and show that this climatic event has been preserved both in deep-water (Tõugjärv) and shallow-water (Plaani) lake sediments.

Human impact and crop cultivation in the central part of the Haanja Heights started rather late, indicating that upland areas of inland Estonia were colonized and tilled later than coastal areas. This finding is in good accordance with archaeological records. The abundance of tree pollen in pollen diagrams of the Haanja Heights remains high (ca 80%) even during the periods of intensive arable farming.

#### **Paper IV. Vegetation and land-use dynamics in southeastern Estonia**

This paper summarizes the main results of the palynological study of three pollen profiles in southeastern Estonia (L. Plaani, Verijärv, and Lasva), which form a transect from the central part of the Haanja Heights over its northern slope to the ancient buried valley at its foot, and describes peculiarities of vegetation and land-use history in different landscape regions.

High-resolution sedimentological and palaeobotanical study together with AMS <sup>14</sup>C dates, archaeological records and written sources served as the basis for reconstructing the vegetation and land-use history.

High-resolution pollen records from different landscape regions of SE Estonia display vegetation changes from the early Holocene to present and the land-use history since the Late Mesolithic period. The vegetation dynamics in SE Estonia has several distinctive features, such as the early arrival of *Picea*, *Ulmus* and *Quercus*, long-term broad-leaved woods owing to the presence of suitable habitats in the mosaic landscape, and delayed human influence. Numerical zonation and correlation of the studied profiles suggest six pollen-assembly zones, which serve as a new regional pollen assembly zonation.

Comparison of the expansion and distribution patterns of thermophilous taxa (*Ulmus*, *Tilia*, *Quercus* and *Fraxinus*) reveals a clear south-north direction in their spatial dynamics. In the southernmost sequence all the mentioned taxa flourished earlier and persisted longer at greater abundance than in the northern sites.

Despite the mosaic landscape, the human impact patterns are rather similar throughout the study area. The pollen diagrams suggest only a modest Neolithic human impact, due to the absence of settlement directly on the shore. Reflec-

tions of human impact intensified in the vicinity of L. Verijärv at 3500 cal BP and in the L. Plaani area around 2700 cal BP. Limited crop growing in the study area appeared in the Late Bronze Age with *Triticum* and *Hordeum* cultivation but crop farming became the primary source of subsistence in the Late Iron Age. Rye cultivation peaked between 1300 and 200 cal BP, but decreased considerably after AD 1860–1870 as a result of changes in land ownership and introduction of potato cultivation. Annually laminated sediment sequences from L. Verijärv and Lasva enable linkage of several historical and political events as reflected by pollen records with historical data – foremost wars, crop failures, plagues and famines, abolition of serfdom and collectivization, which affected agrarian activities, and which are revealed in pollen diagrams as declines in anthropogenic indicators.

# 1. INTRODUCTION

Studies of vegetation history are important, as past vegetation distribution and development provide information on the development of the Earth's climate, palaeoecological conditions, as well as on the migration and activity of early humans. Usually microfossils, especially pollen and spores, are used to reconstruct the vegetation history. Correlation of palynological diagrams has enabled study of the dynamics and migration of various plant taxa and dating of sediment sequences providing relative geological time-scale. Modern geological time-scales are dated preferably radiometrically and pollen is used mostly for reconstruction of vegetation and climate history. Nonetheless, accurately dated and pronounced changes in vegetation history can be used as markers for correlation with earlier studied sequences without radiometric dating.

Recent palaeoecological studies combine litho-, bio- and chronostratigraphical approaches with archaeological investigations to achieve more precise information on vegetation dynamics. Combining different methods, land-use history in Europe has been intensely studied by numerous authors (Birks *et al.* 1988; Berglund 1991; Gaillard *et al.* 1991, 1994; Behre 1986, 1988 and others).

About 400 pollen diagrams which completely or partially cover the Holocene are available in Estonia. Palynostratigraphical studies, especially those concerning human impact and therefore carried out in more detail, have concentrated on coastal areas (Veski 1998; Poska 2001), which have been more intensively better in an archaeological context (Lang 1996; Kriiska 2001).

Sedimentary processes in lakes in the Temperate Zone have a cyclic character, being under certain conditions reflected as annual lamination of lake sediments. The well-developed seasonal contrasts, spring floods and water column stratification are the main causes of the formation of laminated sediments in boreal environments (Ojala *et al.* 2000; Lotter and Birks 2003). Laminated sediments have been described on different continents, both in small and large lakes, especially during the last years (Pettersen 1999; Snowball *et al.* 1999; Zillén *et al.* 2003). Laminated sediments provide a reliable tool for compiling precise chronologies in key areas of palaeoenvironmental research.

The first studies of Holocene laminated sediments in Estonia was at the end of the 1980s (Rõuk 1986, 1992) but these studies were neglected for almost 15 years. Systematic palaeoecological research of laminated lake sediments in Estonia resumed in 2000. Laminated sediments which were believed to be annually laminated (varved) were discovered in deep lakes in the Haanja Heights, southeastern Estonia. This discovery sparked high-resolution palynological research on the vegetation history in SE-Estonia (Veski *et al.* 2004, 2005; Niinemets and Saarse 2006, 2007a, b), which had not been studied extensively and in fine detail earlier.

Several profiles from the Haanja Heights and Aluksne Heights (Latvian part of the same heights) have been previously studied palynologically: the Mäetilga, Kõverjärv and Karuniidu profiles (Mäemets 1983); Tuuljärv and

Vaskna (Ilves and Mäemets 1987); Remmeski and Senno (Sarv 1983); Hino mire (Laul and Kihno 1999); Kirikumäe mire and lake and Lake Punso (Saarse and Rajamäe 1997); Vällamäe (Punning *et al.* 1995); Lake Tõugjärv (Veski *et al.* 2005) and Ruusmäe (Punning *et al.* 2004). Previously examined and <sup>14</sup>C-dated pollen diagrams of mires and nearby shallow lakes have distinguished the main features of vegetation development in the Haanja Heights (Ilves and Mäemets 1987; Punning *et al.* 1995; Saarse and Rajamäe 1997). However, the resolution of palynological analyses in the earlier studies was inadequate to highlight human impact and rapid changes in vegetation dynamics. Only three detailed studies of human impact in southeast Estonia have been published (Laul and Kihno 1999; Punning *et al.* 2004; Veski *et al.* 2005). Available palynological profiles from the Latvian part of the Heights (Aluksne) are undated and lack resolution (Vanaga 1970).

To carry out a comprehensive study on the vegetation history of SE-Estonia, using modern case-study approach, three lakes of different nature and archaeological background were selected: one at the top of the Heights (L. Plaani), one on the slope of the Heights (L. Verijärv) and one at the foot of the Heights (L. Lasva). Lake sediments in L. Lasva and Verijärv are laminated and supposedly provide a very precise time-scale.

The main aims of the present thesis are:

- 1) to reconstruct vegetation and land use history of the upland area of southeastern Estonia, analyzing events from pollen spectra combined with sediment composition, and to distinguish features specific to the studied area;
- 2) to analyze evidence of human impact on vegetation and to document the character of transition to farming in southeastern Estonia;
- 3) to discover general and individual changes in the sedimentation in the three lakes that could reflect climate changes and human activity in the region.

## 2. STUDY AREA

The *relief* of Estonia is generally low and plain. Southeastern Estonia differs from the rest of the country by its higher altitude (over 250 m in the centre of Haanja Heights) and by an upland hummocky mosaic landscape with numerous hillocks and deep lakes (Fig. 1). The relief is built up of thick Quaternary sediments dominated by glacial and glaciofluvial deposits and to a lesser extent by glaciolimnic sediments, and underlain by Middle Devonian sedimentary rocks of the Gauja and Amata regional stages. The modern landscape with its numerous post-glacial accumulative and kettle hole lakes was formed during recession of the Weichselian ice sheet before 14 000 cal BP (Hang 2001; Kalm 2006). *Climatically* Haanja lies at the border between the influence of the Atlantic zonal flow and the Eurasian continental climate. The climate of the Haanja Heights differs from the rest of Estonia by its continentality, the country's greatest temperature range (the average air temperature is  $-6.2^{\circ}\text{C}$  in January,  $17.2^{\circ}\text{C}$  in July), by considerably higher precipitation (up to  $700\text{--}750\text{ mm yr}^{-1}$ ) and by a longer and thicker snow cover (Jaagus 2002). However, the annual average temperature ( $6\text{--}6.6^{\circ}\text{C}$ ) is higher than in more eastern areas at the same latitude (Jaagus 2002).

Due to the mosaic topography, soils and microclimatic conditions are diverse. The most widespread *forest type* in the high central part of the Haanja Heights is boreo-nemoral forest dominated by *Picea*, fragmentary hardwood forest and dry meadows (Laasimer 1965). The slopes of moraine hills are wooded by *Pinus*, the most widespread species, followed by *Betula* and occasional *Alnus*, *Populus* and other hardwood species.

Archaeologists long believed that the Estonian upland areas, e.g., the Haanja Heights, were inhabited later than the coastal region (Jaanits *et al.* 1982). This view changed in the 1990s upon discovery of Mesolithic settlements on the slopes of the heights (Jaanits and Moora 1999; Kiristaja 2003; Konsa 2003). Evidence of human settlement in the surroundings of L. Plaani since the Middle Iron Age has been affirmed by discovery of settlement sites and burial places (Peets 1988; Laul 2001). The earliest human presence in the L. Lasva area comes from the Neolithic period and is recognized by the artifacts from two settlement sites – Kääpa and Villa (Fig. 1A; Jaanits *et al.* 1982). The cultural layer at the Kääpa settlement site, 3.6 km north of L. Lasva, contains Narva-type ceramics and has been dated to the third millennium BC (Jaanits 1976). Osteological analysis of skeletal remains from these settlement sites proves that the main economy of the Neolithic people was hunting (Paaver 1965; Lõugas 1997). The Middle Iron Age (1550–1200 cal BP) barrow cemetery near the Kääpa Neolithic settlement site and the Iron Age settlement site had been in use since Middle Ages (Tamla and Laul 1979). This provides additional information on past human influence on the vegetation and landscape.

*Lake Plaani Külajärv* (hereafter L. Plaani) is a small lake formed in a depression in the central part of the Haanja Heights (Figs 1–3, Table 1). The

lake is surrounded by mosaic hills up to 281 m a.s.l. built up of gravel, sand and till beds. The temporarily drained lake has a small inlet stream to the northwest and a temporal outlet to the northeast. Damming of the outflow stream in the 1960s caused the water level to rise about 60 cm. The water is rich in organic substances and poor in mineral compounds. Macrophytes include *Equisetum fluviatile*, *Typha latifolia*, *Polygonum amphibium*, *Nuphar*, *Sparganium*, *Potamogeton*, and *Myriophyllum* (Mäemets 1977).

**Table 1.** Specific features of studied lakes (Eesti järved 1968).

	<b>Lake Plaani</b>	<b>Lake Verijärv</b>	<b>Lake Lasva</b>
Coordinates	57°40'30''N 27°04'30''E	57°48'30''N 27°03'30''E	57°51'30''N 27°10'30''E
Location in Heights	In the centre of the Haanja Heights	Northern slope of the Haanja Heights	On the northern foot of the Haanja Heights
Elevation, m a.s.l.	244.1	90	71.8
Surface area, ha	20	20	10.9
Water depth, m	5	19.5	19.5
Water column	Unstratified	Thermally stratified, oxygen depleted in the bottom	Thermally stratified
Water chemistry	Weakly alkaline, pH 7.2	Epilimnion alkaline, pH 8.3–8.4	pH 8.0 near the surface, 6.7 deeper
Sediments	Homogeneous	Laminated	Laminated

The lake lies in an actively used agrarian area, where podzols and gleyzols dominate. The catchment is covered mostly by fields, meadows and pastures, steep hills are covered with *Pinus*, *Picea* and *Betula*, with occasional *Alnus*, *Populus* and other hardwood species.

High position in the upland and relative shallowness of the lake (Figs 1–2) result in a homogenous sedimentary succession in which organic matter dominates (more than 50%, Fig. 7A).

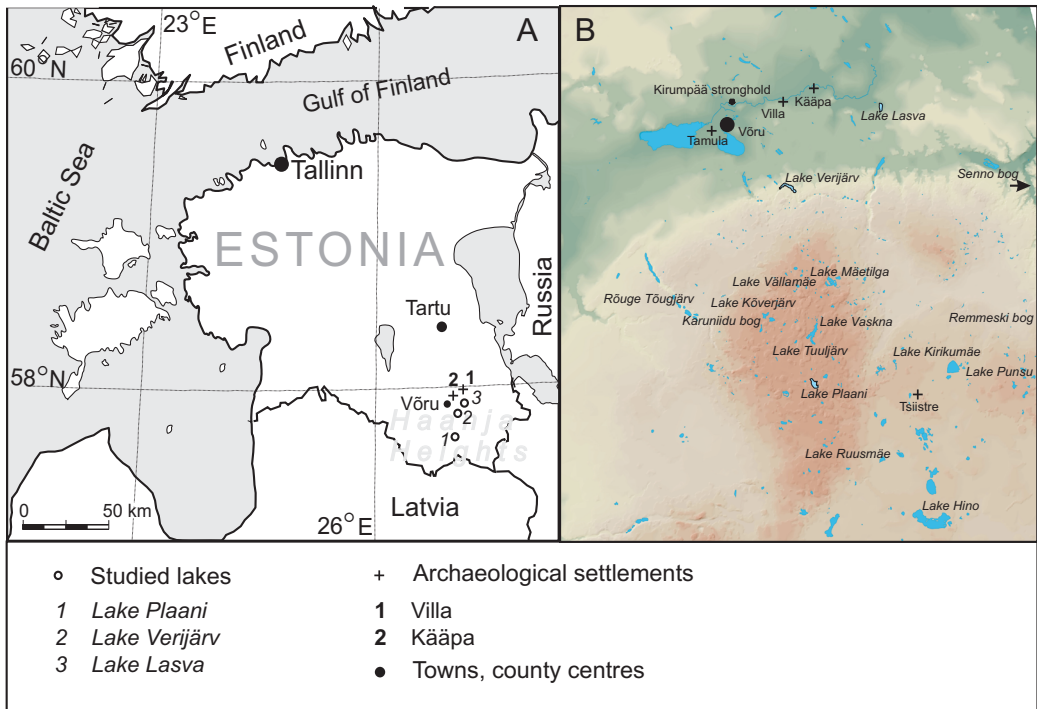
Eutrophic *Lake Verijärv* (Figs 1, 2, 4) is a relatively small but deep lake (Table 1) on the northern slope of the Haanja Heights at the crossing of two ancient valleys, and has therefore a bow-shaped outline. L. Verijärv is sheltered from wind by 30-m high hills on all sides. It is a hard-water dimictic overflow lake with two inlet streams, one outlet and several bottom springs. Coniferous and deciduous coppices, meadows, fields and gardens, bushes and thickets of reeds cover the catchment of L. Verijärv. A rim of *Alnus* woods borders the lake to the east and southeast.

Lake Verijärv hosts 22 plant species, the most common of which are *Phragmites* sp., *Scirpus lacustris*, *Typha latifolia*, *Potamogeton* sp., *Equisetum* sp. (Mäemets 1977).

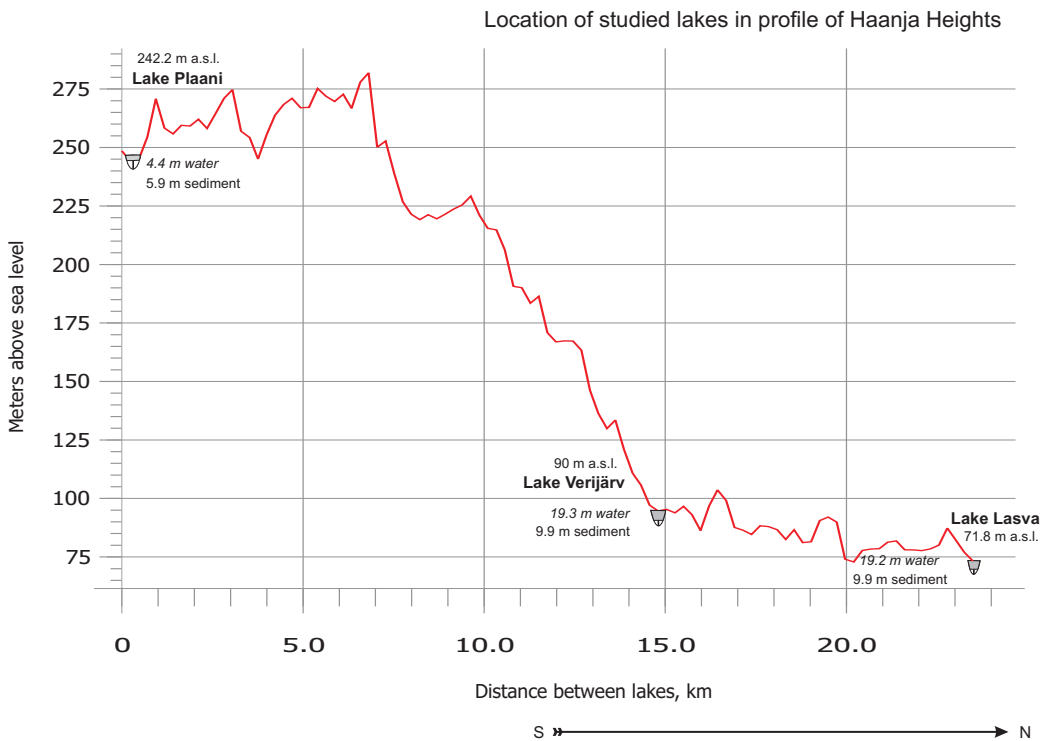
Specific conditions — great depth with a relatively small surface area and stratified water column (Table 1) — result in the formation of laminated sediments with mineral matter content over 50% (Fig. 8B).

*Lake Lasva* is a small but deep lake north of the Haanja Heights (Figs 1, 2, 5; Table 1). It is considered to be a kettle hole lake, which was formed after retreat of the ice-sheet. This elongated eutrophic hard-water lake is slightly drained; it has an inflow to the south and a temporal drainage ditch that joins a river to the northwest. Glaciolacustrine silt and sandy loam with small spots of till near the north-eastern shore cover the catchment of the lake. *Pinus* grows north of the lake on the sandy hill extending 87.7 m a.s.l. Generally the landscape is agrarian, with some abandoned fields and farms. At the northern shore the lake bottom is covered by sand, elsewhere by gyttja. The water is yellow-green, moderately transparent (2.3 m) and strongly stratified (Mäemets 1977). Macrophytes are represented by nineteen species, among which *Acorus calamus*, *Typha latifolia*, *Nuhpar lutea*, *Polygonum amphibium*, *Potamogeton perfoliatus*, *Elodea canadensis*, and *Myriophyllum spicatum* are most common.

L. Lasva has a lower altitude and is deeper and has a smaller surface area than L. Plaani and Verijärv (Figs 1–2, Table 1). These features, together with a stratified water column, have resulted in the formation of thick laminated sediments, which have the highest content of mineral matter among the three lakes (more than 60%, Fig. 9A)



**Fig. 1** Location of the study area. **A.** Location of the Haanja Heights in southeastern Estonia. **B.** Topography of the Haanja Heights and location of the previously studied pollen sites.



**Fig. 2** Profile of the Haanja Heights showing the location and altitude of the studied lakes in the profile of the Haanja Heights.



**Fig. 3** Panorama of L. Plaani from the northern coast, which is used for swimming.



**Fig. 4** Panoramic view of L. Verijärv from the east.



**Fig. 5** Panorama of L. Lasva from the northern coast, which is sandy and used for swimming.

## 3. MATERIAL AND METHODS

### 3.1 Coring

Two continuous overlapping sediment cores were extracted through the ice with a 1 m long Russian (Belarus) peat sampler at the water depth of 19.3 m (Figs 1, 2, 4 and Fig. 2 in Paper I) from L. Verijärv in the winter of 2000. The coring penetrated 9.9 m into the sediment i.e. 29.2 m below the water/ice surface. In addition, four parallel frozen sediment slabs from the uppermost one meter loose sediment sequence were obtained two years later.

A 9.85-m core from L. Lasva was taken through the ice from the deepest part of the lake (water depth 19.15 m; Figs 1, 2, 5 and Figs 1, 3 in Paper II) with the same sampler reaching 29 m below the water/ice surface in the winter of 2000. Four parallel frozen sediment slabs from the uppermost one-meter unconsolidated sediment sequence were taken with a freezer corer.

In the early spring of 2006, two overlapping 5.90-m-long cores were recovered from the ice-covered Lake Plaani from the depth of 4.40 m (Figs 1–3 and Fig. 1 in Paper III).

All the cores were described visually in the field, wrapped in plastic and transported to the laboratory, where the frozen slabs were cleaned, photographed, digitized and retained in a fridge.

### 3.2 Dating

The sediment column of L. Verijärv exhibited generally discernible laminations from top to bottom (Fig. 2 in paper I). In the field, lamination was visible throughout the core, but later the surface of the monolith (except for the frozen slabs) turned almost evenly black. Laminae were counted within the uppermost meter by T. Alliksaar and L. Saarse. To verify the annual character of lamination and to confirm the varve-counting results,  $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$  and  $^{241}\text{Am}$  dating (determined at the Kiev Hydrometeorological Institute) was performed.  $^{210}\text{Pb}$  activity was measured by direct gamma assay and CRS (constant rate of supply) Pb dating model was used to determine dates. Seven  $^{14}\text{C}$  radiocarbon accelerator mass spectrometry (AMS) determinations were obtained at the Ångström Laboratory, Uppsala University, and one at the Lund University AMS Dating Laboratory.

Dates from L. Lasva were obtained by AMS radiocarbon dating carried out at two different laboratories. Four AMS  $^{14}\text{C}$  dates were determined at  $^{14}\text{C}$  Laboratory of Poznań (Poland) and one date was determined at the Ångström Laboratory, Uppsala University (Sweden). The samples for AMS dating were pre-treated following the procedure outlined in Wohlfarth *et al.* (1998). The

laminae of the uppermost meter of the sediment core from L. Lasva were counted by L. Saarse.

In order to construct a time-scale for L. Plaani, seven conventional radiocarbon dates were determined at the Institute of Geology at Tallinn University of Technology and two AMS dates at <sup>14</sup>C Laboratory of Poznań.

The radiocarbon dates of all three lake cores were calibrated at one-sigma confidence level using the INTCAL 5.01 program (Stuiver *et al.* 2005). Calibrated ages before present (cal BP) were used in the present study.

Times-scales were calculated by the Tilia program (Grimm 1991), which incorporated all data (e.g. varve counts, radiometric dates).

### 3.3 Loss-on-ignition analyses

Sediment from all three lakes was analyzed by the same method. Loss-on-ignition (LOI) analyses were performed on a continuous series of 1-cm-thick samples to estimate the contents of organic and mineral matter and carbonate compounds (Bengtsson and Enell 1986; Heiri *et al.* 2001). The organic matter (OM) content was measured at 525°C and expressed as percentages of dry matter. The percentage of carbonate (CaCO<sub>3</sub>) was calculated after burning of the LOI residue for 2 hours at 900°C. The amount of residue containing clastic material and biogenic silica was deemed mineral matter and calculated from the sum of organic and carbonate compounds. The LOI results were plotted using the TgView program (Grimm 1991).

### 3.4 Pollen analyses

Pollen analyses of L. Verijärv were carried out along the entire core with samples taken at 1–3 cm intervals for the last millennium, 5 cm for the rest of the upper part and 10 cm for the lower part of the sequence. The core from L. Lasva was studied palynologically with sample intervals of 5 cm. Pollen analysis of the Lake Plaani was carried out with intervals of samples routinely 5–10 cm; in the lower part, where the 8200 cal BP cold event was expected, single centimeter samples were analyzed.

Samples were prepared using the traditional acetolysis method (Berglund and Ralska-Jasiewiczowa 1986; Erdtman 1936; Fægri and Iversen 1989; Moore *et al.* 1991). A volume of 0.4–1 cm<sup>3</sup> of sample was taken, depending on the material (larger samples from mineral-rich sediment), and two tablets of *Lycopodium* spores were added to determine the pollen concentration (Stockmarr 1971). Samples with a large amount of mineral matter were treated for three days with HF (Berglund and Ralska-Jasiewiczowa 1986). The prepared samples were stored in glycerin. A minimum of 500 pollen grains was counted for

regular analyses and a minimum of 1000 pollen grains was counted for samples containing cereals, using  $\times 250$  magnification for routine counting and  $\times 1000$  magnification with phase contrast for more complicated determinations.

In the Verijärv core, a total of 172 samples were analyzed and 135 pollen taxa identified; in L. Lasva 201 samples were analyzed and 136 pollen taxa identified; and in L. Plaani 115 samples were analyzed and 101 pollen and spore taxa identified.

Pollen diagrams were constructed with the Tilia and TgView programs on the basis of total terrestrial pollen, using the sum of arboreal (AP) and non-arboreal pollen (NAP), which was used to construct the percentage diagram. The human impact diagrams were compiled on the basis of species indicative of landscape use related to human economic activity and settlement (Poska 2001). The land-use indicators were divided into seven groups: cultivated land, ruderals, meadows and pastures, dry meadows, grazed forest, wet meadows, and general apophytes (Behre 1981; Berglund and Ralska-Jasiewiczowa 1986; Poska 2001).

As pollen analyses were made on volumetric samples, pollen concentrations were also calculated and influx diagrams drawn. The pollen accumulation rates ( $\text{grains cm}^{-2} \text{yr}^{-1}$ ) were calculated using the concentration data and reconstructed timescales.

The charcoal and spheroidal fly ash particles were counted during the routine pollen analysis without discerning charcoal particles on the basis of size.

Rarefaction analysis (Birks and Line 1992) was carried out on the basis of  $E(T_{500})$  using the Psimpoll computer program (Bennett 1998, 1994) to estimate the palynological richness (Birks and Line 1992; Odgaard 1999). The analysis included pollen of terrestrial plants and was standardized to the lowest pollen sum.

Both the percentage and accumulation diagrams were used to reconstruct land-use history.

### **3.5 Pollen diagram zonation**

The zonation of the pollen diagrams of L. Verijärv and Lasva was performed according to the dendrogram (constrained cluster analysis), which was generated by the Coniss computer program using the Euclidean distance method. Zonation of pollen diagrams of L. Plaani was accomplished with the Psimpoll program (Bennett 1994), using binary splitting by the sums-of-squares method.

Zonation of the human impact diagrams is in accordance with the archaeological time-scale by Lang and Kriiska (2001).

## 4. RESULTS

Results in detail on each lake are presented in papers I–IV. A concise description of the results is presented below.

### 4.1 Chronology

The chronology of sequences in the current study is a combination of different methods: radiocarbon dating, varve counting, and correlation with earlier dated pollen diagrams. All  $^{14}\text{C}$  dating results are presented in Table 2.

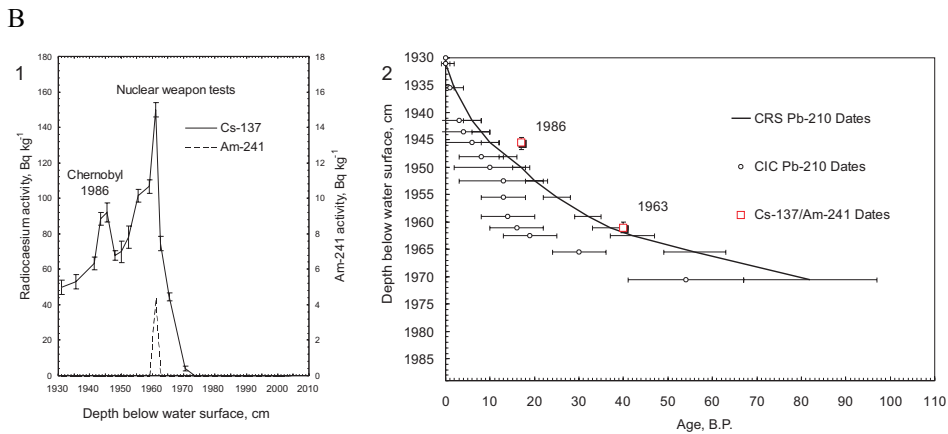
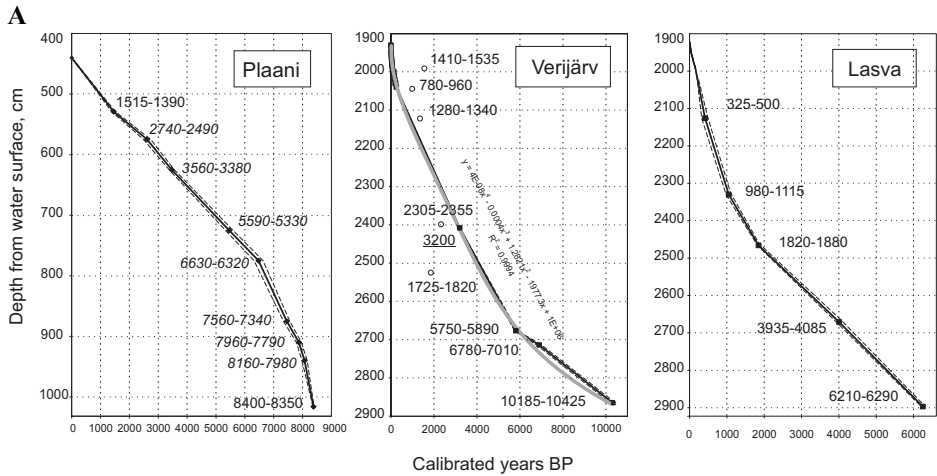
The age-depth curve of L. Plaani was constructed on the basis of seven conventional radiocarbon dates and two AMS radiocarbon dates from the bulk gyttja (Table 2). Dates fit well a linearly interpolated curve (Fig. 6A), indicating a relatively steady rate of sedimentation throughout the mid- and late Holocene. In the deeper part (1029–770 cm) the sedimentation rate was higher,  $0.95 \text{ mm yr}^{-1}$ . From 6500 cal BP until the present (770–440 cm), sedimentation was slower than earlier and quite stable, approximately  $0.5 \text{ mm yr}^{-1}$ , consistent with the average sedimentation rate of gyttja in Estonian lakes (Saarse 1994).

The AMS  $^{14}\text{C}$  dates of L. Verijärv were obtained from eight samples (Table 2), varve counting and 15  $^{137}\text{Cs}$ ,  $^{241}\text{Am}$  and  $^{210}\text{Pb}$  radiometric dates (Fig. 6A and 6B). Not all AMS  $^{14}\text{C}$  dates agreed with the age curve, therefore, the establishment of the time-scale was complicated and is discussed in the next chapter.

The chronology of the L. Lasva sequence was compiled using varve counts and 5 AMS  $^{14}\text{C}$  dates (Table 2). The AMS  $^{14}\text{C}$  dates fit well with the varve counts and are interpolated linearly (Fig. 6A).

**Table 2.** AMS and conventional  $^{14}\text{C}$  measurements from L. Plaani, Verijärv and Lasva. Ages are calibrated according to INTCAL 5.01 (Stuiver *et al.* 2005) and given with  $1\sigma$  certainty. \* denotes conventional dating.

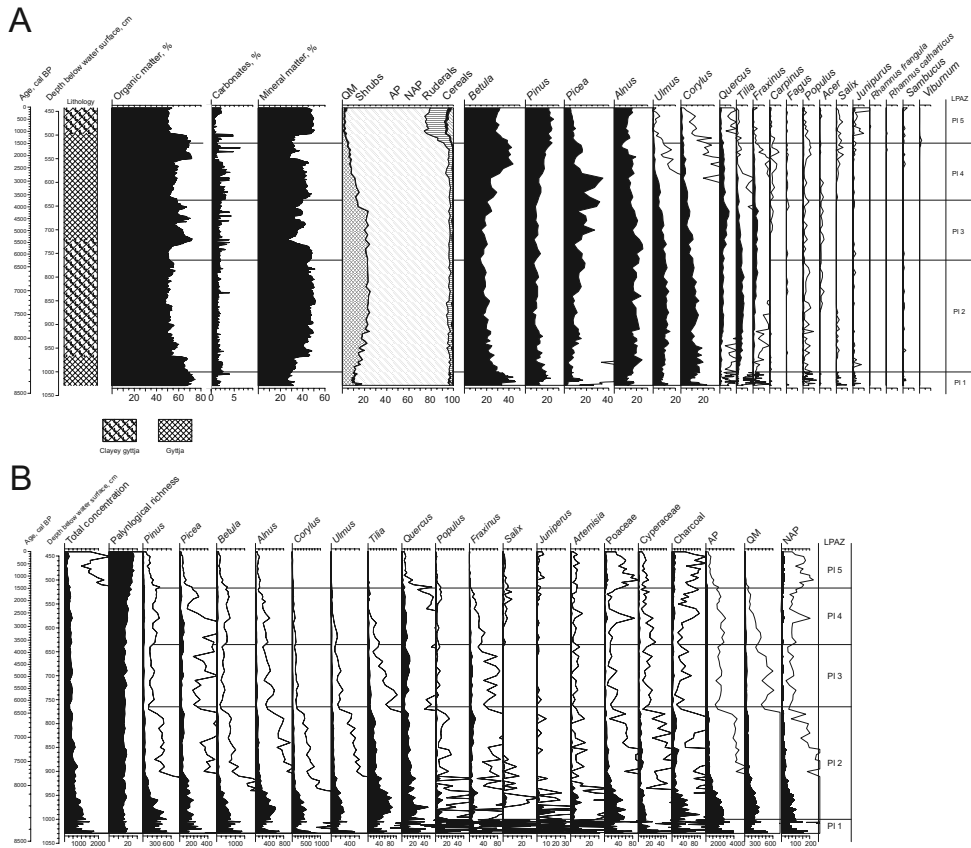
Lake name	Lab. No	Depth below water surface, cm	$^{14}\text{C}$ age BP	Dated material	Calibrated age BP
Plaani	Poz-19613	528–530	1545±40	gyttja	1390–1515
Plaani*	Tln-2921	570–580	2520±60	gyttja	2490–2740
Plaani*	Tln-2926	620–630	3235±70	gyttja	3380–3560
Plaani*	Tln-2924	720–730	4775±70	clayey gyttja	5330–5590
Plaani*	Tln-2923	770–780	5680±145	clayey gyttja	6320–6630
Plaani*	Tln-2927	870–880	6550±85	clayey gyttja	7340–7560
Plaani*	Tln-2929	905–915	7040±90	clayey gyttja	7790–7960
Plaani*	Tln-2930	935–945	7235±80	clayey gyttja	7980–8160
Plaani	Poz-19507	1015–1917	7560±40	gyttja	8350–8400
Verijärv	Ua-19533	1995	1590±60	aquatic moss	1410–1535
Verijärv	Ua-19791	2046–2050	990±50	bulk gyttja	780–960
Verijärv	Ua-19534	2125	1365±60	wood	1255–1340
Verijärv	Ua-23874	2400	2300±40	twigs	2305–2355
Verijärv	Ua-23875	2525	1840±40	bark	1725–1820
Verijärv	Ua-23876	2677	5065±50	bark	5750–5890
Verijärv	Ua-23877	2714	6050±90	fish scales	6780–7010
Verijärv	LuA-4754	2865	9110±110	<i>Salix</i> wood	10185–10425
Lasva	Ua-19792	2126	380±50	wood	325–500)
Lasva	Poz-13746	2330	1145±30	plant macroremains	980–1115
Lasva	Poz-13747	2466	1900±30	plant macroremains	1820–1880
Lasva	Poz-13749	2669–2673	3680±35	gyttja	3935–4085
Lasva	Poz-13771	2897	5450±40	wood	6210–6290



**Fig. 6** Dates and calculation of ages of the studied sequences. **A.** AMS dates are indicated in regular font, conventional  $^{14}\text{C}$  dates in italics; the underlined date is based on the correlation of QM decline with the Lake Hino radiocarbon dated sequence. Circles in the Lake Verijärv diagram show dates not used for time scale calculation. Solid lines mark means of calculated ages, dashed lines mark the upper and lower error limits. Gray solid line is the polynom used for the time-scale. **B.** Radiometric chronology of the topmost part of sediment sequence of the Lake Verijärv supporting the varve counts. **B1.**  $^{137}\text{Cs}$  peaks in AD 1986 (Chernobyl catastrophe).  $^{137}\text{Cs}$  and  $^{241}\text{Am}$  results refer to the main nuclear weapon tests in AD 1963. **B2.**  $^{210}\text{Pb}$  chronology for the uppermost sequence of L. Verijärv. Constant initial concentration (CIC) and constant rate of supply (CRS)  $^{210}\text{Pb}$  dating model were used to calculate age. CRS model was accepted to determine dates.

## 4.2 Sediment composition

Sediment composition of L. Plaani allowed differentiation alternating gyttja and clayey gyttja beds, which comprise four distinct units in the sediment column (Fig. 7A; Fig. 3 in Paper III). The lowest unit (1029–967 cm) is blackish-grey homogeneous gyttja, which was formed before 8250 cal BP. The second unit (967–721 cm) is clayey gyttja, which accumulated between 8250 and 5400 cal BP. The third gyttja unit (721–497 cm; 5400–1100 cal BP) differs in the variability of its sediment composition. The topmost unit (497–443 cm; 1100 cal BP to the present) is represented by clayey gytt



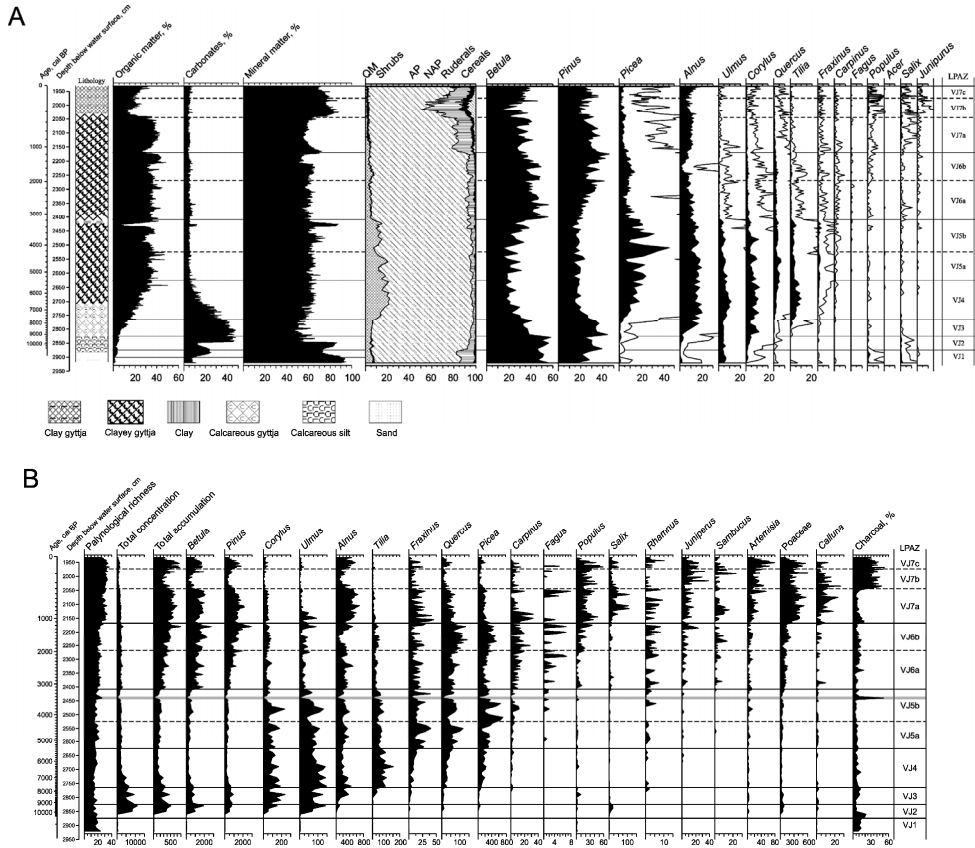
**Fig. 7** Lake Plaani, pollen analyses and sediment composition. **A.** Pollen percentage diagram and LOI results. **B.** Pollen influx diagram with palynological richness. Total concentration is divided by 1000, individual tree taxa are divided by 100.

Gyttja (units I, III) is characterized by high OM content, commonly 60–70%. In clayey gyttja (units II and IV) the abundance of organic and mineral matter are roughly equal. Carbonates constitute less than 5% of the sequence. The low content (25–35%) of mineral matter in the bottommost unit (–8300 cal BP) could reflect a drier climate and low lake levels in Estonia (Saarse and Harrison 1992). The increase in mineral compounds over 40% in the second unit is most plausibly the result of increased inputs of material from the steep slopes eroded by greater precipitation. High but variable OM content in sediments that accumulated between 5400 and 1100 cal BP suggests fluctuations in water level and sedimentation patterns. The sharp increase in mineral matter from 30 to 40% in the topmost unit (1100 cal BP–present) is indicative of the onset of arable farming and intensive erosion.

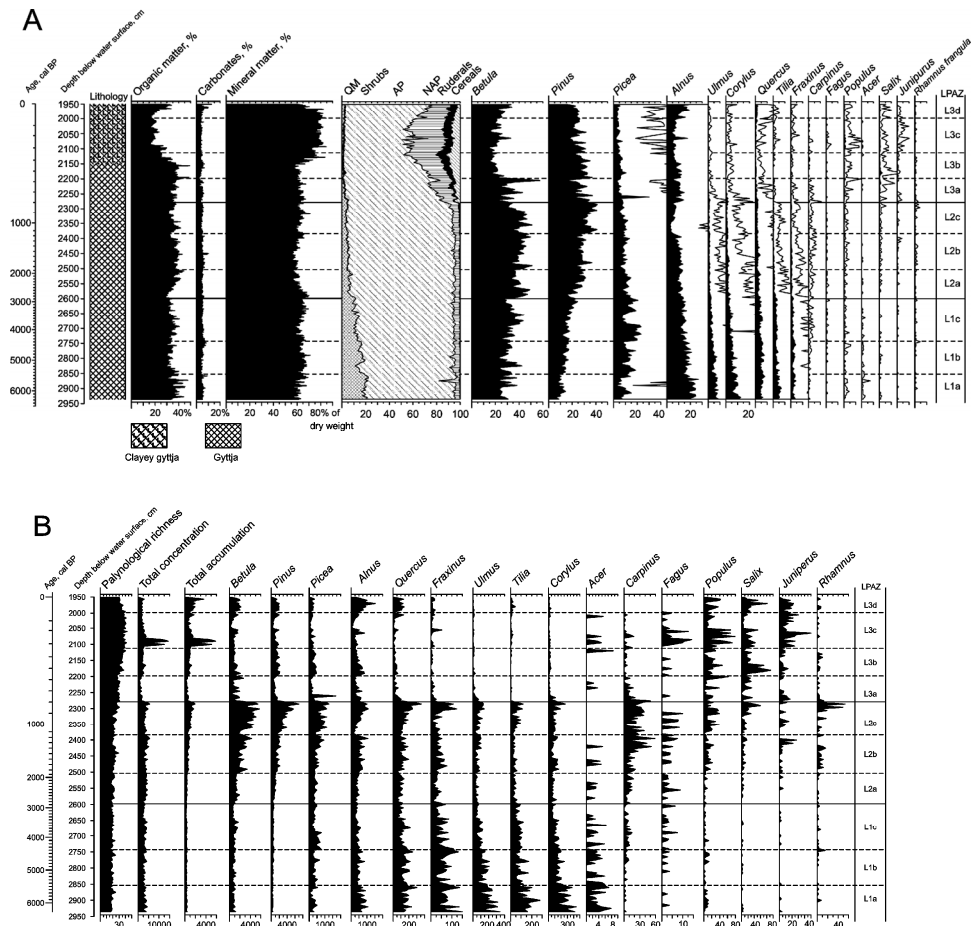
Sediment lithology of the profile of Verijärv is displayed in Fig. 8A. Seven distinct units were recognized in the main core. The lowest unit (2920–2865 cm) consists of sand with plant remains (Table 1 in Paper I). It is overlain by grey, slightly calcareous silt (2865–2850 cm), containing 10–25% carbonates and 71–86% mineral compounds (Fig. 8A; Fig. 3 in Paper I). Dispersed organic matter (OM) content is 1–4%. This unit is covered by laminated calcareous gyttja (2850–2734 cm) in which carbonates comprise up to 46–47%. Clayey gyttja at 2734–2030 cm forms the main sediment unit. Its composition is generally constant, except for the basal part between 2734 and 2650 cm, where the OM content steadily increases and then stabilizes around 35%, whereas the carbonate content decreases. In the rest of the clayey gyttja unit, the content of mineral and organic compounds is 50–60% and 30–40%, respectively. The portion of carbonates is low and unvarying, generally 3–5%. This unit contains a 9-cm thick clayey band characterized by high mineral matter (up to 85%) and low OM content (around 5%). Sediment composition is more variable in the uppermost part of the sequence. A decrease in organic matter content is seen at a depth of 2170 cm and in the topmost 1-m thick clay gyttja. Between 2039–2024 cm, OM content decreases from 35% to 5%, whereas mineral matter increases from 60 to 86%. Near the sediment surface OM content increases again to 33%.

The core of L. Lasva, consisting of gyttja and clayey gyttja, is characterized by a high sedimentation rate and homogeneous sediment composition, which becomes more minerogenic towards the surface (Fig. 9A; Fig. 2 in Paper II). The entire core exhibits by and large visible lamination (Fig. 3 in Paper II). The varves are thick, especially in the uppermost meter, in which 200 varves were counted. Some abrupt changes in organic (25–48%) and mineral matter content (48–69%) were observed in L1a PAZ, followed below by a rather uniform interval, in which organic matter comprised 30–35% and mineral matter 60–65%. The mineral matter content rose rapidly at 400 cal BP to 75–84% (Fig. 2 in Paper II). The proportion of organic matter declined first to ca 20%, and then increased to 30%, with a simultaneous inverse trend in the mineral matter

content. The carbonate content was almost constant, accounting for about 5% throughout the sequence (Fig. 2 in Paper II).



**Fig. 8** Verijärvi, pollen analyses and sediment composition. **A.** Pollen percentage diagram and LOI results. **B.** Pollen influx diagram with palynological richness. Total concentration is divided by 1000, individual tree taxa are divided by 100.



**Fig. 9** Lake Lasva, pollen analyses and sediment composition. **A.** Pollen percentage diagram and LOI results. **B.** Pollen influx diagram with palynological richness. Total concentration is divided by 1000, individual tree taxa are divided by 100.

### 4.3 Pollen stratigraphy

#### *Lake Plaani*

Both percentage and pollen accumulation diagrams were constructed (Fig. 7A, B). Pollen analyses of the Plaani sequence have revealed a continuous record from the beginning of the mid-Holocene (8400 cal BP) until the present. Five local pollen assemblage zones (LPAZ, Fig. 7; Figs 4, 5 in Paper III) were distinguished by means of numerical methods; their description is presented in Table 3. Pollen influx is the most abundant in PI 1 and in the lower part of PI 2, after which it decreases and remains stable in PI 3 and PI 4. Influx of arboreal pollen decreases in PI 5, while that of non-arboreal pollen increases (Fig. 7 B).

Pl 1 (1029–1000 cm; 8430–8310 cal BP) is characterized by abundant *Betula*, *Pinus* and *Picea* and a sharp decline in thermophilous species (Fig. 7A). Pollen assemblages between 1000 and 1020 cm (8310–8400 cal BP) were considered to correspond to the 8200 cal BP cold event (Paper III), which featured a decline in *Alnus*, *Corylus* and *Quercetum Mixtum* abundance and influx were recorded in this interval.

**Table 3.** Local pollen assemblage zones (LPAZ) of L. Plaani. P – *Pinus*, B – *Betula*, A – *Alnus*, Pi – *Picea*, Q – *Quercus*, T – *Tilia*, U – *Ulmus*, C – *Corylus*, NAP – non-arboreal pollen.

Local pollen assemblage zones (LPAZ)	Depth below water level (cm)	Age cal BP	Zone character
Pl 5 (Cereals-NAP)	441–517	0–1470	Maximum frequencies of cereals and NAP; open landscape, maximum palynological richness
Pl 4 (B-Pi-P-A)	517–635	1470–3710	Maxima of <i>Betula</i> and <i>Picea</i> , rise in <i>Pinus</i> , high <i>Alnus</i> with major decline at the end of LPAZ, decline in QM; the first sporadic occurrences of cereals and <i>Cannabis</i>
Pl 3 (Pi-A-Q)	635–765	3710–6270	<i>Picea</i> maximum, high <i>Alnus</i> , maximum of <i>Quercus</i>
Pl 2 (A-C-U-T)	765–1000	6270–8310	High frequency of <i>Alnus</i> , <i>Corylus</i> , <i>Ulmus</i> and <i>Tilia</i> ; increasing share of thermophilous species, concurrent with <i>Betula</i> decline
Pl 1 (B-P)	1000–1029	8310–8430	<i>Betula</i> and <i>Pinus</i> peaks coinciding with remarkable decline in <i>Alnus</i> and <i>Corylus</i> .

Pl 2 (1000–765 cm; 8310–6270 cal BP) is defined by an increasing abundance in thermophilous species coinciding with a decline in *Betula* pollen (Fig. 7A). Influx values decrease in the second half of the LPAZ (Fig. 7B).

Pl 3 (765–635 cm; 6270–3710 cal BP) is characterized by high abundance of *Picea* and maxima of *Quercus* and *Fraxinus*. *Alnus*, *Corylus*, *Ulmus* and *Tilia* pollen show a decline throughout the LPAZ. Pollen accumulation values are lower than the previous LPAZ, except for those of *Picea*, *Quercus* and *Fraxinus*.

Pl 4 (635–517 cm; 3710–1470 cal BP) is characterized by *Betula* and *Pinus* rising to their maxima, while *Picea* and QM decline (Fig. 7A). *Carpinus* achieves its maximum spreading. At the end of the LPAZ, *Alnus* declines, coinciding with an increase in non-arboreal pollen (Fig. 7A, B).

Pl 5 (517–441 cm; 1470 cal BP–present) consists of pollen assemblages indicative of landscapes influenced by human activity. Among trees, *Betula*,

*Pinus* and *Alnus* dominate, whilst *Picea* declines (Fig. 7A). Herb pollen increase and the tree pollen decrease almost 20% as a result of forest clearances and crop cultivation.

#### *Lake Verijärv*

Percentage and pollen accumulation diagrams are displayed in Fig. 8 A, B. Numerical zonation distinguished seven local pollen assemblage zones (LPAZ) (Table 4; Fig. 8; Figs 6, 7 in Paper I). The lowest pollen zone (VJ1) is characterized by large amounts of non-arboreal pollen, especially Cyperaceae and very low pollen influx. The following two LPAZ-s (VJ2 and VJ3) are characterized by abundant *Pinus* and *Betula*. PAZ-s VJ4 and VJ5 are distinguished by increased amounts of *Quercetum Mixtum* (QM). VJ6 is characterized by decreased QM, high abundance of *Betula* and an increase in *Pinus*. VJ7 is the LPAZ in which human impact is clearly noticeable due to decreased arboreal pollen and a high abundance of cereal pollen.

VJ 1 (2920–2875 cm; >10,300 cal BP) is noted for a high occurrence of *Betula*, *Pinus*, *Ulmus* and NAP and indicates a semi-open landscape (Fig. 6 in Paper I). *Populus* and *Salix* as pioneer trees during open landscape forestation are also present in relatively high abundance (Fig. 8A). Accumulation of pollen was low because of rapid sedimentation of sand (Fig. 8B).

VJ 2 (2875–2825 cm; 10,300–9159 cal BP) is characterized by maximum abundances of *Betula* (55%) and *Pinus* (45%) pollen. *Alnus* has its rational limit at the top and *Corylus* at the base of the zone (Fig. 8A). NAP decreases at the border of VJ1/VJ2. Total pollen concentration maximizes at the end of this LPAZ (Fig. 8B).

VJ 3 (2825–2765 cm; 9159–7700 cal BP) is depicted by the emergence of *Picea*, *Tilia* and *Quercus* almost simultaneously at the end of the zone (Fig. 8A). Accumulation for *Corylus* pollen reaches its maximum (Fig. 8B). Greatly decreased herb pollen suggests a more wooded landscape (Fig. 6 in Paper I).

VJ 4 (2765–2625 cm; 7700–5350 cal BP) is characterized by relatively low abundance of *Betula* (ca. 20%) and *Pinus* (<20%) but increased *Picea* and QM (*Ulmus*, *Tilia*, *Fraxinus*, *Quercus*) pollen percentages (Fig. 8A). *Ulmus* pollen percentage values reach its maximum (10%) at 6500 cal BP. As *Betula* and *Pinus* reduce, the total accumulation decreases (Fig. 8B).

VJ 5 (2625–2408 cm; 5350–3200 cal BP) is the LPAZ in which *Picea* dominates. QM, *Alnus* and *Corylus* are also abundant, whereas *Betula* and *Pinus* persist in low abundance (Fig. 8A). Based on *Picea* and QM, this zone is divided into two subzones. VJ 5a is featured by increasing *Picea* and decreasing QM, whereas VJ 5b is noted for decreasing trend of *Picea* and increase of *Betula*. A sharp peak in the charcoal curve and a decrease in all tree and shrub pollen accumulation values 3450 cal BP coincides with a 9-cm thick clayey band in upper part of VJ 5b (Fig. 8A, B). This band refers to a forest fire near Verijärv, which opened the landscape and released erosion and mineral matter influx into the lake.

**Table 4.** Local pollen assemblage zones (LPAZ) of L. Verijärv. P – *Pinus*, B – *Betula*, A – *Alnus*, Pi – *Picea*, Q – *Quercus*, Fr – *Fraxinus*, T – *Tilia*, U – *Ulmus*, C – *Corylus*, Po – *Populus*, NAP – non-arboreal pollen.

Local pollen assemblage zone (LPAZ)	Depth below water level (cm)	Ages cal BP	Zone and subzone character
VJ7c P-B	1930–1974	0–85/ 0–70	Increase in <i>Betula</i> and <i>Alnus</i> and decrease in anthropogenic indicators
VJ7b B-P-cereal	1974–2045	85–330/ 70–305	Maximum of NAP (cereals, ruderals, Poaceae, Cyperaceae, <i>Rumex</i> , <i>Trifolium</i> ), <i>Populus</i> , <i>Juniperus</i> and algae. Reduction of <i>Alnus</i> and <i>Picea</i>
VJ7a B-P-A	2045–2168	305–1170	Reduction of total NAP, upper maximum of <i>Salix</i> . Regular records of <i>Secale</i> . Rise of algae
VJ6b Pi-B-P	2168–2268	1170–1970	Maximum of <i>Pinus</i> , slight rise in <i>Picea</i> , minimum of <i>Alnus</i>
VJ6a B-P-Pi	2268–2408	1970–3200	<i>Betula</i> , <i>Pinus</i> and <i>Alnus</i> dominating
VJ5b Pi-Q-Fr	2408–2525	3200–4250	Rise of <i>Betula</i> , maximum of <i>Picea</i> after which reduction begins. Sharp decrease in QM at zone upper limit
VJ5a A-T-Pi-Q	2525–2625	4250–5350	Maxima of <i>Quercus</i> , <i>Fraxinus</i> . Large proportion of QM
VJ4 U-T-C-Pi	2625–2765	5350–7700	Rise in <i>Picea</i> , <i>Quercus</i> , <i>Fraxinus</i> . Maximum of <i>Ulmus</i> , <i>Tilia</i> ; low abundance of <i>Betula</i> and <i>Pinus</i>
VJ3 A-U-C	2765–2825	7700–9150	<i>Betula</i> reduces strongly, rise in <i>Alnus</i> , <i>Corylus</i> , appearance of <i>Tilia</i> , <i>Picea</i> , and <i>Quercus</i> .
VJ2 B-P-U	2825–2875	9150–10300	High frequency of <i>Betula</i> and <i>Pinus</i> , relatively abundant <i>Salix</i> and Cannabaceae pollen. Abundance of <i>Tetraedron minimum</i> particles. Significant drop in NAP.
VJ1 B-P-U-Po	2875–2920	10300<	High share of <i>Betula</i> , <i>Pinus</i> and <i>Populus</i> and NAP. Early arrival of <i>Ulmus</i> . <i>Tetraedron minimum</i> particles are richly present. Semi-open land.

VJ 6 (2408–2168 cm; 3200–1170 cal BP) is characterized by decreased values of *Picea*, *Ulmus*, *Tilia* and *Fraxinus* and increases in *Betula* and *Pinus* pollen. Among QM, *Quercus* pollen is the most abundant (Fig. 8A). In the lower part of the zone, subzone VJ 6A is distinguished by high percentages of *Betula* and an increasing trend of *Pinus*. In VJ 6B, *Alnus* reaches its minimum between 1500–1650 cal BP, which coincides with the start of continuous cereal curve (Fig. 6 in Paper I). The second rise of *Picea* occurs at the same time (Fig. 8).

VJ 7 (2168–1930 cm; 1170 cal BP–present) is the LPAZ containing pollen indicative of cultural landscapes. An abrupt rise of herb pollen occurs, among which *Secale*, Poaceae, Cyperaceae and *Rumex* are the dominating taxa (Fig. 6 in Paper I). *Betula* and *Pinus*, and to a lesser extent *Alnus* dominate among trees. *Picea* declines to less than 5%. The maxima of crop farming indicators (*Secale*, *Triticum*, *Hordeum*), cattle breeding indicators (Poaceae, *Rumex*, *Trifolium*, *Juniperus*) and ruderal communities are observed (*Artemisia* and *Urtica*; Fig. 8 in Paper I). High abundance of *Salix*, *Populus* and *Juniperus* also indicates a more open landscape (Fig. 8B). Subzones are described in Table 4.

#### *Lake Lasva*

Both percentage and pollen accumulation diagrams were constructed also for the L. Lasva profile (Fig. 9 A, B). Three major local pollen assemblage zones (PAZ) were identified in the Lake Lasva, roughly corresponding to the Atlantic (with the broad-leaved forest scenery), Subboreal (characterizes transition from a natural *Betula-Pinus* mixed forest to an agricultural landscape) and Subatlantic (mostly spectra of cultural landscape) chronozones (Mangerud *et al.* 1974). These PAZs were divided into ten local pollen assemblages subzones which reflect changes in pollen representation and stratigraphy (Table 5, Fig. 9; Figs 5 and 6 in Paper II).

L 1 (2900–2563 cm; 6275–2870 cal BP) is characterized by high QM frequency, which continuously declines, as does *Alnus*, and by increasing abundance of *Pinus* (Fig. 9A).

L 2 (2563–2243 cm; 2879–800 cal BP) is characterized by a decrease in *Picea* and QM and increasing *Betula* and *Pinus*, especially their accumulation values. This section also sees a maximum in *Carpinus* (Fig. 9A, B). A decrease in *Alnus* is similar to other lakes and occurs in this LPAZ at about 1200–1100 cal BP.

L 3 (2243–1915 cm; 800 cal BP–present) is the LPAZ of human-influenced landscape, in which non-arboreal pollen increases to 40% (Fig. 9A). The pollen concentration initially decreased almost half, started to recover at 550 cal BP and peaked at 300 cal BP (Fig. 9B).

**Table 5.** Local pollen assemblage zones (LPAZ) of L. Lasva. NAP – non arboreal pollen, P – *Pinus*, B – *Betula*, U – *Ulmus*, T – *Tilia*, Fr – *Fraxinus*, Pi – *Picea*, QM – *Quercetum mixtum*.

Local pollen assemblage zone (LPAZ)	Depth below the water level (cm)	Ages cal BP	Zone and subzone character	
L3d	1915–1963	1–55	P-B-Cerealia-NAP	Rise in <i>Betula</i> and <i>Alnus</i>
L3c	1963–2078	55–340		Maximum of <i>Rumex</i> and Poaceae
L3b	2078–2163	340–570		Maximum of <i>Secale</i>
L3a	2163–2243	570–800		Rise in Poaceae and Cerealia
L2c	2243–2348	800–1150	B-P	Minimum of <i>Alnus</i> , maximum of <i>Pinus</i>
L2b	2348–2468	1150–1870		Stable period
L2a	2468–2563	1870–2870		Decline in <i>Picea</i>
L1c	2563–2708	2870–4380	U-T-Fr-Pi	Maximum of <i>Picea</i>
L1b	2708–2818	4380–5460		Decline in QM
L1a	2818–2900	5460–6275		Highest QM, <i>Corylus</i> and <i>Alnus</i>

## 5. DISCUSSION

### 5.1 Chronology

There were no difficulties in constructing time-scales for L. Plaani and Lasva. All available  $^{14}\text{C}$  dates fit well with the age curve (Fig. 6A). Construction of time-scale for L. Verijärv was more complicated and is discussed below.

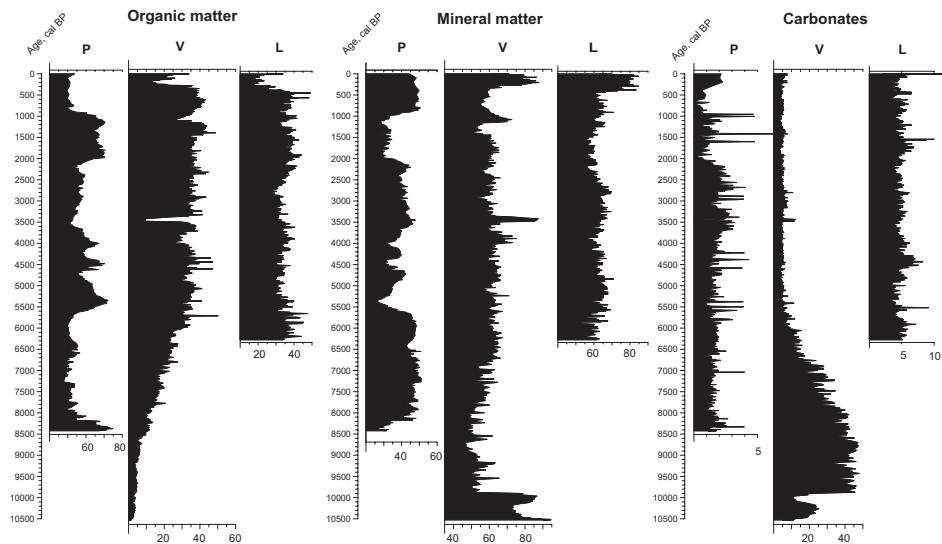
In the upper part of the Verijärv sequence the laminated structure of deposits is rather irregular: one varve sometimes consists of up to five laminae, which makes actual annual lamination difficult to distinguish (Fig. 2 in Paper I). This irregularity could be a reflection of strong rainfall, floods or economic events (road building, field extension, lake level regulation), which may give rise to additional laminae in the sequence. As an experiment, laminae within one meter of sediment were counted. The complication arising from conspicuous varve character was overcome by combining varve counting and radioactive dating. The age-depth model of the uppermost meter is based on varve counts supported by  $^{137}\text{Cs}$ ,  $^{241}\text{Am}$  and  $^{210}\text{Pb}$  dating (Fig. 6B and Fig. 4 in Paper I). A gamma counting of  $^{137}\text{Cs}$  and  $^{241}\text{Am}$  identified a peak at a depth of 1961 cm that was interpreted as a result of nuclear weapon testing in 1963 (Fig. 4 in Paper I). This peak correlates well with the varve counts. The sample at the depth of 1945 cm shows a distinct peak from the Chernobyl event in 1986 and also correlates with the varve count results, thus verifying the annual nature of lamination in the topmost part of the sequence.

The chronology of the rest of the Verijärv sequence is based on the AMS dates and correlation with the radiocarbon-dated pollen diagrams from the Hino kettlehole and Tõugjärv (Kihno 1998; Laul and Kihno 1999; Veski *et al.* 2004, 2005). However, some AMS  $^{14}\text{C}$  dates do not fit the previous pollen stratigraphy (Saarse *et al.* 1996). The  $990\pm 50$  BP (bulk gyttja) and  $1590\pm 60$  BP (aquatic moss) dates are too old. The AMS date  $1365\pm 60$  BP (Ua-19534) of a piece of wood also appears to be too old and the wood could have been redeposited. Similarly, the AMS date  $2300\pm 40$  BP (Ua-23874) on twigs, dating a sharp decline of broad-leaved trees in southeast Estonia, seems to be too young. The reason for such diversity of AMS  $^{14}\text{C}$  radiocarbon dates is unclear as — judging from the preserved lamination — sedimentological disturbance is unlikely. With respect to the aquatic moss and bulk gyttja dates, a reservoir effect and contamination with older carbon is possible (Olsson and Kaup 2001, 2002). Variable sources of carbon (bicarbonate in water, carbon from humus, dissolved  $\text{CO}_2$  from the atmosphere, dissolved bicarbonate from limestone and other weathered rock) are available to the plants forming gyttja and this can make radiocarbon dates of gyttja and plants problematic (<http://www.c14dating.com/mud.html>). All these dates showed notable negative  $\delta^{13}\text{C}$  values. These dates were excluded from the age-depth curve, which is calculated as the fourth-power polynomial (Fig. 6A). The sharp and final decline of broad-leaved trees is correlated with the chronology of peat from the

Hino kettle hole ( $3065 \pm 75$  BP, Tln-1981; Laul and Kihno 1999) and taken as 3200 cal BP which was the most reliable date before the Verijärv study. The other  $^{14}\text{C}$  AMS dates are consistent with the pollen stratigraphy and earlier radiocarbon dates from the studied mires and lakes nearby (Ilves and Mäemets 1987; Punning *et al.* 1995; Veski *et al.* 2004). The good correlation of mid- and early Holocene dates with the pollen stratigraphy could indicate a stable environment, as most of the lake catchment was wooded, hindering erosion and inhibiting the inflow of old carbon (Poska and Saarse 2002).

## 5.2 Sediment composition and interpretation

Reconstructed timescales allowed construction of summary diagrams of LOI results on the timescale for comparative analysis of sedimentation in different lakes (Fig. 10). The order of lakes in the figures with time-scale diagrams (Plaani – Verijärv – Lasva) follows the direction from south to north and from the top of the heights to its foot (Fig. 2).



**Fig. 10** Comparison of LOI results on the age-scale. P – Lake Plaani, V – Lake Verijärv, L – Lake Lasva.

### *Organic and mineral matter*

L. Lasva and Verijärv are deep and their visually uniformly laminated sediments display no notable events from 6000 cal BP in Lasva and 9500 cal BP in Verijärv until 1000 ca BP with the exception of a beige clay band (3450 cal BP, 2434–2443 cm) in L. Verijärv that coincides with a charcoal peak

obviously resulting from a large forest fire. This fire event opened the landscape, enhanced erosion and mineral matter influx into the lake (Paper I). The sharp increase in mineral matter in the topmost parts of the named sections before 1000 cal BP is correlated well with the start of arable farming (Figs 14–15) and intensive erosion (Fig. 10). In L. Verijärv, the generally increasing content of mineral matter between 1200 cal BP and present shows two peaks. This may infer that the people who established the area moved their fields away from the lake until 300 cal BP, when the lake shores were cultivated again. An increase in organic matter in all lakes during the last 100 years is probably related to the increasing use of fertilizers, which caused an elevated organic production in lakes.

Sediment composition in L. Plaani is much more complex than that of L. Verijärv and Lasva, due obviously to its different morphology. L. Plaani is shallow, which means that the water is warmer and light reaches the bottom, facilitating production of organic matter. The changing contents of organic and mineral matter in L. Plaani reflect changes in climatic conditions, i.e. warming or cooling, which increased or decreased organic production. Similarly, the sediment layers low in mineral matter in the lower part of the Plaani sediment column (before 8000 cal BP) could also be the result of drier climatic conditions, which inhibited deposition of mineral matter (Saarse and Harrison, 1992).

### *Carbonates*

Carbonate content (Fig. 10) is low in the studied lakes (about 5% in L. Lasva and Verijärv, 2–3% in L. Plaani). Nonetheless, the carbonate pattern in L. Verijärv is quite peculiar. Sediments older than 10,000 cal BP are minerogenic and rich in carbonates. About 10,000 cal BP, mineral matter content decreased very sharply, whilst carbonates increased and remained abundant until 8000 cal BP. This sharp change in sediment composition reflects perhaps a major change in feeding of the lake. As L. Verijärv is located at the crossing of two ancient valleys, this change in sediment composition most probably resulted from termination of mineral matter inflow through one or both valleys and isolated the lake. A gradual decrease in carbonate concentration from 8000 cal BP until 6000 cal BP, during warming climate of Atlantic chronozone, reflects either elevated organic production resulting in a drop in pH or an end of carbonate-rich groundwater feeding the lake.

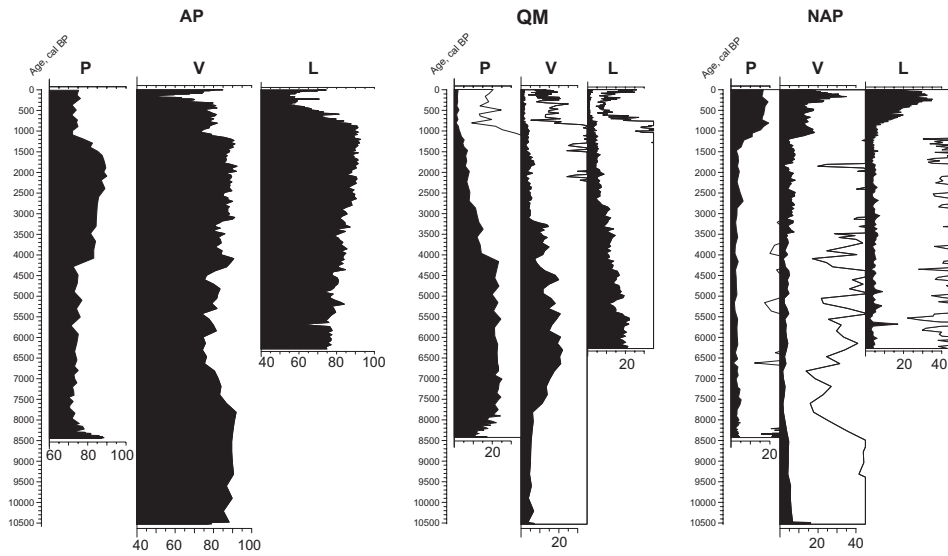
### 5.3 Vegetation dynamics

Pollen analyses of the Lake Verijärv sequence revealed a continuous record since the Early Holocene (10,500 cal BP), that of the Lake Plaani sequence since the beginning of the mid-Holocene (8400 cal BP) and of the Lake Lasva since the mid-Holocene (ca 6300 cal BP). A brief description of pollen assemblage zones distinguished by numerical methods is presented in Tables 3–5. The Verijärv diagram (Fig. 8 A) and Table 4 give evidence for the emergence of a forest in the district 10,500 cal BP. This forest started with scattered *Betula* and *Pinus* woods with some *Ulmus*. *Corylus* and *Alnus* gained prominence along the previous species about 9000 cal BP. *Tilia* and *Picea* are richly present since 8000 cal BP and *Quercus* several centuries later. Broad-leaved trees persist in high amount until about 3000 cal BP in all three lakes. Large scale forest clearance and land opening started 1500 cal BP in the Lake Plaani area, 1300 cal BP in the Lake Verijärv surroundings and 800 cal BP in the vicinity of Lake Plaani.

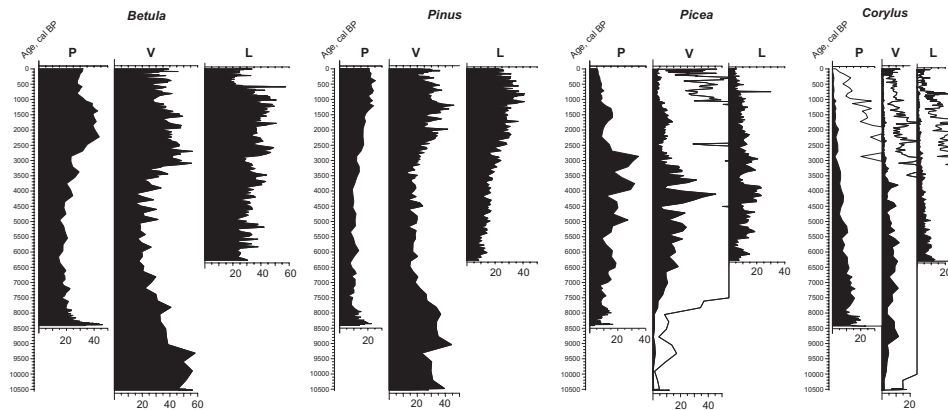
Compared to other parts of Estonia, the Haanja Heights are distinguished by an earlier arrival of *Picea*, *Ulmus*, and *Quercus*; and by longer-lasting common broad-leaved deciduous forests (Paper IV). The latter may be attributed to a mosaic landscape with suitable habitats and to a delayed human influence compared to other parts of Estonia.

Use of the common timescale allowed comparison of the distribution of the taxa in the lakes (Figs 10–14). A summary diagram of arboreal (AP) and non-arboreal pollen (NAP) and *Quercetum Mixtum* (QM, Fig. 11) shows higher amounts of QM in southernmost Lake Plaani compared to the northern lakes. A forest decline at about 1000 cal BP also started first at L. Plaani before reaching L. Verijärv and Lasva.

Comparison of pollen percentages of different tree taxa shows prevalence of *Betula* and *Pinus* pollen between 10,500–7800 cal BP (Fig. 12). Their share was higher in Verijärv than in Plaani, because some thermophilous tree taxa were already present in the central part of Haanja Heights at this time. Afterwards both *Betula* and *Pinus* rapidly decreased, being surpassed until 3200–3000 cal BP by QM species and *Picea* (Figs 11 and 12). Since 3000 cal BP, *Betula* and *Pinus* have been the dominant species, although intensive human activity and crop cultivation around 800–1000 cal BP diminished forests in general, reducing *Betula* and *Picea* in particular (Fig. 12).



**Fig. 11** Comparison of the general pollen percentage diagrams of different lakes on the age scale. AP – arboreal pollen, QM – *Quercetum mixtum*, NAP – non-arboreal pollen, P – Lake Plaani, V – Lake Verijärv, L – Lake Lasva.



**Fig. 12** Comparison of dominant tree pollen percentage diagrams of different lakes on the age scale. P – Lake Plaani, V - Lake Verijärv, L - Lake Lasva.

*Picea* immigrated into Estonian territory from the south-east (Saarse and Veski 2001; Saarse *et al.* 1999). The first appearance of *Picea* is not recorded in the L. Lasva diagram, but the earlier arrival of the *Picea* front into the Plaani area compared to the Verijärv area (Fig. 12) is clearly noticeable. This is consistent with the known immigration pattern of *Picea* (Saarse 2004). Maxima of *Picea*

in the lakes occurred between 4500 and 3000 cal BP, starting a bit later in the Plaani area and ending a bit earlier in the Verijärv area.

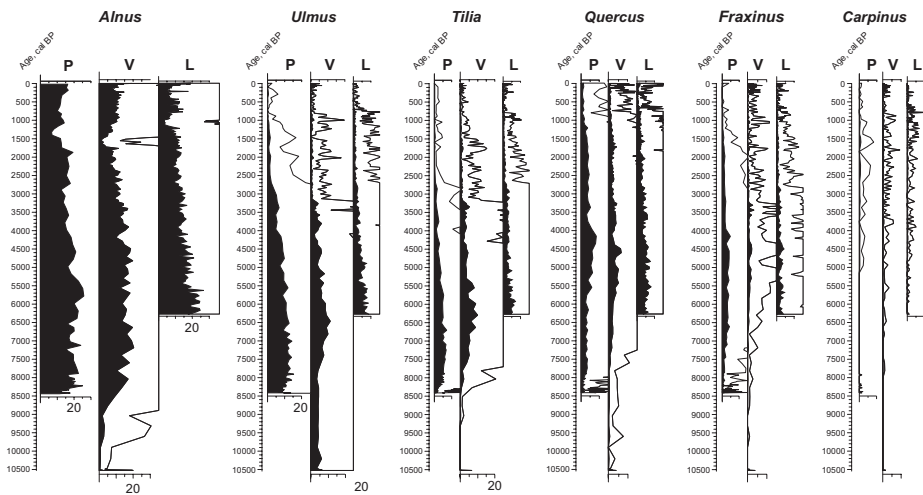
*Corylus* immigrated into the area before 10,000 cal BP (Fig. 12) from the west (Saarse and Veski 2001) and about 200 years earlier than *Alnus* (Saarse 2004). Between 9000 cal BP and 5000 cal BP, *Corylus* was particularly abundant — especially in the Plaani area — being one of the five dominant tree species. Afterwards its share slowly decreased and it lost its importance first in the Verijärv area. Since 3000 cal BP *Corylus* has been present as a second-order tree species (Fig. 12).

According to the isochrone maps of tree arrivals to Estonia (Saarse 2004), most broad-leaved taxa (*Ulmus*, *Tilia*, *Quercus*) arrived from the south; only *Alnus* seems to have immigrated from the coastal districts, though it was present in the Haanja Heights a little earlier than its surrounding areas. Compared to the biostratigraphical sites in the east and west, the Haanja Heights seems to serve as an immigration bridge between south and north. Compared to the data from Saarse 2004, most of the tree taxa immigrating from the south were present in this region first.

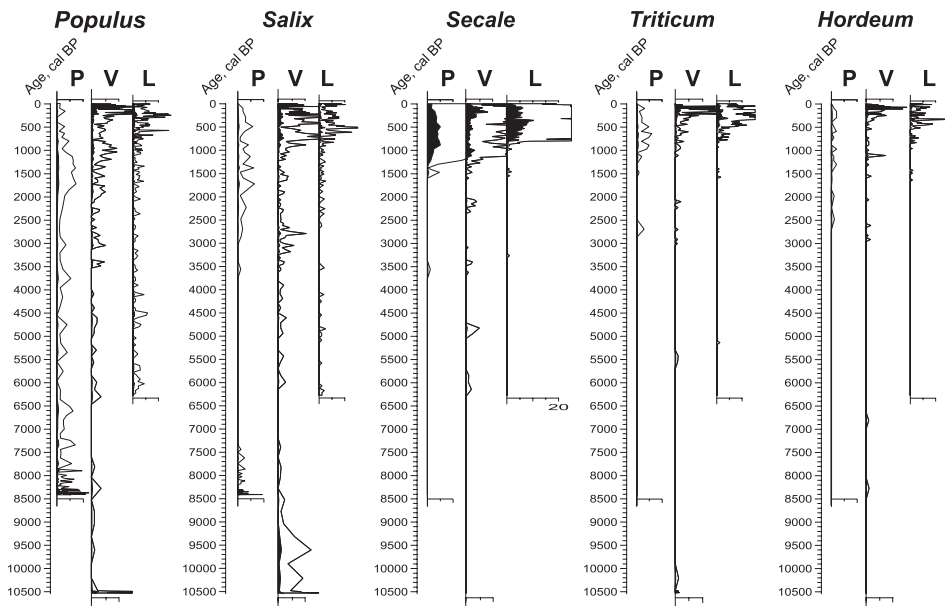
*Ulmus* was present from the early Holocene and culminated around 6500 cal BP, with a maximum best expressed in Verijärv (Fig. 13), but less distinct in Plaani. Perhaps due to good growing conditions in the Plaani area, the presence of *Ulmus* was around 10 % until 5000 cal BP and a distinct maximum is unrecognizable. Afterwards it gradually declined with several small scale recoveries. Its final decline occurred at about 3200 cal BP.

All broad-leaved species suffered during the cold event between 8500 and 8000 cal BP, which corresponds to the so-called “8200 cold event”. This change was studied in detail in the Plaani sequence in which great declines in *Alnus*, *Corylus* and *Quercetum Mixtum* (QM) percentages and influx values were recorded (Fig. 6 in Paper III; Fig. 7B here). Similar changes are also observed in the Rõuge Tõugjärv site (ca 10 km to north-west of Plaani; Fig. 1) between 8400 and 8080 cal BP and also interpreted as “the 8200 cold event” (Veski *et al.* 2004). This climate reversal is characterized by cold winters, humid summers and strong seasonal contrasts (Hammarlund *et al.* 2005; Seppä *et al.* 2005).

*Alnus* frequencies (Fig. 13) were high between the “8200 event” until 1500 cal BP, when *Alnus* suffered a major decline in the Plaani and Verijärv areas, but subsequently recovered quickly to the previous level. The same event occurred in the Lasva area somewhat later, around 1200 cal BP. Similar non-contemporaneous (700, 1000 and 1400 cal BP) *Alnus* declines have been documented in southern Finland (Sarmaja-Korjonen 2003) and are related to the onset of the Iron Age human activity. The same relationship could also apply in Estonia; just after the *Alnus* decline a continuous curve of *Secale* starts (Fig. 14). *Alnus* coppices were obviously cleared for new fields, as *Alnus* grows on fertile soils. *Alnus* could also have been used as fuel for iron melting.



**Fig. 13** Comparison of termophilous pollen percentage diagrams of different lakes on the age scale. P – Lake Plaani, V – Lake Verijärv, L – Lake Lasva.



**Fig. 14** Comparison of shrub and cereal pollen percentage diagrams of different lakes on the age scale. P – Lake Plaani, V – Lake Verijärv, L – Lake Lasva.

*Tilia*, *Quercus* and *Fraxinus* started to expand almost simultaneously between 8500–8000 cal BP (Fig. 13), although *Fraxinus* was less abundant than the others. *Tilia* peaked around 6300–6000 and declined after 5300 cal BP. A major decline in *Tilia* started around 3300 cal BP in Verijärv and about 2700 cal BP in

Plaani and Lasva similarly to *Ulmus*. *Quercus* also immigrated to the Haanja Heights rather early, but was long surpassed by *Tilia* and *Ulmus* and reached maximum between 4500 and 4000 cal BP, first in Verijärv and then in Plaani. In Lasva the *Quercus* maximum is not clearly expressed, because of its overall high abundance level (around 5%) before 4000 cal BP. The first regular occurrence of *Fraxinus* starts 8500–7500 cal BP with a maximum between 7000–4000 cal BP in Plaani and perhaps in Lasva. In the Verijärv region both the share and distribution of *Fraxinus* is smaller. *Carpinus* immigrated about 6500 cal BP and its regular low finds were registered up to 1000–700 cal BP (Fig. 13). Scattered grains of *Populus* and *Salix* were encountered throughout the entire Holocene, being more regular during the last 2000 years (Fig. 14).

The broad-leaved trees were abundant between 8000–3000 cal BP when the Haanja Heights was rather densely forested. Comparison of pollen immigration and distribution in L. Plaani and Verijärv clearly reveals a south-north direction in dynamics of thermophilous taxa (*Ulmus*, *Tilia*, *Quercus* and *Fraxinus*). In the southernmost site (Lake Plaani) all these taxa immigrate earlier and remain longer at high frequencies than in more northern regions (Fig. 13). In the northernmost L. Lasva the broad-leaved trees maintained their high abundance about as long as in Plaani. At 1300–1000 cal BP large-scale forest clearances and expansion of farming started and *Ulmus* and *Quercus*, which were already in low abundance, diminished even further (Fig. 13).

All studied limnic pollen records have distinctive features incomparable with the other lakes; they are described in papers I–III. The L. Plaani pollen diagram displays a decrease in *Corylus*, *Alnus* and QM values characteristic of the cold event around 8500 cal BP. These changes are like those of Tõugjärv, where this cold event was first recognized, and confirm that this climatic signal can be recognized both in deep (Tõugjärv) and shallow (Plaani) settings. The L. Verijärv sequence displays evidence of a catastrophic forests fire about 3450 cal BP, which led to intensive soil erosion and the accumulation of a thick clay layer, as indicated by a peak in charcoal and a decrease in arboreal pollen. In the L. Lasva sequence, a sharp peak of aquatics (*Nuphar*, *Nymphaea*) at about 5700 cal BP can be attributed to water level changes or a random aggregate of aquatic pollen collected and dropped by a bee.

## 5.4 Human impact reflected in pollen diagrams and land-use history of the Haanja Heights

### *Early Mesolithic* (before 8500 cal BP)

In wooded areas, the environmental impact of pre-agrarian humans is generally insignificant and could be traced in the abundance of apophytes, in changes in tree pollen spectra, in the ratio of arboreal to non-arboreal pollen and in charcoal dust (Behre 1981; Berglund 1991). In the L. Verijärv area, some traces of human presence may be indicated by the continuous curve of ruderals (Fig. 15) and less common dry pastures, but this pattern could also be entirely natural. The first finds of *Triticum*-type pollen is also related to this period, but this observation is not in accordance with earlier studies (Paper III) and may be a result of modern contamination (pollen were counted in summer when cereals were blooming) or originate from wild grasses with similar pollen morphology.

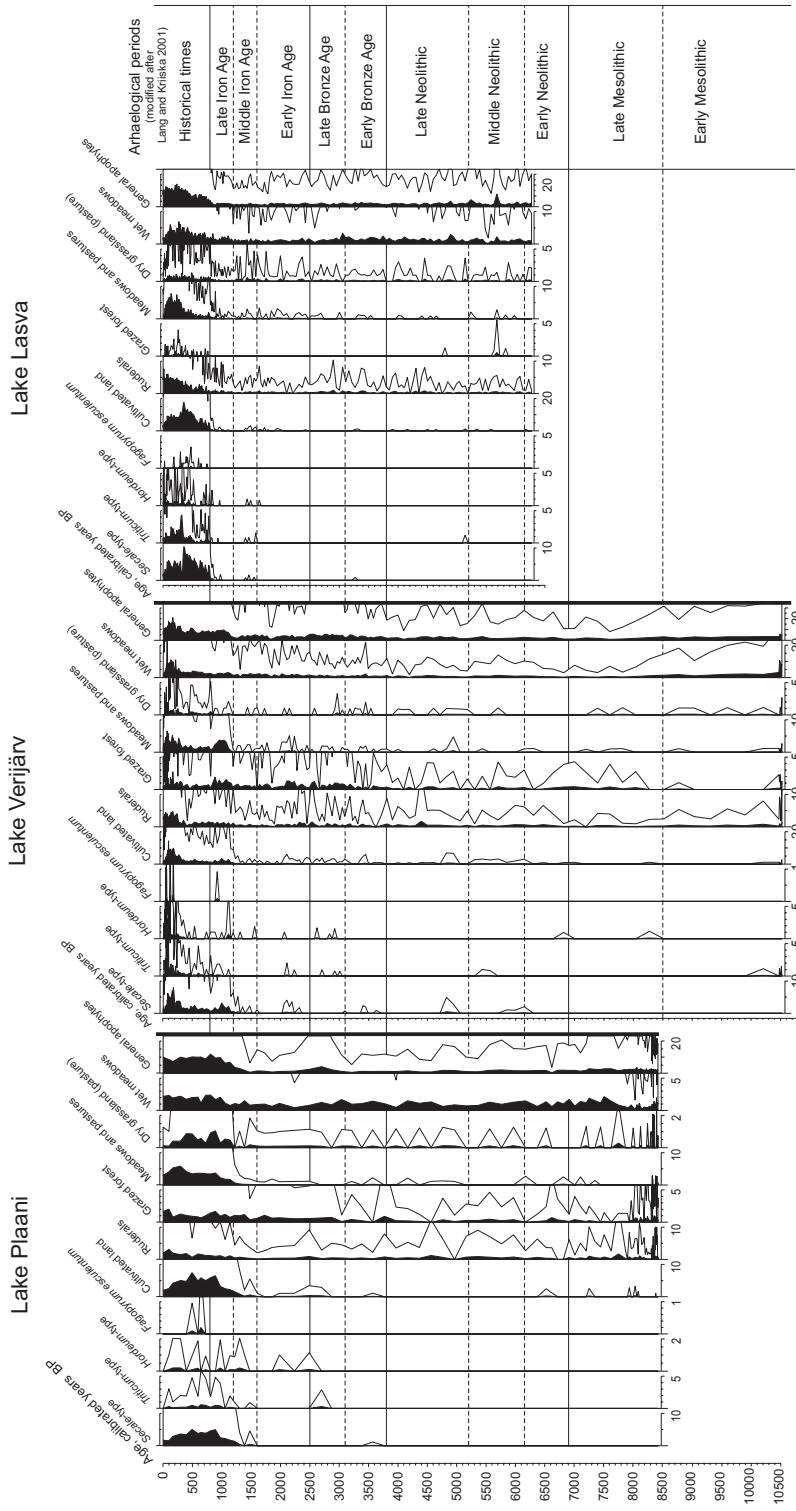
### *Late Mesolithic* (8500–6900 cal BP)

Increased NAP values, especially *Urtica*, and elevated charcoal particles in the Late Mesolithic in the L. Plaani section (between 7700–7200 cal BP; Fig. 7 in Paper III) may be evidence of small-scale human disturbance. Artifacts and radiocarbon dates from the recently discovered settlement sites confirm the presence of Mesolithic communities in the Haanja Heights (Kiristaja 2003; Konsa 2003). Low but almost continuous curves of ruderals, dry pasture and grazed forest indicators, especially *Artemisia*, Chenopodiaceae and *Urtica* pollen, and occurrence of *Pteridium* spores (Fig. 8 in Paper I) may be related to some extent to human influence at the end of Mesolithic period in the vicinity of Lake Verijärv (Fig. 15), but human impact on vegetation is still very insubstantial.

### *Neolithic* (6900–3800 cal BP)

Indicators of Neolithic human activity in pollen diagrams are also rather weak and only the combination of pollen and archaeological data suggest human impact on vegetation.

Several indicators might refer to human activity. A decrease in *Picea*, and scattered finds of *Rhamnus frangula*, *Viburnum* and *Sambucus* pollen could be a consequence of small-scale opening of the landscape (Königsson *et al.* 1998; Ralska-Jasiewiczowa and van Geel 1998). Changes in *Corylus* may also indicate human influence (Dumayne-Peaty and Barber 1998). Spruce, pine and birch declined in particular, due to their being used for heating and building of houses during Neolithic period (Jaanits *et al.* 1982). Nonetheless, the pollen record is insufficient to reveal human impact without archaeological data.



**Fig. 15** Summary pollen diagrams on human impact.

The first sign of Neolithic human impact in the pollen spectra is found in the Middle Neolithic (6100–5100 cal BP) and comprises a short-term QM decline in the L. Verijärv and Lasva diagrams (Fig. 11). This decline coincides with the establishment of the Tamula settlement and burial site with more than 20 graves about 7 km NW of Verijärv and is dated as 5310±85, Ua-4828 (5950–6190 cal BP) (Jaani *et al.* 1982). According to artifacts, this settlement site was in use until at least 4000 cal BP (Lang and Kriiska 2001) (a radiocarbon date from a wooden pole is 3650–4150 cal BP). During the existence of the Tamula settlement site (ca 6000–3600 cal BP), *Ulmus* and *Tilia* influx values decreased and regeneration occurred only after abandonment of the settlement (Fig. 7 in Paper I). A similar decline in *Ulmus* and QM species is noticeable also in percentage data (Fig. 8A). Middle Neolithic human impact also initiated the first single *Triticum*-type pollen appearance associated with *Convolvulus*, *Urtica*, and *Humulus/Cannabis*-type pollen in L. Verijärv (Fig. 8 in Paper I) and could be indicative of restricted tillage. Pollen grains of *Secale*-type appearing at the beginning of the Middle Neolithic and in Late Neolithic obviously represent weed rye (Fig. 15). In the L. Lasva diagram (Fig. 11), a sharp peak in NAP and a decline in QM (Fig. 9 A) coincide with the founding of the Kääpa settlement. *Triticum* pollen appeared at the Middle/Late Neolithic transition above the peaks of NAP and charcoal (Fig. 5 in Paper II, Fig. 15). As the first pollen of *Plantago lanceolata* was recorded soon after this event, some kind of tillage is likely to have occurred.

A reduction in *Ulmus*, fluctuations in *Betula* and *Picea* and good representation of *Artemisia*, *Urtica* and *Pteridium* in all diagrams are interpreted as traces of forest disturbance in the Late Neolithic period (5100–3800 cal BP; Paper IV). These modest disturbances may be related to pastoral farming rather than crop cultivation, as there is a gap in cereal pollen throughout the entire Late Neolithic. *Secale*-type pollen (0.5%) in the L. Verijärv sequence at 4900 cal BP could be weed rye (Behre 1992), but concurrent finds of *Centaurea cyanus* remain difficult to interpret (Fig. 8 in Paper I). Scattered finds of *Plantago lanceolata* (Fig. 8 in Paper I) are contemporaneous with the Neolithic settlements (Kääpa and Villa) and could originate from ruderal plants on hunters' clearings. The main reason for reduced farming pressure could have been deteriorating climate (Seppä and Poska 2004), which inhibited cattle breeding and crop farming.

The presence of species representing cultivated land (includes cereals, *Linum*, *Cannabis*, *Convolvulus*, *Centaurea cyanus*, and *Spergula*) is low but generally continuous in the L. Verijärv area during the Neolithic, although *Secale* grains are believed to be a weed rye. *Triticum* pollen is registered in both L. Verijärv and Lasva (Fig. 15). During the Neolithic there is also continuous representation of ruderals in all three lake pollen diagrams, grazed forest in L. Plaani and Verijärv and dry grassland in L. Plaani and Lasva (Fig. 15).

### *Bronze Age (3800–2500 cal BP)*

*Secale*-type pollen is indicated in all three pollen diagrams of the Early Bronze Age (Fig. 15). In the Late Bronze Age, small-scale cultivation of *Triticum* and *Hordeum* probably began in the surroundings of L. Plaani and Verijärv (Fig. 15). However, the record of cultivated land is fragmentary, being a bit more continuous in L. Verijärv.

Pastoral farming developed in the surroundings of L. Verijärv in the Bronze Age. Increases in NAP, especially Poaceae, and more frequent *Juniperus* and *Pteridium* (Fig. 8 in Paper I) are indicative of grassland development. Indicators of agriculture (*Triticum*, *Hordeum* and *Cannabis/Humulus*-type pollen) appear in low frequencies in the Late Bronze Age (Fig. 15; Fig. 8 in Paper I). *Pteridium* and increased amounts of charcoal dust clearly indicate regular fires of anthropogenic origin, resulting from small clearings or domestic fires situated close to the lake (Bennett and Birks 1990). An abrupt charcoal peak in the Early Bronze Age together with a clay band in the sediment column of L. Verijärv indicates a forest fire, possible anthropogenic (Fig. 7 in Paper I). A decrease in *Ulmus* and *Tilia* and an increase in *Betula* and Poaceae together with finds of *Plantago lanceolata* at the beginning of the Late Bronze Age (Figs 12–13, Fig. 8 in Paper I) obviously indicate clearances and evidence of grazing.

Landscape opening in the surroundings of L. Plaani was more extensive in the Late Bronze Age, about 2800 years ago, as indicated by a sharp decrease in *Picea*, the final decline in *Ulmus* and increases in *Salix*, *Juniperus* and total NAP (Fig. 7 in Paper III). This suggests woodland clearances and human-induced disturbances, foremost more intensive utilization of landscapes in the lake catchment area.

### *Iron Age (2500–800 cal BP)*

From the Early Iron Age onward, crop cultivation has been the dominant means of subsistence (Lang 1999) and human impact can be confirmed in the pollen spectra without archaeological evidence. The indications of forest disturbance and crop cultivation in the Early Iron Age (2500–1550 cal BP) are more frequent occurrence of *Cannabis/Humulus*-type pollen, scattered finds of *Secale*-, *Triticum*-, and *Hordeum*-type, *Plantago major/media*, *P. lanceolata* pollen and *Pteridium* spores, which suggest small fields close to the lakes (Fig. 15 and human impact figures in Papers I–IV). Both the Plaani and Verijärv diagrams display a short-term recession of anthropogenic indicators at the beginning of the Roman Iron Age, about 1900 cal PB, clearly evident in the Verijärv cultivated land summary curve (Fig. 15). Extensive rye cultivation was first established in the L. Plaani area, ca 200 years earlier than at L. Verijärv, which in turn started 500 years earlier than in the L. Lasva area. This could be attributed to the foundation of a permanent settlement directly on the shore of L. Plaani about 1500–1900 cal BP (Laul 2001). The later start of extensive crop farming in the surrounding of L. Lasva might have been caused by the prevalence of clayey soils, which were unsuitable for the then-current tools.

Since the Late Iron Age, crop cultivation has become the main subsistence and human influence on vegetation is clearly represented on the pollen diagrams. Arboreal pollen decreased sharply with the establishment of fields and grasslands, because the landscape opened. Among cereals, *Secale* became the major contributor to pollen diagrams representing different part of Estonia (Poska and Saarse 1996; Poska *et al.* 2004). High frequency of *Secale* pollen is accounted for partly by extensive wind beyond the pollen source area (Koff and Punning 2002). As the *Rumex* pollen percentage curve resembles that of *Secale*, it seems that *Rumex* entered rye cultures and became a common crop field weed (Behre 1981, 1992). The scattered character of *Triticum* and *Hordeum* pollen curves probably reflects the mobile character of slash-and-burn cultivation, the main cultivation practice at least in SE Estonia. Extensive crop cultivation started in the Plaani area between 1500 and 1300 cal BP, in the Verijärv area at 1300 cal BP and finally in the Lasva area about 800 cal BP (Fig. 15). Diversity increased considerably due to the more open landscape. In Plaani, the first *Linum usitatissimum* pollen was registered for 1200 cal BP, *Fagopyrum esculentum* and *Centaurea cyanus* for 850 cal BP (Fig. 7 in Paper III). This is in accordance with the suggestion that *Linum usitatissimum* was among cultivated plants since at least the 10<sup>th</sup> century. *Fagopyrum esculentum* pollen has been identified rarely and so far only in southern and central Estonian pollen records (Kihno, pers. comm). This implies that *Fagopyrum* was introduced to Estonia from the south or east. According to written records, *Fagopyrum* was cultivated in southern Estonia until the 16<sup>th</sup> century (Kihno and Valk 1999).

In the Late Iron Age, the decline of *Alnus* before or at the beginning of extensive crop cultivation is the result of onset of genuine Iron Age human activity in this region (Sarmaja-Korjonen 2003). It is possible that *Alnus* was used as a fuel for iron melting or *Alnus* coppices were cleared for new fields.

#### *Historical Times* (800 cal BP to present)

Historical times are characterized by sharply declining AP, increasing NAP, especially cereals, ruderals, Poaceae and charcoal particles (human impact figures in Papers I–IV). Taking *Centaurea cyanus* pollen as an indicator of the use of permanent fields (Vuorela 1986); this practice was initiated at the beginning of Historical Times. Abundant charcoal particles (Human impact figures in Papers I–IV) attests to the view that slash-and-burn was practice until the mid 19<sup>th</sup> century in Estonia (Kahk 1992). Agrarian expansion started in the Lasva area at ca 800 cal BP (Fig. 7 in Paper II) after the invasion of German crusaders and the beginning of the Christian period. Flourishing arable farming developed rapidly and crops as *Secale*, *Triticum*, *Hordeum*, *Fagopyrum*, and *Linum* were cultivated. In the Plaani and Lasva diagrams, *Cannabis* appeared with first rise of *Secale*, as in some pollen diagrams from Poland (Ralska-Jasiewiczowa and van Geel 1998).

It is possible to correlate fluctuations of cerealia with wars, accompanying outbreaks of epidemics and famines, during which the population reduced,

many farmsteads were deserted and fields remained uncultivated (Tarvel 1992; Tarand and Eensaar 1998). The first serious setback in arable farming occurred in the 14<sup>th</sup> century (1347) when the Black Death spread over Europe (Yeloff and van Geel 2007). In the L. Lasva pollen diagram, this is reflected by a decrease in human impact indicators, especially in cereal influx values (Fig. 16). The Great Famine of 1695–1697 brought about severe population losses in Estonia, due to extremely unfavorable climatic conditions — a very rainy autumn and a severe winter, followed by a rapid thaw that devastated the yield (Liiv 1938). This event is most clearly expressed in the Lasva human impact diagram (Fig. 7 in Paper II) as a remarkable decline in cereal pollen influx, especially in *Secale*, *Triticum* and *Cannabis* and farming activity generally. Before the famine Estonia had been one of greatest exporters of grain — especially rye — in the Baltic (Palli 1996). After the famine all anthropogenic indicators increased rapidly. Dating of this event is in good agreement with the radiometrically constructed timescale (Fig. 16).

Crop cultivation started to decline between 1860 and 1870 (Fig. 16). This coincides with the abolishment of serfdom, the founding of new farms scattered between numerous bogs, lakes and hillocks, commonly on less fertile fields with scanty yield. Another reason for decreasing rye cultivation could have been the introduction of potatoes, which cannot be recognised in the pollen record because of poor representation of *Solanum tuberosum* (Molloy and O'Connell 2004).

During the last 60 years, crop cultivation in the Haanja Heights has diminished, as the hilly mosaic landscape does not favor use of heavy equipment. This decline is reflected in the pollen record as a drop in cereals and an increase in tree pollen curves (Figs 11, 15). This trend has accelerated since the re-establishment of the Estonian Republic in 1991 due to changes in agrarian policy and land ownership. Agricultural declines have favored regeneration of trees, especially *Alnus*, *Betula*, *Quercus* and brushwood.



## CONCLUSIONS

- About 10,000 cal BP, mineral matter content in the sediments of Lake Verijärv decreased from ca. 80% to 50% and that of carbonates increased from 10% to 45% remaining high until 8000 cal BP. This sharp change in sediments composition reflects a major change in feeding of the lake. As L. Verijärv is located at the crossing of two ancient valleys, this change in sediment composition marks the end of mineral inflow through one or both valleys and the formation of an isolated lake. A gradual decrease in carbonates from 8000 cal BP until 6000 cal BP, during the warming of climate in the Atlantic chronozone, indicates increased organic production and a decrease in the pH in the lake water. An alternative explanation is the end of carbonate-rich groundwater feeding.
- Increased concentration of organic matter in the sediments of all lakes during the last 100 years is related to increasing use of fertilizers, which caused elevated organic production in lakes.
- Forest development in the Haanja Heights started with scattered *Betula* and *Pinus* stands with some *Ulmus*. *Corylus* and *Alnus* became remarkably abundant along with the previous species about 9000 cal BP. *Tilia* and *Picea* were richly present by 8000 cal BP and *Quercus* several centuries later. Broad-leaved trees persisted in high abundance until about 3000 cal BP in all three lakes. Forest clearance and land opening started in different areas at different times. Vegetation dynamics in SE Estonia differs from the rest of Estonia through an earlier arrival of *Picea*, *Ulmus*, and *Quercus*, longer-lasting broad-leaved woods, and later human influence.
- Compared to the sites to the east and west, the Haanja Heights served as an immigration bridge between south and north. Most of the tree taxa immigrating from the south were present earlier than sites to the east and west.
- Comparison of the Plaani and Verijärv tree pollen immigration and distribution reveals a clear south-north direction in the dynamics of thermophilous taxa (*Ulmus*, *Tilia*, *Quercus* and *Fraxinus*). In the southernmost Plaani site, all these taxa immigrated earlier and stayed longer in greater abundance than in the northern L. Verijärv area (Fig. 13). In the northernmost L. Lasva the broad-leaved trees remained in high frequency (more than 10%) about as long as in Plaani.
- All three lakes reveal some distinctive features in the pollen diagrams. The Plaani pollen diagram displays a decrease in *Corylus*, *Alnus* and QM values, characteristic of the “8200 cold event” recorded around 8500 cal BP. The Verijärv sequence displays a catastrophic forest fire about 3450 cal BP, which enhanced soil erosion and deposition of a thick clay layer. In the L. Lasva sequence, a sharp peak in aquatics (*Nuphar*, *Nymphaea*) at about 5700

cal BP is attributed to sharp water level changes or by a random aggregate of aquatic pollen collected and dropped by a bee.

- Neolithic human impact as depicted on the pollen diagrams was modest when settlements were distant from the lakes. In the Lasva sequence, which was located close to Neolithic settlement sites, a sharp decline in broad-leaved tree pollen was recorded contemporaneously with the establishment of the settlements.
- Reflections of human impact intensified at 3500 cal BP in the surroundings of L. Verijärv and at around 2700 cal BP in the L. Plaani area. Signs of limited arable farming in the study area appeared in the Late Bronze Age with *Triticum* and *Hordeum* cultivation. Declines in arable farming during the second half of the Early Iron Age is well expressed in the Plaani and Verijärv diagrams. Extensive arable farming began in the Late Iron Age and culminated at different times, being more remarkable in the vicinity of Lasva, where the sum of anthropogenic indicators surpassed 50% and indicators of cultivated land reached 20%.
- The main crop in the Haanja Heights was rye, extensive cultivation of which started in the Plaani area at about 1500 cal BP, in the Verijärv area at 1300 cal BP and in the Lasva area about 800 cal BP. Rye cultivation flourished between 1200–200 cal BP. Since 1860–1870, rye cultivation has declined considerably, as a result of changes in land ownership and the start of potato cultivation. Coinciding with the start of rye cultivation, the short-term *Alnus* declines probably indicate the onset of Iron Age agrarian activity in the region. Cultivation of *Fagopyrum* indicates contacts between the local people and others to the south-east.
- Several historical and political events, foremost wars, crop failures, plagues and famines, abolition of serfdom, and collectivization affected agrarian activities and are featured in the pollen diagrams as declines in anthropogenic indicators.

## ACKNOWLEDGEMENTS

First of all, my biggest gratitude goes to my supervisors, Tõnu Meidla and Leili Saarse. Leili is thanked very much for directing my scientific research and collaboration with the published papers. Both Leili and Tõnu are thanked for critical reading and commenting the manuscript of this thesis.

I also thank Atko Heinsalu, Siim Veski and Toivo Tubli, who went out on cold winter days and cored on the lake ice to obtain the cores I used for this study.

Leili Saarse, Tiiu Alliksaar and Siim Veski are highly appreciated for participating in varve counts, as well as for valuable comments during writing the papers. Anneli Poska, Anto Raukas, and Atko Heinsalu are also acknowledged for their comments. Anneli Poska is thanked personally for carrying out the rarefraction analyses.

I am very grateful to Maris Rattas who helped me to create the profile of Haanja Heights.

Helle Kukk and Anne Noor are thanked for revising our English during writing published papers. I am also grateful to Robert Szava-Kovats for improving my English in this thesis.

My studies were supported by Estonian Target Financing SF0332710s06 and HM0331758s01 and Estonian Science Foundation grant 6736 and 4963.

Very special words of thanks go to my family. To my parents, who raised me to be the person I am today. To my father, who always believed in me, in spite of my turnarounds in education. To my brother, who has always been my example of a true scientist. To my husband, who lets me to be who I am. And to my lovely children for being such nice spunky children, about whom I need not worry too much.

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## SUMMARY IN ESTONIAN

### HAANJA KÕRGUSTIKU TAIMESTIKU JA MAAKASUTUSE AJALUGU HOLOTSEENIS

Hoolimata tõsiasjast, et Eesti kohta on olemas ligi 400 õietolmudiagrammi, on enamik neist halvasti dateeritud ning hõredalt proovitud, mistõttu suurem osa neist ei sobi taimestiku ja inimõju arengu detailseks uurimiseks. Täpsemad diagrammid on koostatud peamiselt rannikualade kohta. Peale viirkihiliste setete avastamist Kagu-Eestis sai seal alguse ulatuslik taimkatte arengu uurimine. Tänu täpsele ajaskaalale, mille loomist võimaldavad aastakihilised setted, on seal võimalik uurida taimestiku ja inimõju arengut väga detailselt.

Doktoritöö eesmärgiks oli uurida Haanja kõrgustiku taimestiku arengut ning inimõju rolli selles protsessis, tuginedes peamiselt muutustele õietolmu-spektris ning sette koostises. Katmaks erinevaid osi Haanja kõrgustikust, sai käesolevasse töösse lülitatud setted kolmest järvest: viirkihilised setted suhteliselt sügavaveelistest Lasva ja Verijärvest, vastavalt kõrgustiku jalamil olevast ürgorust ning kõrgustiku nõlvalt, ning madalamaveelisest Plaani järvest Haanja kõrgustiku keskosas.

Settetulbad võeti talvel järve jää pealt Belarus tüüpi turbapuuriga aastatel 2000 (Lasva ja Verijärv) ja 2006 (Plaani). Sette uurimiseks kasutati mitmeid erinevaid meetodeid. Dateerimiseks kasutati nii varvide loendamist, AMS ja konventsionaalseid radiosüsiniku meetodeid kui ka  $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$  ja  $^{241}\text{Am}$  radiooloogilist dateerimist. Sette koostist uuriti kuumutuskaotuse meetodil, kuumutades 1 cm intervalliga võetud proove 525 ja 900°C juures, mille tulemusel saadi kõverad mineraalse, orgaanilise ja karbonaatse aine osakaalu kohta settes. Õietolmuanalüüs teostati esmalt proovidest tihedusega 10 cm, hiljem tihendati prooviseeriat kohati kuni 1 cm intervallini vastavalt huvipakkuvale probleemile (inimõju ilmumine, kliimamuutus). Nii kuumutuskaotusanalüüsil kui õietolmuanalüüsil saadud andmetest koostati protsendilised diagrammid, õietolmuandmetest ka akumulatsioonidiagrammid, mille põhjal interpreteeriti taimestiku arengut.

Dateeringud on erinevatel järvedel erineva täpsusega. Kui Lasva ja Plaani järve dateeringud on probleemidevabad, siis Verijärve puhul ei sobinud mitu saadud dateeringut ajakõverale ning tuli seetõttu kasutamata jätta. Sellegipoolest oli võimalik koostada graafikud taksonite levikust erinevatest järvedest, kasutades ühtset ajaskaalat, ning see võimaldas täpsemalt märgata erinevusi kolme järve ümbruse taimestiku levikus.

Orgaanilise ja mineraalne suhe Lasva ja Verijärve viirkihilistes setetes on suhteliselt püsiv kuni 1000 AD. Ainsaks erandiks on beež savikiht Verijärves, vahemikus 2434–2443 cm, vanusega 3450 aastat. Selle tekkepõhjuseks on arvatavasti järve lähedal toimunud tulekahju, mis vallandas erosiooni. Madalas Plaani järves on sette koostis vaheldusrikkam – põhjuseks võib olla nii ajutine orgaanilise aine rikkalikum settimine kui vähestest sademetest põhjustatud

mineraalne sissekande vähenemine. Umbes 1000 AD suureneb kõigi järvede setetes mineraalne osakaal, mis viitab põllumajandustegevuse algusele. Verijärves on mineraalne sisalduse suurenemise kõveral kaks tippu, mis viitab asjaolule, et põllulapid jäid teatud perioodil järvest kaugemale.

Karbonaatsete ühendite osakaal on järvede setetes üldiselt madal (2–5%). Verijärve vanemas settes (enam kui 6000 aastat tagasi) on aga karbonaate rohkesti. Rohkem kui 10 000 aastat tagasi oli karbonaate umbes 20%, siis tõusis nende osakaal väga järsult muu mineraalne sisalduse vähenemise arvelt üle 40%. Selline järsk sette koostise muutus võib viidata järve isoleerumisele, mille käigus mineraalne sissekanne järsult vähenes. Järgnev karbonaatide sisalduse vähenemine kliima soojenemise taustal Atlantikumis viitab orgaanilise aine produktsiooni tõusule, mis põhjustas järve vee pH taseme languse.

Haanja kõrgustiku metsastumine algas hõredate kase- (*Betula*) ja männi- metsadega (*Pinus*), milles esines arvestataval hulgal jalakat (*Ulmus*) juba varem kui 10500 aastat tagasi. Sarapuu (*Corylus*) ja lepp (*Alnus*) esinesid arvestataval hulgal umbes 9000 aastat tagasi. Pärn (*Tilia*) ja kuusk (*Picea*) olid rikkalikult esindatud alates 8000 aastat tagasi, tamme (*Quercus*) levik laienes mõnisada aasta hiljem. Laialehelised metsad laiusid Haanja kõrgustikul veel 3000 aastat tagasi, edasi vähenes nende osakaal küllaltki järsult. Metsade järsk vähenemine algas 1500 aastat tagasi Plaani järve ümbruses, 1300 aastat tagasi Verijärve ümbruses ning ligi 800 aastat tagasi Lasva järve ümbruses. Haanja kõrgustiku taimestiku arengu omapära, võrreldes teiste Eesti aladega on kuuse, jalaka ja tamme varasem sissēränne ning laialeheliste metsade kauasem püsimine, ilmselt tänu sobivate elupaikade mitmekesisusele ja inimõju hilisele lisandumisele.

Võrreldes õietolmudiagrammidega idas ja läänes on märgatav lõunast sissērändavate liikide varasem jõudmine Haanja kõrgustikule. Seetõttu võib oletada, et kõrgustik toimis nn. immigratsioonisillana lõuna ja põhja vahel. Soojalembeste liikide (*Ulmus*, *Tilia*, *Quercus* ja *Fraxinus*) leviku võrdlus kolme järve setetes näitab nende liikide saabumist lõuna suunast, kuna kõik neist on esmalt esindatud lõunapoolseima Plaani järve õietolmuspektris. Lasva ja Plaani järvede ümbruses on laialehelised liigid püsinud kauem kui Verijärve ümbruses.

Iga järve õietolmuspektris on märgata mõningaid ainult neile iseloomulikke sündmusi. Plaani õietolmudiagrammil on võimalik näha nn. “8200 aasta tagust külmasündmust”, millele viitab sarapuu, lepa ja laialeheliste liikide õietolmu sisalduse järsk vähenemine ja hilisem kiire taastumine umbes 8500 aastat tagasi. Verijärve setted peegeldavad laiaulatusliku tulekahju toimumist umbes 3450 aasta tagasi, mil puude õietolmu osakaal vähenes ning suurenes söeosakeste ja mineraalne osakaal settes. Lasva järve umbes 5700 aasta vanusest proovist leitud rohkearvuline veetaimede (*Nuphar*, *Nymphaea*) õietolmu viitab kiirele järve veetaseme muutusele, või siis on lihtsalt tegemist mõne putuka poolt kogutud juhusliku õietolmuagregaadiga.

Neoliitikumis on inimõju kajastused taimestikule tagasihoidlikud neil õietolmudiagrammidel, mis ei asu vahetult asulakohtade lähedal. Lasva läbilõikes,

mis paikneb neoliitilise asulakoha lähedal, on märgata järsku laiialeheliste puude õietolmu sisalduse vähenemist, mis kaasnes asustuse tekkimisega.

Inimmõju Verijärve ümbruses intensiivistus umbes 3500 aastat tagasi ja Plaani piirkonnas umbes 2700 aastat tagasi. Vähesed põllunduse märgid ilmusid hilisel pronksiajal seoses nisu (*Triticum*) ja odra (*Hordeum*) kultiveerimisega. Varasel rauaajal teraviljakasvatus vähenes, mida on märgata nii Verijärve kui Plaani diagrammidel. Laialdasem maaviljelus sai alguse hilisel rauaajal ning saavutas maksimumi erinevate järvede ümbruses erineval ajal. Kõige intensiivsemalt hariti põldu Lasva järve ümber, kus antropogeense päritoluga õietolmu hulk ületas 50% ja haritud maa indikaatorite väärtus oli kuni 20%.

Põhiliseks teraviljaks Haanja kõrgustikul oli rukis, mille laialdane kasvamine algas Plaani piirkonnas umbes 1500 aastat tagasi, Verijärve ümbruses 1300 aastat tagasi ja Lasva ümbruses umbes 800 aastat tagasi. Rukkikasvatuse kõrgaeg oli siin piirkonnas 200–1200 aastat tagasi. Alates aastatest 1860–1870 AD vähenes rukkikasvatus oluliselt seoses maaomanduse muutuse ja kartulikasvatuse algusega. Rukki kasvatamise algusega enam-vähem üheaegselt ilmneb õietolmukõveral lühiajaline märgatav lepa (*Alnus*) osatähtsuse vähenemine. Leppa võidi kasutada rauasulatamisel küttena, või siis puhastati lepa all asuvad maad põldudeks. Tatra (*Fagopyrum*) viljelemine viitab Haanja kõrgustikul elanud inimeste kontaktidele naabritega idas ja/või lõunas.

Mitmeid ajaloolisi sündmusi nagu sõjad, ikaldused, katk ja näljahädad, pärisorjuse kaotamine ja kollektiviseerimine on võimalik õietolmudiagrammil jälgida antropogeensete indikaatorliikide osatähtsuse muutumise kaudu (Lasva).

Viimase 100 aasta vältel ilmnenud orgaanilise aine sisalduse suurenemine järvesettes on ilmselt seotud tööstuslike väetiste kasutuselevõetuga, mis põhjustas biomassi vohamise järvedes.

## **PUBLICATIONS**



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Niinemets, E., Saarse, L. Vegetation and land-use dynamics  
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(Submitted manuscript).

# HOLOCENE VEGETATION AND LAND-USE DYNAMICS OF ESTONIAN SOUTH-EASTERN REGION

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## ABSTRACT

Palynological, chronological and sedimentological studies were performed at three Holocene sediment profiles from south-eastern Estonia (lakes Plaani, Verijärv and Lasva), which form a transect from the central part of the Haanja Heights over northern slope up to the ancient buried valley at its foot. The aim of the study was to utilize pollen records to investigate vegetation and land-use dynamics. The pollen stratigraphy of Verijärv starts 10 500, Lasva – 8400 and Plaani – 6300 cal BP. The early arrival of *Picea*, *Ulmus* and *Quercus*, long-lasting broad-leaved woods owing to the presence of suitable habitats in the mosaic landscape and delayed human interference are outlined. Limited crop growing started in the Later Bronze Age with *Triticum* and *Hordeum* cultivation, but became the primary source of subsistence in the Late Iron Age. Changes in agricultural practices, population densities, historical and political events affected agrarian activities and are registered in pollen diagrams as declines in anthropogenic indicators. Rye cultivation was blooming between 1300 and 200 cal BP, but since AD 1860–1870 considerably decreased as a result of changes in land ownership and start of potato cultivation.

**Key words:** Laminated lake sediments, vegetation dynamics, and human impact, SE ESTONIA

## 1. INTRODUCTION

Our understanding of the vegetation history in the south-eastern marginal area of Estonia has advanced considerably during the last two decades (Ilves and Mäemets, 1987; Punning et al., 1995; Saarse and Rajamäe, 1997; Laul and Kihno, 1999; Veski et al., 2004, 2005). Still, the timing of tree immigration,

spread of broad-leaved taxa and the human interference are weakly documented and have contradictory results. Latest palynostratigraphical studies of SE Estonia have shown, that broad-leaved woods survived there longer compared to the other regions of Estonia and contradict to the opinion given in our stratigraphic chart (Raukas et al., 1995). The land-use history started earlier than it was suggested (Jaanits et al., 1982). To study the vegetation and land-use dynamics we selected tree lakes from SE Estonia, which located at different elevation in different landscape types: Plaani on the central highest part of the Haanja Heights, Verijärv on its slope and Lasva in a wide west-east-running ancient valley that separates the Otepää and Haanja Heights (Fig. 1).

The aim of the study was to compare pollen diagrams from three lakes of different landscape types, reconstruct the human-induced changes, determine the introduction and establishment of agriculture in the marginal area, define regional pollen assemblage zones and revise the existing regional stratigraphic chart. The laminated structure of sediments enabled to carry out high-resolution study, to apply detailed pollen and loss-on-ignition analyses and to use archaeological records and accelerator mass spectrometry (AMS)  $^{14}\text{C}$  dates as a basis for the interpretation of land-use history. The current investigation forms a part of the ongoing scientific research project of Estonia “Environmental and climate changes and their modelling possibilities”.

## **2. GEOLOGICAL AND ARCHAEOLOGICAL BACKGROUND**

Haanja Heights is characterized by mosaic landscape and deep lakes, which offer sediment archive where continuous high-resolution records are available. Its hilly topography developed during and after the recession of the Weichselian ice sheet approximately 14 400 cal BP (Hang, 2001; Kalm, 2006). The relief is built up of a thick (average 60–70 m) Quaternary cover dominated by glacial and glaciofluvial sediments, to a lesser extent by limnoglacial ones and underlain by the Upper and Middle Devonian sedimentary rocks (Kajak, 1968). Examined Verijärv and Lasva are both deep (Table 1), thermally stratified lakes whose bottom water is depleted in oxygen (Mäemets, 1977). Great water depth, stratification, inflow streams and well-developed seasonal contrasts favour the formation of laminated sediments in such lakes (Tiljander et al., 2003). Plaani is a shallow small waterbody (Table 1). Its water is rich in organic substances and poor in mineral compounds (Mäemets, 1977). Coniferous and deciduous coppices, meadows, fields and gardens cover the catchment of studied lakes.

For a long time it was assumed that Estonian upland areas, including Haanja, were inhabited late compared with the coastal areas (Jaanits et al., 1982). Extensive archaeological surveys during the last decades indicated presence of Mesolithic settlement sites confirmed by artefacts and radiocarbon dates from charcoal beneath the gravestone (6440±85, Le-6355; 7290–7425 cal BP)

(Konsa, 2003; Kiristaja, 2003). Radiocarbon dated human bones ( $5310 \pm 85$ , Ua-4828; 5990–6195 cal BP) from the Tamula site (Fig. 1) attest the presence of people at the end of the Middle Neolithic (6200–5000 cal BP) in SE Estonia (Lang and Kriiska, 2001). Tamula, with settlements Kääpa, Villa and graves nearby, was obviously the main Neolithic inhabitation centre in SE Estonia (Jaanits et al., 1982; Fig. 1). Osteological analysis shows prevalence of elk bones, followed by beaver, wild boar and dog, which indicates that the main economy of the Neolithic people was hunting (Paaver, 1965; Lõugas, 1997).

Archaeological material from the Bronze Age (3800–2500 cal BP) is sparse. Stone-graves from the Pre-Roman Iron Age (2500–1950 cal BP) on the Haanja Heights give evidence on the birth of permanent settlements. The stray finds and burial places dated back to the Pre-Roman and Roman Iron Age were located on the cultivated land (fields), which refers to the adoption of crop farming. Archaeological records from the Middle Iron Age (1550–1200 cal BP) include sand barrow graves and several stray finds near the studied lakes (Laul, 2001). Later the population density increased rapidly with several setbacks caused by famines and wars, among which consequences of the Black Death (AD 1347–1352) and Great Famine (AD 1695–1697) have been recorded in written sources.

### 3. MATERIAL AND METHODS

In early spring 2001 and 2002 four parallel sediment slabs were extracted from the central deepest parts of ice covered lakes Lasva and Verijärv with a crust-freeze corer from the uppermost one metre thick loose sediment and two overlapping sediment cores from the rest of the sequences by a Belarus (Russian) peat sampler reaching 29.2 m in Verijärv and 29 m in Lasva. Cores from Verijärv were 990-cm thick and those from Lasva – 985 cm. From Plaani two overlapping 590-cm-long cores were recovered during winter 2004.

In order to control the age-scale of annual lamination,  $^{210}\text{Pb}$  dating and accelerator mass spectrometry (AMS)  $^{14}\text{C}$  were carried out (Saarse and Niinemets, 2007). Altogether 15 AMS  $^{14}\text{C}$  dates of the terrestrial macrofossils and bulk organic rich sediment slices were performed in the Ångström Laboratory of Uppsala University and in the Poznan radiocarbon laboratory (Table 2),  $^{210}\text{Pb}$  chronology was determined in the Laboratory of the Center for Environmental Monitoring and Technology in Kiev, Ukraine. The selection and pre-treatment of macrofossils for AMS dating followed Wohlfarth et al. (1998). Seven conventional radiocarbon dates from Plaani sediments were carried out in the Institute of Geology at Tallinn University of Technology and calibrated at the one-sigma confidence level using the CALIB 5.0.1 program by Stuiver et al. (2005). Calibrated ages before present (cal BP) were applied in the present study.

To quantify the organic and mineral matter and carbonate content, loss-on-ignition (LOI) at 525 and 900 °C was continuously measured by taking 1-cm thick slices. The organic matter (OM) content was expressed in percentages of dry matter. The percentage of carbonate (CaCO<sub>3</sub>) content was calculated after burning the LOI residue for two hours at 900 °C. The amount of residue containing clastic material and biogenic silica was described as mineral matter and calculated against the sum of organic and carbonate compounds.

Pollen analyses were carried out from the master cores of all three lakes with intervals of samples being routinely 5–10 cm. In Plaani, where an 8200 cal BP cold event was expected, every centimetre was analysed. The samples were treated by the acetolysis method (Berglund and Ralska-Jasiewiczowa, 1986; Fægri and Iversen, 1989). Sediment samples of 0.5–1 cm<sup>3</sup> were taken depending on the character of material, and two tablets of *Lycopodium* marker spores were added to each sample for the determination of pollen concentration prior to further treatment (Stockmarr, 1971). The samples with a large amount of mineral material were treated with fluoride acid (HF) for three days. Approximately 1000 pollen grains were counted per sample, except mineral deposits, using 250 x magnification for routine counting and 1000 x magnification with phase contrast for more complicated determinations. A total of 475 samples were analysed (from Lasva –198, Verijärv – 172, Plaani – 105) and up to 198 palynomorphs identified. Pollen diagrams were plotted with the TILIA and TILIA GRAPH programs (Grimm, 1991, 2004). The base of total terrestrial pollen was the sum of arboreal (AP) and non-arboreal (NAP) pollen, which were used to construct the percentage diagrams. The human impact diagrams were compiled on the basis of the species, that show landscape usage connected with human economic activity and settlement (Behre, 1981; Berglund and Ralska-Jasiewiczowa, 1986; Poska, 2001).

The zonation of the pollen diagram was accomplished with the program psimpoll using binary splitting by the sums-of-squares method (Bennett, 1996) and according to the constrained cluster analysis (CONISS) developed by Grimm (1991). Archaeological time-scale (Lang and Kriiska, 2001) was used to stratify the human impact diagrams.

## 4. RESULTS AND DISCUSSION

### 4.1. Chronology

The Verijärv sequence displays the longest and oldest record starting from 10 500 cal BP. The chronology of the Verijärv upper 1-m-thick sequence relies on several lines of evidence (AMS <sup>14</sup>C dates, pollen analysis, varve counts, <sup>137</sup>Cs, <sup>241</sup>Am and <sup>210</sup>Pb determinations; Fig. 2; Saarse and Niinemets, 2007). The chronology of the rest of the Verijärv sequence is based on the AMS dates and correlation with the radiocarbon dated pollen diagrams nearby (Laul and Kihno, 1999; Veski et al., 2004, 2005; Poska et al., 2008). Unfortunately, some AMS

$^{14}\text{C}$  dates from Verijärv do not fit with the pollen stratigraphy, obviously due to the reservoir effect, which results from the photosynthetic uptake of old carbon by organisms living in lake water that has a lower  $^{14}\text{C}/^{12}\text{C}$  ratio than the atmosphere (Olsson, 1986). Dissolved organic carbon, which may be vertically redistributed, could also cause wrong dates (Nilsson et al., 2001). These dates were excluded from the age-depth curve, which was calculated as the fourth-power polynomial (Fig. 2). The chronology of the Lasva sequence starts from 8400 cal BP and was compiled using varve counts and five AMS  $^{14}\text{C}$  dates (Fig. 2; Table 2). The AMS  $^{14}\text{C}$  dates fit well with the varve counts. The age-depth curve of Plaani, based on seven conventional and two AMS  $^{14}\text{C}$  dates, covers time span from 6300 cal BP (Fig. 2). Age-depth curves of Lasva and Plaani are calculated linearly (Fig. 2).

#### **4.2. Sediment lithostratigraphy and interpretation**

The Verijärv and Lasva sequences exhibit visible annual lamination. The varves are thick, especially in the uppermost one-metre part, where about 200 varves were counted. Due to shallowness Plaani sediment does not expose lamination. In the investigated sequences clayey gyttja and gyttja formed the main portion of sediment (Fig. 3A–C). The lowest part of the Verijärv sequence is represented by sand overlain by calcareous gyttja, which gradually became more organic between 7000 and 6000 cal BP (Fig. 3C). Clayey gyttja contains about 40% OM and *c.* 60% mineral compounds, clay gyttja *c.* 20% OM. The carbonate content was almost constant throughout the whole studied sequence accounting for about 1–5% (Fig. 3). An exception is the VJ 2 unit of the Verijärv sequence where the carbonate content reaches 40% (Fig. 3C). In the VJ 3 unit (Fig. 3C) a beige clay band (3450 cal BP) coincides with the charcoal peak obviously resulting from a great forest fire, which opened up the landscape, released erosion and a mineral matter flux into the lake. The sharp increase in mineral matter in the topmost units (Fig. 3A–C) is in good correlation with land cultivation and intensive erosion. The increase in organic matter during the last 50 years is probably related to the increasing use of chemical fertilizers, which caused an elevated organic production in lakes.

The sediment composition of Plaani (Fig. 3B) is much more complex than that of Verijärv and Lasva (Fig. 3A, C), obviously related to the lake morphometry (shallowness). The low content of mineral matter in the bottom part of Plaani could be a result of drier climate and low lake levels in Estonia (Saarse and Harrison, 1992), which promoted carbonate precipitation in Verijärv. A noteworthy increase in mineral compounds between 8200 and 5500 cal BP can be most plausibly explained with increased erosion of steep slopes. The high but variable OM content in sediments accumulated between 5500 and 1100 cal BP could be explained by water-level changes and sedimentation pattern.

### 4.3. Pollen stratigraphy and tree dynamics

Pollen percentages of different tree taxa shows prevalence of *Betula* and *Pinus* pollen between 10 500 and 7800 cal BP (Fig. 4). Afterwards both taxa rapidly decreased and were surpassed by QM species and *Picea* by 3200–3000 cal BP. Since 3000 cal BP *Betula* and *Pinus* once again became dominant species although intensive human activity and crop cultivation since 1200–800 cal BP brought along the diminishing of woods.

*Picea* immigrated into Estonia from the south-east and slowly expanded towards north-west (Saarse, 2004). Earlier establishment of *Picea* in the Plaani area compared to Verijärv (Fig 4) is well consistent with its immigration pattern. Maxima of *Picea* remain between 4500 and 3000 cal BP, starting somewhat later in the Plaani area and ending earlier in the Verijärv area. *Corylus* immigrated before 10 000 cal BP (Fig. 4) from the west (Saarse, 2004). Between 9000 and 5000 cal BP *Corylus* was present in quite numerously (Fig. 4), belonging among five dominant tree species, especially in Plaani (Fig. 4). Afterwards it decreased slowly losing its position first in Verijärv. Since 3000 cal BP *Corylus* has been present as a minor tree species (Fig. 4).

According to the isochrone maps most of broad-leaved trees (*Ulmus*, *Tilia*, *Quercus*) immigrated from the south, only *Alnus* seems to have immigrated from the west and north-west (Saarse, 2004). *Alnus* frequencies were rather high until 1500 cal BP, when *Alnus* had a short-term major decline in Plaani and Verijärv diagrams; in Lasva the decline occurred somewhat later, around 1200 cal BP (Fig. 4). A similar distinct noncontemporaneous *Alnus* decline was recorded in southern Finland and it is related to the onset of the Iron Age human activities (Sarmaja-Korjonen, 2003). The same pattern was recorded in several sequences of Estonia where just after the *Alnus* decline a continuous curve of *Secale* started. *Ulmus* was present from the early Holocene and culminated around 6500 cal BP, which is best expressed in the Verijärv diagram (Fig. 4). Due to good growing conditions in the Plaani area (more fertile soils, mosaic landscape, wide variability of habitats), the appearance of *Ulmus* there is quite high (around 10%) until 5000 cal BP (Fig. 5A). Afterwards it gradually declined with several small-scale recoveries. The final decline of *Ulmus* occurred about 3200 cal BP, when it usually made up less than 1–2%.

*Tilia*, *Quercus* and *Fraxinus* started to expand almost simultaneously between 8500 and 8000 cal BP (Fig. 4), although the share of *Fraxinus* is smaller than that of the other two. *Tilia* reached a maximum around 6300–6000 and declined from 5300 cal BP onwards. A major decline of *Tilia* started around 3300 cal BP in Verijärv and about 2700 cal BP in Plaani and Lasva, in the pattern similar to that of *Ulmus* (Fig. 4). *Quercus* immigrated to the Haanja Heights rather early, but was for a long time surpassed by *Tilia*. *Ulmus* reached a maximum between 4500 and 4000 cal BP, first in Verijärv and then in Plaani. In Lasva the *Quercus* maximum is not clearly expressed because of its overall high occurrence level (around 5%) there before 4000 cal BP. The first regular occurrence of *Fraxinus* starts 8500–7500 cal BP with a maximum between 7000

and 4000 cal BP in Plaani and perhaps in Lasva. In the Verijärv region both the share and distribution of *Fraxinus* are smaller. Scattered grains of *Populus* and *Salix* were encountered throughout the Holocene, being more regular during the last 2000 years (Fig. 5). *Carpinus* immigrated about 5000 cal BP and its regular low finds were registered up to 1000–700 cal BP (Fig. 4).

All broad-leaved species suffered during the 8200 cal BP cold event, which was studied in detail in the Plaani sequence where a remarkable decline in *Alnus*, *Corylus* and *Quercetum mixtum* (QM) percentages and influx values was recorded (Niinemets and Saarse, 2007b). This event is profoundly described in the Rõuge site (c. 10 km to north-west of Plaani) between 8400 and 8080 cal BP (Veski et al., 2004). It is assumed, that the 8200 BP climate reversal was caused by cold winters, humid summers and strong seasonal contrasts (Hammarlund et al., 2005; Seppä et al., 2005) and lasted roughly 150 years (Kobashi et al., 2007).

#### **4.4. Regional pollen assemblage zones (RPAZ)**

Comparison of pollen records from lakes and mires of SE Estonia enabled revision of the regional stratigraphic chart proposed ten years ago (Saarse et al., 1996). Based on new material, six regional pollen assemblage zones (RPAZ) for SE Estonia are proposed:

The first RPAZ (*Betula-Pinus-Ulmus*, ?–9000 cal BP; Table 3) is described by a high frequency of *Betula*, *Pinus* and *Ulmus*, great abundance of *Salix* and *Populus* and elevated values of NAP. Proposed RPAZ is similar to that of set up earlier (Table 3). The second RPAZ (*Ulmus-Alnus-Corylus*, 9000–7800 cal BP) is defined by an increasing share of *Alnus*, immigration of *Tilia*, *Quercus* and *Fraxinus*, re-expansion of *Picea* (*Picea* was present in SE Estonia during the Younger Dryas; Saarse and Rajamäe, 1997) and concurrent high but decreasing share of *Betula* and *Pinus* (Fig. 5A, B). In the third RPAZ (*Ulmus-Tilia-Alnus-Corylus-Picea*, 7800–5500 cal BP) *Ulmus*, *Tilia* and *Corylus* pollen reached their maxima and *Picea* frequency increased considerably (Fig. 5A–C). *Alnus* was still well represented. In the earlier scheme the last two RPAZ's were described as one with limits 9200–4500 cal BP. The fourth RPAZ (*Picea-Alnus-Quercus-Fraxinus*, 5500–3000 cal BP) is characterized by rising but strongly fluctuating *Picea* values and maximum occurrence of *Quercus* and *Fraxinus*. The total amount of QM declined. In earlier scheme *Fraxinus* was not included and RPAZ limits (4500–2900 cal BP) differ. The fifth RPAZ (*Betula-Pinus-Picea-Alnus*, 3000–1300/800 cal BP) is described by rising *Betula* and *Pinus* to their maxima, while *Picea* and QM declined noticeably. Later than other QM species *Carpinus* now gained its maximum. Throughout RPAZ 5, sporadic occurrence of *Secale*, *Triticum*, *Hordeum* and *Cannabis/Humulus*-type pollen is recorded. Earlier this RPAZ was defined as *Picea* with limits 2900–1800 cal BP. The sixth RPAZ (*Pinus-Betula-Cerealia-NAP*) started at different times in different localities and marked the vegetation community characteristic of the landscape influenced by man. The herb pollen has drastically increased and that

of tree pollen reduced to about 50% due to large-scale forest clearances and crop cultivation. In the previous chart two different RPAZ'is (*Picea-Betula-Pinus* and *Pinus-Betula*) were distinguished with limit between 450 cal BP.

#### 4.5. Land-use dynamics

##### 4.5.1. Late Mesolithic (before 6900 cal BP)

In such a wooded area as Haanja Heights, the pre-agrarian human impact on the environment is generally insignificant and could be traced in the abundance of apophytes, changes in tree pollen spectra, ratio of AP to NAP and charcoal dust (Behre, 1981; Berglund, 1991). Increased NAP values, especially of *Urtica* and elevated charcoal particle values in the Late Mesolithic at Plaani (between 7700 and 7200 cal BP; Fig. 6) give evidence of a small-scale disturbance and creation of openings. Obviously Mesolithic hunters and fishermen visited this region, as numerous lakes and woods suggest fish and plentiful game could be found in natural forest. Artefacts and radiocarbon dates from the settlement sites lately discovered confirm the presence of Mesolithic man on the Haanja Heights (Kiristaja, 2003; Konsa, 2003). It seems that at the end of the Mesolithic period also the Verijärv area was to some extent influenced by man (Fig. 7) as can be concluded from the low but almost continuous ruderals, dry pasture and grazed forest indicators, especially *Artemisia*, Chenopodiaceae and *Urtica* pollen and occurrence of *Pteridium* spores. All these evidences are rather faint and could be interpreted as natural changes in the forest development as well.

##### 4.5.2. Neolithic (6900–3800 cal BP)

The first apparent sign of Neolithic human impact was traced in the Middle Neolithic (6200–5000 cal BP) as a short-term QM decline in the Verijärv diagram (Fig. 5B). It coincides with the establishment of the Tamula settlement and burial site with more than 20 graves about 7 km NW of Verijärv dated to 5310±85, Ua-4828 (5950–6190 cal BP) (Jaanits et al., 1982). According to artefacts this settlement site was in use up to 4000 cal BP (Lang and Kriiska, 2001) or even longer, as the radiocarbon date of a woody pole was determined to 3600±180, TA-10 (3650–4150 cal BP). During the existence of the Tamula settlement site (c. 6000–3800 cal BP) *Ulmus* and *Tilia* influx values sharply decreased, but generated after the abandonment of the settlement (Niinemets and Saarse, 2006). Scattered finds of *Juniperus*, *Rhamnus frangula*, and *Viburnum* pollen in the Middle Neolithic could be a consequence of small-scale opening up of the landscape (Königsson et al., 1998; Ralska-Jasiewiczowa and van Geel, 1998). Changes in *Corylus* may also indicate interference of humans (Dumayne-Peaty and Barber, 1998). *Picea*, *Pinus* and *Betula* suffered most strongly being used for heating and building (Jaanits et al., 1982; Fig. 5). Middle Neolithic human impact involves also first single *Triticum* pollen appearance associated with *Convolvulus*, *Urtica* and *Humulus/Cannabis*-type in Verijärv (Fig. 7) and could be evidence of restricted tillage. Pollen grains of *Secale*-type appearing at the beginning of the Middle Neolithic obviously

represent weed rye (Fig. 7). In the Lasva diagram (Fig. 8) the sharp peak in NAP (c. 5300 cal BP) coincides with the foundation of Kääpa settlement and distinct forest clearances. *Triticum* pollen appeared at the Middle/Late Neolithic transition after peaks of NAP and charcoal (Fig. 8). As soon after that the first pollen of *Plantago lanceolata* is recorded some kind of tillage could be expected. The existence of livestock grazing is difficult to confirm as pollen types exclusively indicative of grazing is absent (Taavitsainen et al., 1998).

Reduction of *Ulmus*, fluctuating *Betula* and *Picea*, good representation of *Artemisia*, *Urtica* and *Pteridium* in all diagrams (Figs 5–8) could be interpreted as traces of forest disturbances in the Late Neolithic period (5000–3800 cal BP). These modest disturbances are obviously related to the pastoral farming rather than crop cultivation, because throughout the Late Neolithic there was a gap in the cereal pollen record. *Secale*-type pollen (0.5%) in the Verijärv sequence 4900 cal BP could be interpreted as weed rye (Behre, 1992), but concurrent finds of *Centaurea cyanus* are not easily explained (Fig. 7). Scattered finds of *Plantago lanceolata* (Fig. 8) occur concurrently with the Neolithic settlements (Kääpa and Villa) and could be regarded as a ruderal plant on the hunter clearings (Niinemets and Saarse, 2007a). The reason of reduced farming pressure could be deteriorated climate (Seppä and Poska, 2004) and/or societal.

#### 4.5.3. Bronze Age (3800–2500 cal BP)

After the abandonment of Neolithic settlements Kääpa and Villa sporadic cereal pollen disappeared from the Lasva diagram but ruderals and *Pteridium* increased and the charcoal value almost doubled (Fig. 8), obviously connected with pastoral farming, which was less developed in SE Estonia compared to northern regions. Pastoral farming developed also in the surroundings of Verijärv, evidenced by increase in NAP, especially Poaceae, and more frequent *Juniperus* and *Pteridium* (Fig. 7). Indicators of agriculture (*Triticum*, *Hordeum* and *Cannabis/Humulus*-type pollen) appear in low frequencies accompanied with single *Plantago lanceolata* pollen grains in Verijärv (Fig. 7). *Plantago lanceolata* is one of the most reliable indicators of pastoral and arable farming and it does not occur in closed woodland (Behre, 1981, 1988; Tinner et al., 2007). In the Estonian pollen diagrams *P. lanceolata* is rather weakly represented and never gave a continuous curve in the Neolithic and Bronze Age. *Pteridium* and increased charcoal obviously indicate regular fires of anthropogenic origin resulting from small clearings or domestic fires situated close to the lake (Bennett et al., 1990). The drastic charcoal peak in the Verijärv diagram at 3450 cal BP indicates a forest fire set up by accident or on purpose (Fig. 7). A decrease in *Ulmus* and *Tilia* and an increase in *Betula* and Poaceae with finds of *Plantago lanceolata* at the beginning of the Later Bronze Age (Fig. 7) obviously indicate clearances and are evidence of grazing (Lagerås, 1996).

Landscape opening up in the surroundings of Plaani was more advanced in the Later Bronze Age about 2800 years ago as evidenced by a sharp decrease in

*Picea*, final decline of *Ulmus*, increase in *Salix*, *Juniperus* and total NAP (Figs. 5A, 6). This suggests woodland clearances and human induced disturbances, first of all more intense utilization of landscape on the lake catchment.

#### 4.5.4. Iron Age (2500–800 cal BP)

From the Iron Age land cultivation became step by step the predominant branch of subsistence. Indications of forest disturbance and crop cultivation in the Early Iron Age (2500–1550 cal BP), evidenced by more frequent occurrence of *Cannabis/Humulus*-type pollen, scattered finds of *Secale*, *Triticum*, *Hordeum*, *Plantago major/media*, *P. lanceolata* and *Pteridium* are suggesting small fields present not far from lakes (Figs 6–8). These species are less expressed on the Plaani pollen diagram, where human impact regression is recorded (Fig. 9). All diagrams display short-term recession of anthropogenic indicators at about 1900 cal PB, which is best seen on the Verijärv summary diagram (Fig. 9). *Secale* cultivation was first established in the Plaani area, c. 200 years earlier than at Verijärv and even 400 years earlier than at Lasva. The reason could be the foundation of a permanent lakeside settlement directly on the L. Plaani shore about 1500–1900 cal BP (Laul, 2001). The delay in the start of extensive crop farming in the surroundings of Lasva could have been caused by prevalence of clayey soils, which exasperate their usage by primitive implements.

Since the Late Iron Age crop cultivation has become the main source of subsistence. The continuous occurrence of cereal pollen is assumed to reflect permanent settlement near the lakes (Taavitsainen et al., 1998). Among cereals *Secale* was one of the major contributor observed in pollen diagrams from different parts of Estonia (Poska and Saarse, 1996; Poska et al., 2004). High frequency of *Secale* pollen is partly explained by *Secale* pollination by wind, higher than other cereal pollen production and its distribution beyond the relevant source area (Koff and Punning, 2002). According to historical sources *Secale* was the main crop also in Finnish slash-and-burn cultivation (Taavitsainen et al., 1998). As *Rumex* pollen percentage curves resemble that of *Secale*, it seems that *Rumex* entered rye cultures and became a common crop field weed (Behre, 1981, 1992). The scattered character of *Triticum* and *Hordeum* pollen curves is probably due to the mobile character of slash-and-burn cultivation, which was widely spread practice, at least in SE Estonia. In the Plaani diagram the first *Linum usitatissimum* pollen was registered 890 cal BP, *Fagopyrum esculentum* and *Centaurea cyanus* 650 cal BP. This is in accord with the suggestion that *Linum usitatissimum* was among cultivated plants at least since the 10<sup>th</sup> century. *Fagopyrum esculentum* pollen has been identified rarely and so far only in southern and central Estonian pollen records (K. Kihno, pers. comm). This implies that *Fagopyrum* was introduced to Estonians from contacts with neighbours (Russians and Latvians). According to written sources *Fagopyrum* was levied in southern Estonia until the 16<sup>th</sup> century (Kihno and Valk, 1999).

#### 4.5.5. Historical Time (800 cal BP up to the present)

Historical Time is characterized by sharply declining AP, increasing NAP, especially cereals, ruderals and Poaceae, and charcoal particles (Figs 6–8). As *Centaurea cyanus* pollen is considered as one indicator of the usage of permanent fields (Vuorela, 1986) this economy started in SE Estonia at the beginning of Historical Time. Slash-and-burn farming was practised in southern Estonia up to the end of the 19<sup>th</sup> century, which is in good accordance with high charcoal particle percentages (Figs 6–8). Agrarian expansion in the Lasva area started c. 800 cal BP. Flourishing arable farming developed fast with crops such as *Secale*, *Triticum*, *Hordeum*, *Fagopyrum* and *Linum* grown. In the Plaani and Lasva diagrams *Cannabis* appeared with the first rise of *Secale* like in some pollen diagrams from Poland (Ralska-Jasiewiczowa and van Geel, 1998).

Fluctuations in cereal curves resulted from population density, agricultural practices as well as changing climate and wars with accompanying outbreaks of epidemics and famines during which the number of population fell, many farmsteads were deserted and fields remained uncultivated (Tarvel, 1992; Tarand and Eensaar, 1998). The first serious setback in crop farming occurred in the 14<sup>th</sup> century when the Black Death spread over Europe (Yeloff and van Geel, 2007). It is reflected in pollen diagrams as a decrease in human impact indicators, especially in cereal influx values (Niinemets and Saarse, 2007a). The Great Famine in AD 1695–1697 brought about severe population losses in Estonia, caused by a very rainy autumn and severe winter, followed by a sharp thaw which ruined all the crop (Liiv, 1938). Before the famine, Estonia had been one of the greatest exporters of grain, especially rye, in the Baltic (Palli, 1996). This event is most clearly expressed in the Lasva human impact diagram as a reduction in NAP, *Secale* and *Cannabis* and the farming activity generally (Fig. 8). After that all anthropogenic indicators rapidly increased. Extensive crop farming brought about increased erosion of deforested land and increased mineral matter fluxes into the lakes (Fig. 3) and resulted in the creation of the present cultural landscape in the Haanja Heights with a high floral diversity.

Rye cultivation started to decrease since AD 1860–1870. This coincides with the abolishment of serfdom and foundation of new farms scattered between numerous bogs, lakes and hillocks, commonly on less fertile fields with scanty yield. Another reason in the decrease of grain cultivation could be the introduction of potatoes, not recorded because *Solanum tuberosum* (potato) pollen is poorly represented (Molloy and O'Connell, 2004). This period was known as slash-and-burn crisis, because the rapid increase in human population and demand for food production increased slash-and-burning areas and shortened the cultivation cycle, depleted of nutrients from soils and resulted in poor harvest (Taavitsainen et al., 1998). Smaller fluctuations in the cereal pollen curve were connected with crop failure, which were rather frequent in the 18<sup>th</sup> and 19<sup>th</sup> centuries (Liiv, 1938).

During the last 50 years crop cultivation and stock farming have diminished in the Haanja Heights because the hilly mosaic landscape did not favour use of

heavy machinery. This is reflected in pollen diagrams as a decline in cereals and herb pollen curves. This tendency accelerated after the restoration of the independent Republic of Estonia in 1991 accompanied by rearrangement of agrarian policy and changes in land ownership. The setback of land cultivation favoured regeneration of trees, especially *Alnus*, *Betula*, *Quercus* and brushwood.

## 5. CONCLUSIONS

- High-resolution pollen records from different landscape types of SE Estonia display vegetation changes that occurred from the early Holocene up to the present and land-use history since the Late Mesolithic period. The vegetation dynamics in SE Estonia has several specific patterns, such as the early arrival of *Picea*, *Ulmus* and *Quercus*, long-lasting broad-leaved woods owing to the presence of suitable habitats in the mosaic landscape and delayed human interference.
- The sediment sequences of lakes Verijärv and Lasva are annually laminated. The high sedimentation rate and laminated structure enabled us to carry out a high-resolution palaeoecological study and comparison of pollen records with historical data.
- All pollen records have their specific patterns. The Plaani pollen diagram displays a decrease in *Corylus*, *Alnus* and QM values characteristic of the cold event around 8200 cal BP. The Verijärv sequence displays a catastrophic forest fire about 3450 cal BP, set up accidentally or deliberately by humans. The fire released intensive soil erosion and sedimentation of a thick clay layer. The Lasva pollen diagram displays sharp expansion of arable farming since the starting of Christian period.
- Good correspondence between archaeological evidence and human impact signals obtained from pollen records was detected. The establishment of Neolithic settlements coincides with the sharp decline in broad-leaved tree pollen as timber started to be used for construction and heating.
- The Neolithic human impact is reflected in pollen diagrams modestly, obviously because of the absence of settlement sites directly on the studied lakeshores. Reflections of human impact intensified in the surroundings of Verijärv 3500 cal BP and in Plaani around 2700 cal BP. The setback in land cultivation at the beginning of the Roman Iron Age is best expressed in the Verijärv diagram.
- The Neolithic settlers, as testified by the cereal pollen finds, must have known agriculture. Limited crop growing in the study area appeared in the Later Bronze Age with *Triticum* and *Hordeum* cultivation but crop farming became the primary source of subsistence in the Late Iron Age.

- Rye cultivation was blooming between 1300 and 200 cal BP, but since AD 1860–1870 considerably decreased as a result of changes in land ownership and start of potato cultivation.
- Changes in agricultural practices, population densities, historical and political events (wars, crop failures, plagues and famines, abolition of serfdom collectivization) affected agrarian activities and are registered in pollen diagrams as declines in anthropogenic indicators.

## ACKNOWLEDGEMENTS

The authors would like to thank Atko Heinsalu, Siim Veski and Toivo Tubli who assisted in the field. Siim Veski, Anneli Poska and the anonymous referees are acknowledged for critical remarks and suggestions. The study was supported by Estonian Target Financing SF0332710s06 and Estonian Science Foundation grant 6736. Many thanks to Mrs. T. Kaare who revised the English.

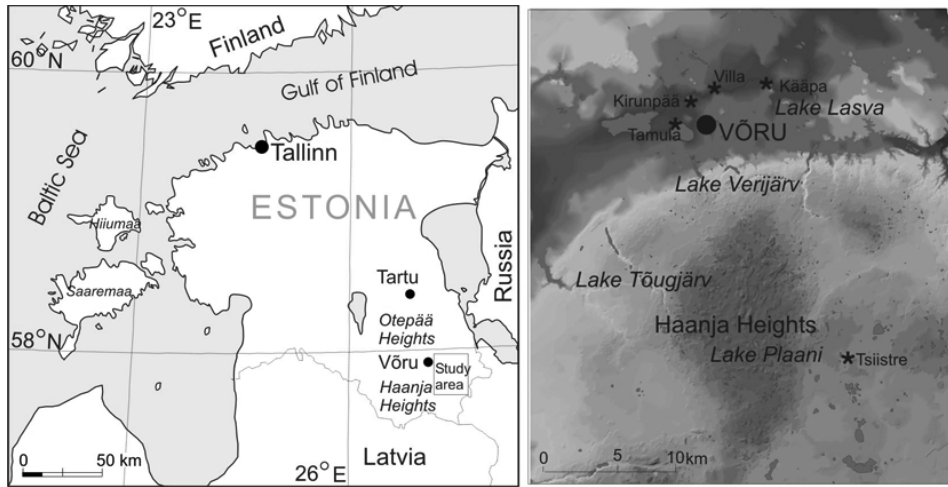
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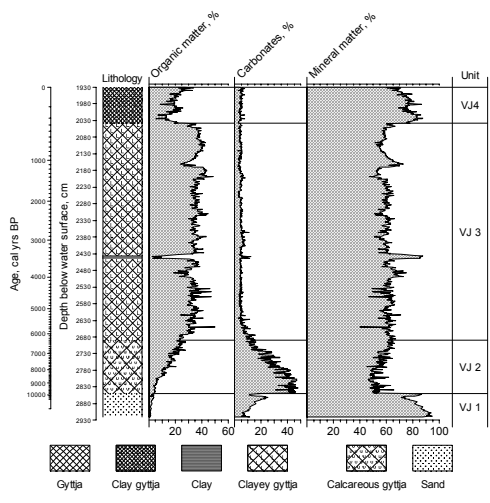
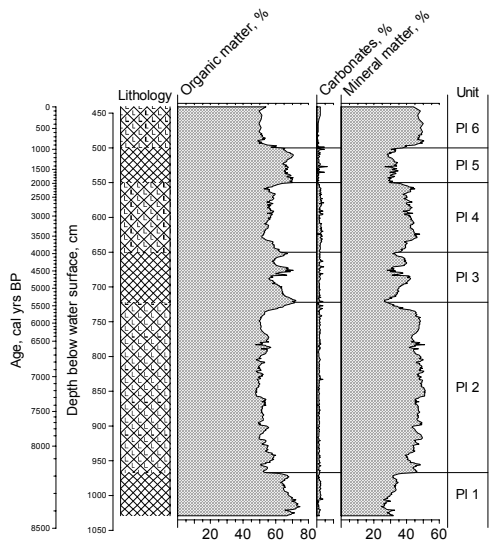
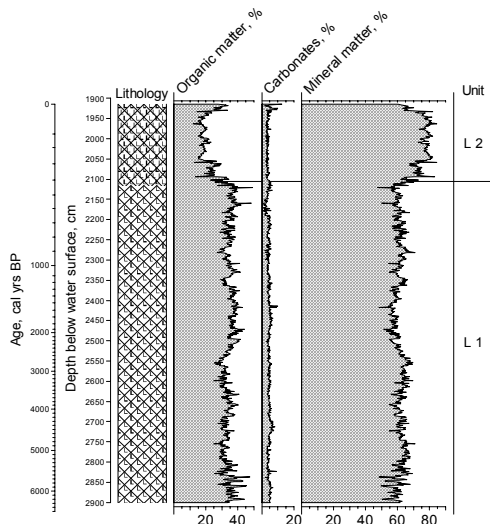
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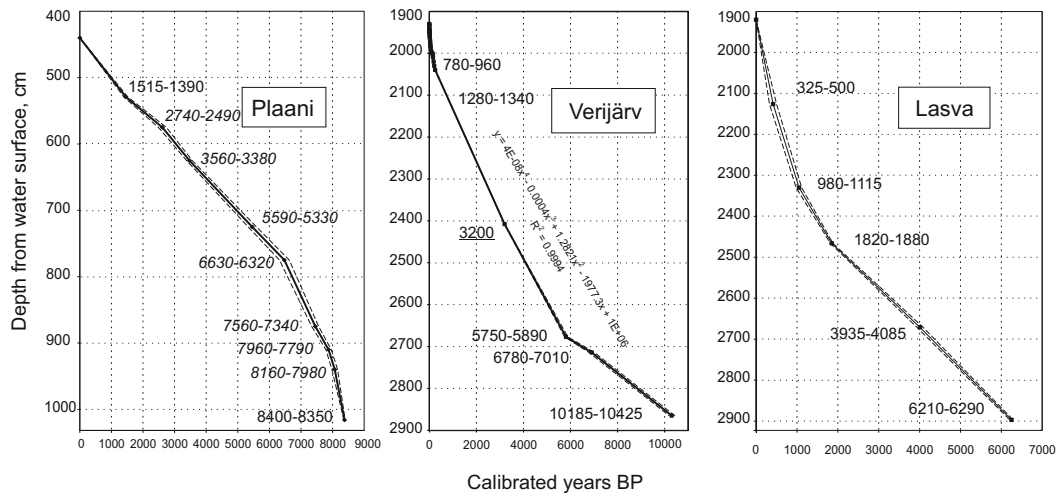
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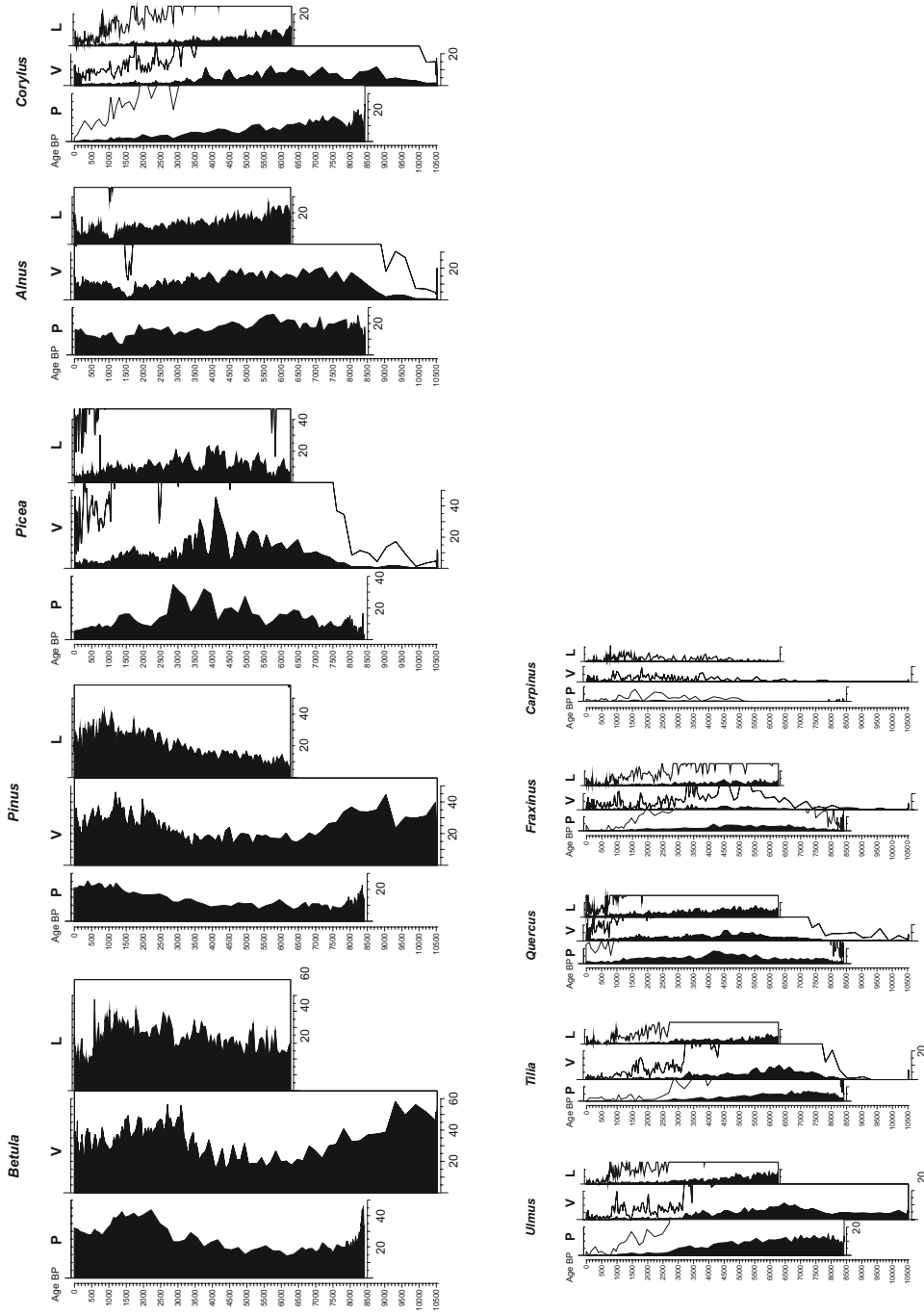
**Fig. 1.** (A) Location of the study area. (B) Map of the study area. Studied lakes are surrounded by circle, archaeological sites marked by starlet.



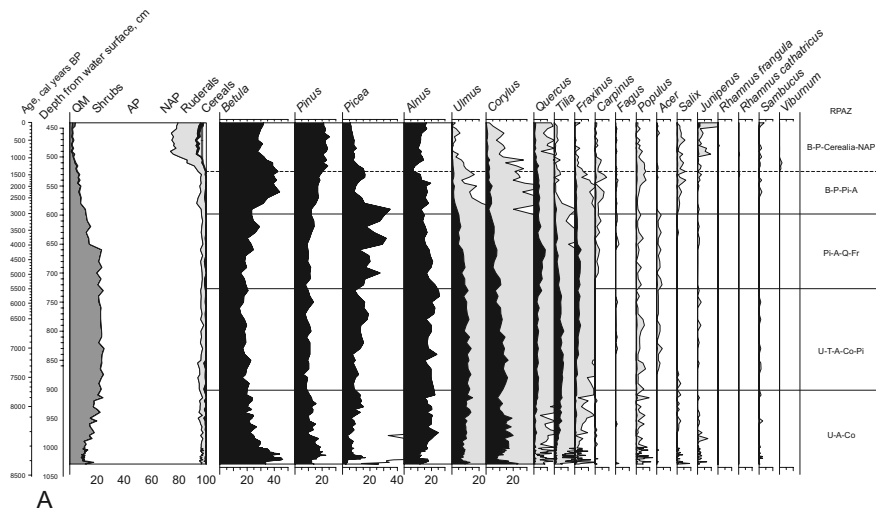
**Fig. 2.** Age-depth curve of the studied lakes.



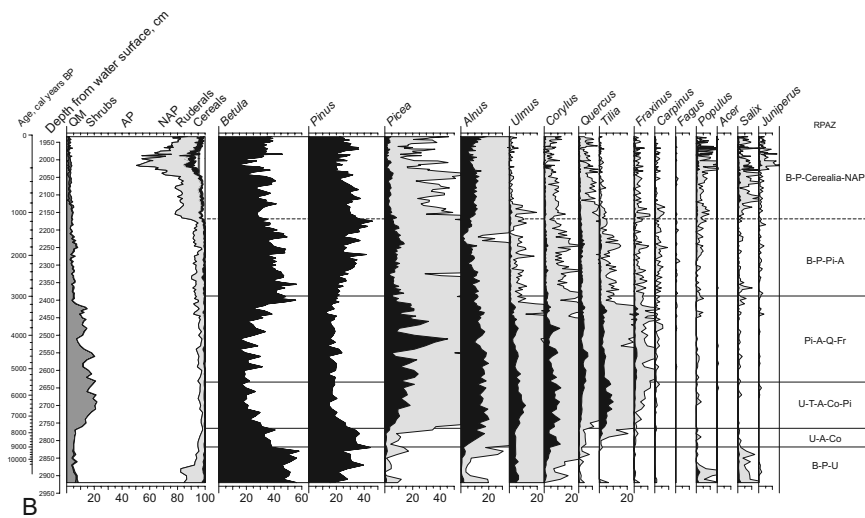
**Fig. 3.** Loss-on-ignition results of lakes Lasva (A), Plaani (B), and Verijärv (C).



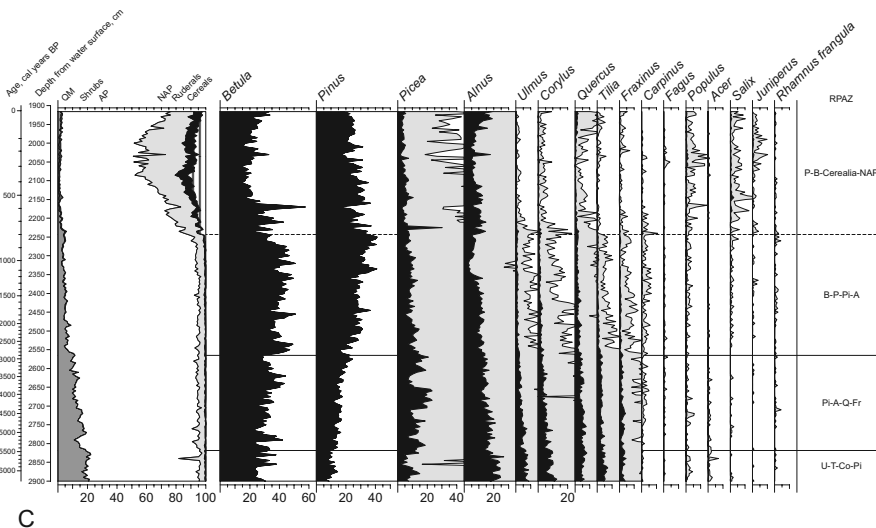
**Fig. 4.** Comparison of *Betula*, *Pinus*, *Picea*, *Alnus*, *Corylus*, *Ulmus*, *Tilia*, *Quercus*, *Fraxinus* and *Carpinus* pollen percentages of Plaani (P), Verijärvi (V) and Lasva (L) lake sediments.



A



B



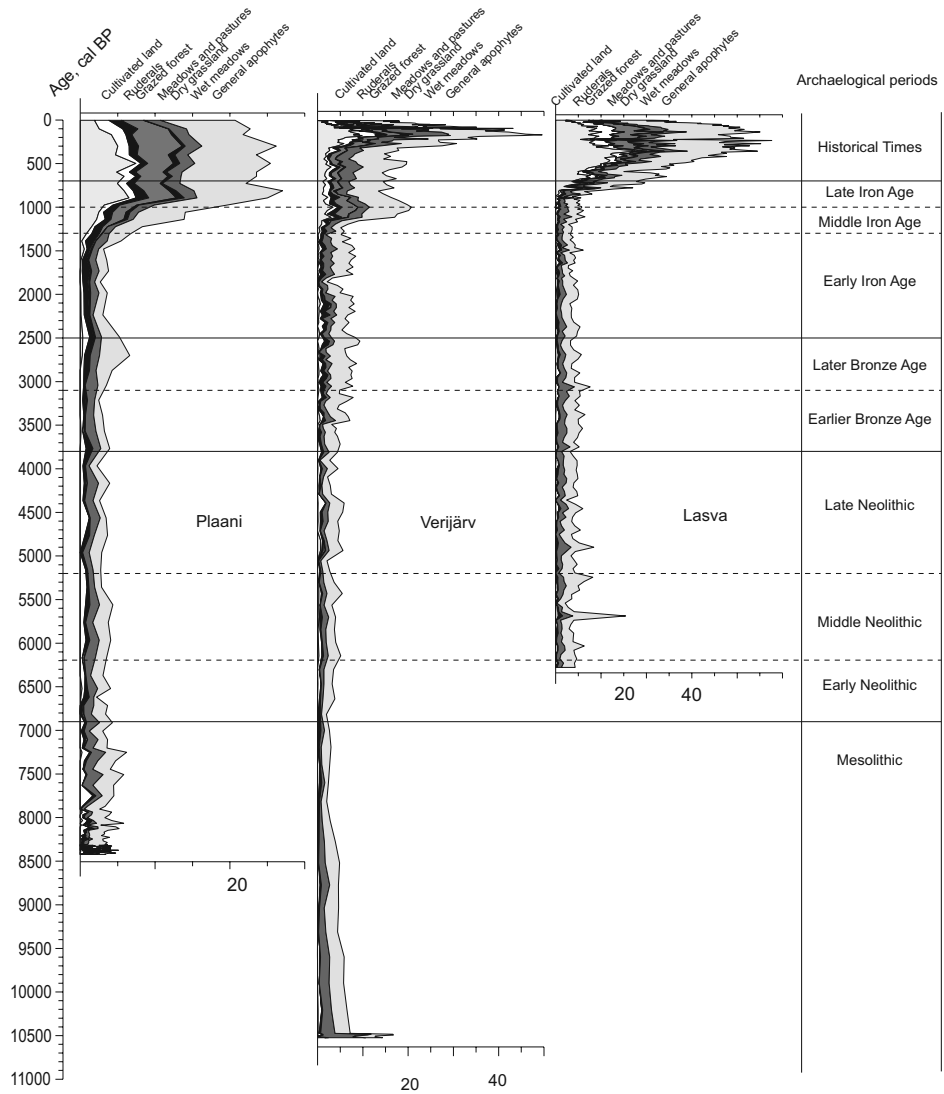
C

**Fig. 5.** Tree-pollen diagrams from Plaani (A), Verijärv (B) and Lasva (C) with indication of regional PAZ'is.









**Fig. 9.** Summary pollen diagram showing the different types of anthropogenic indicators following Behre (1981) and Berglund and Ralska-Jasiewiczowa (1986).

## TABLES

**Table 1.** General characteristics of lakes Plaani, Verijärv and Lasva.

Lake	Coordinates	Area, ha	Elevation, m a.s.l.	Maximum water depth, m	Hydrological type
Plaani	57°40'30'' N 27°04'30'' E	20	244.1	5	Hard-water drainage
Verijärv	57°48'30'' N 27°03'30'' E	20	88.4	19.4	Hard-water drainage
Lasva	57°51'30'' N 27°10'30'' E	10.9	71.1	19.2	Hard-water drainage

**Table 2.** Radiocarbon dates of lake sediments used to establish the age model

Depth below lake level (cm)	<sup>14</sup> C age BP	Lab. no.	Calibrated age BP	Material
<b>Lake Plaani</b>				
528–530	1545±40	Poz-19613	1515–1390	gyttja
570–580	2520±60	Tln-2921	2740–2490	gyttja
620–630	3235±70	Tln-2926	3560–3380	gyttja
720–730	4775±70	Tln-2924	5590–5330	clayey gyttja
770–780	5680±145	Tln-2923	6630–6320	clayey gyttja
870–880	6550±85	Tln-2927	7560–7340	clayey gyttja
905–915	7040±90	Tln-2929	7960–7790	clayey gyttja
935–945	7235±80	Tln-2930	8160–7980	clayey gyttja
1015–1017	7560±40	Poz-19507	8400–8350	gyttja
<b>Lake Verijärv</b>				
1951	1590±60	Ua-19533	1410–1535	aquatic moss
2046–2050	990±50	Ua-19791	780–960	bulk gyttja
2125	1365±60	Ua-19534	1280–1340	wood
2400	2300±40	Ua-23874	2305–2355	twigs
2525	1840±40	Ua-23875	1725–1820	bark
2677	5065±50	Ua-23876	5750–5890	bark
2714	6050±90	Ua-23877	6780–7010	fish scales
2865	9110±110	LuA-4754	10185–10425	<i>Salix</i> wood
<b>Lake Lasva</b>				
2126	380±50	Ua-19792	325–500	wood
2330	1145±30	Poz-13746	980–1115	macroremains
2466	1900±30	Poz-13747	1820–1880	macroremains
2669–2673	3680±35	Poz-13749	3935–4085	gyttja
2897	5450±40	Poz-13771	6210–6290	wood

**Table 3.** Regional pollen assemblage zones (RPAZ)

New proposal	Age, cal BP	Proposed earlier (Saarse et al., 1996)	Age, cal BP
(1) <i>Betula-Pinus-Ulmus</i>	? –9000	<i>Betula-Pinus-Ulmus</i>	? –9200
(2) <i>Ulmus-Alnus-Corylus</i>	9000–7800	<i>Corylus-Alnus-Ulmus</i>	9200–4500
(3) <i>Ulmus-Tilia-Alnus-Corylus-Picea</i>	7800–5500	<i>Alnus-Tilia-Picea-Quercus</i>	4500–2900
(4) <i>Picea-Alnus-Quercus-Fraxinus</i>	5500–3000	<i>Picea</i>	2900–1800
(5) <i>Betula-Pinus-Picea-Alnus</i>	3000–1300/800	<i>Picea-Betula-Pinus</i>	1800–450
(6) <i>Betula-Pinus-Cerealia-NAP</i>	1300/800– up to present	<i>Pinus-Betula</i>	450– up to present

# CURRICULUM VITAE

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1999 – Tartu University, MSc in Palaeontology and Stratigraphy.  
1997 – Tartu University, BSc in Geology, *cum laude*.  
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Languages: Estonian, English, Russian.

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1999–till current TTU Institute of Geology, leading engineer.  
1997–1999 – TTU Institute of Geology; senior lab assistant.  
1995–1996 – Estonian Academy of Sciences, Institute of Ecology; lab assistant.  
1989–1997 in summers – Estonian Agricultural Academy; lab assistant.

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1. Main scientific topic: climate change and vegetation dynamics in the past.

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- Niinemets, E., Saarse, L. 2007. Fine-resolution pollen-based evidences of farming and forest development, south-eastern Estonia. *Polish Journal of Ecology* 55(2), 283–296.
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- Saarse, L., Niinemets, E. 2007. Environmental changes in SE Estonia during the last 700 years. *Boreal Environment Research* 12, 611–621.
- Saarse, L., Vassiljev, J., Miidel, A., Niinemets, E. 2007. Buried organic sediments in Estonia related to the Ancylus Lake and Litorina Sea. *Geological Survey of Finland. Special Paper* 46, 87–92.
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- Niinemets, E. 1999. Ostracods. Lake Peipsi I. Geology. Sulemees Publishers, Tallinn. 90–97.

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### **III. Erialane enesetäiendus**

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### **V. Huvialad**

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