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DISTURBANCES AND VEGETATION PATCHINESS REFLECTED IN POLLEN AND CHARCOAL PROFILES FROM LACUSTRINE SEDIMENTS

Abstract

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CONTENTS

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This thesis is based on the following papers, referred to in the thesis by their Roman numerals I–VI.

I. Koff, T., Punning, J.-M., **Kangur, M**. 2000. Impact of forest disturbance on the pollen influx in lake sediments during the last century. *Review of Palaeobotany and Palynology*, 111, 19–29.

II. **Kangur, M.** 2002. Methodological and practical aspects of presenting and interpreting microscopic charcoal data from lake sediments. *Vegetation History and Archeobotany*, 11, 289–294.

III. Punning, J.-M., **Kangur**, **M.,** Koff, T. & Possnert, G. 2003. Holocene lake-level changes and their reflection in the paleolimnological records of two lakes in northern Estonia. *Journal of Paleolimnology*, 100, 167–178.

IV. Koff, T. & **Kangur, M**. 2003. Vegetation history in northern Estonia during the Holocene based on pollen diagrams from small kettlehole and lake sediments. In: S. Tonkov, (ed.), *Aspects of Paleoecology and Palynology. Festschrift in honour of Elisaveta Bozilova,* pp. 113–126. PENSOFT publishers.

V. **Kangur, M.** 2005. Palynostratigraphy of Holocene lake sediments on the Otepää Heights, southern Estonia. *Proceedings of the Estonian Academy of Sciences. Geology*, 54, 52–68.

VI. **Kangur, M.** 2004. Use of analysis of microscopic charcoal particles in palaeoecological studies. In: E. Kadastik & J.-M. Punning (eds.), *Geoecological studies.* Institute of Ecology at Tallinn Pedagogical University. Publication 8, 20–35 (in Estonian, summary in English).

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Author's contribution

Publication I: The author is responsible for the pollen, charcoal and SFAP analysis and contributed to the interpretation of data and participated in the preparation of the manuscript.

Publication III: The author is responsible for the parts concerning pollen analysis and interpretation of these data, and participated in the preparation of the manuscript.

Publication IV: The author is responsible for the parts concerning pollen analysis from Lake Linajärv deposits and interpretation of these data and participated in composing the manuscript.

PREFACE

The aim of the studies presented in this thesis was to develop and verify the complex methodologies for investigating the basics of pollen profiles formation. Recently, the need for more detailed reconstructions of vegetation development and factors influencing it has become evident. Therefore, more attention has been paid to investigating the relationship between pollen found in sediments and vegetation surrounding the sediment basin. In such studies, it is essential to determine the area surrounding the sediment basin, which vegetation and its changes determine the pollen profiles most significantly.

In this study, the estimation of source area of pollen was carried out by investigating the disturbances in vegetation surrounding the lakes and studying how the lake size and the location and size of the disturbance patch affect the formation of pollen profiles (**I**). For these purposes, four lakes in different parts of Estonia were studied. The vegetation in surroundings of these lakes' has suffered from different disturbances, such as large-scale clear-cuttings or forest fires during the 20th century. One important factor causing the disturbances in forested ecosystems is fire, therefore, a methodological study was carried out to identify the most adequate approach for presenting the results of charcoal analysis whereas the charcoal curve reflects most precisely the history of forest fires (**II**, **VI**).

Landscape characteristics like topography, soils, hydrological regime *etc.*, are one of the main factors determining the vegetation structure of the area around the sediment basin. Therefore, formation of pollen profiles during the Holocene from two test areas with dissimilar diversity of landscape characteristics on main source areas of pollen were compared (**III-V**). The heterogeneity of the soils surrounding the study sites was considered one of the most important factors in formation of vegetation structure, and thus also the pollen profiles.

The present thesis consists of two major parts. The first presents the summary of papers, where the main results of the studies are drawn out and discussed. In the second part, the reprints of the papers are presented.

1. INTRODUCTION

1.1. ESTIMATIONS OF SOURCE AREA OF POLLEN

Since the earliest work in the field of palynology, researchers have been interested in the origin of the pollen found in sediments (von Post, 1916; Firbas, 1934; Erdtman, 1954). Finding out the quantitative relationships between the fossil pollen and the vegetation surrounding the sediment basin have been the objective of investigations for several decades. To describe these relationships, several models have been elaborated (Davis, 1963; Tauber, 1965; Andersen, 1970; Jacobson & Bradshaw, 1981; Parsons & Prentice, 1981; Prentice & Parsons, 1983; Prentice & Webb, 1986; Sugita, 1994).

The essential aspect of the quantitative paleoreconstructions is to determine the source area of pollen (Tauber, 1965; Andersen, 1970; Jacobson & Bradshaw, 1981). The Prentice-Sugita model provides quantitative estimates of the area from which a given proportion of pollen comes in homogeneous vegetation (Prentice, 1985; Sugita, 1994). This area is called “characteristic source area of pollen” (Prentice, 1985, 1988). The size of characteristic source area of pollen is taxon specific (Bradshaw & Webb, III 1985; Jackson, 1990), and depends on the size of sediment basin (Jacobson & Bradshaw, 1981).

In practice, however, the vegetation around the sediment basin is usually heterogeneous. Therefore, the determination of the source area of pollen is complicated. To identify the source area of pollen in the case of heterogeneous vegetation the term “relevant source area of pollen” (RSAP) was defined by Sugita (1994). While investigating the RSAP, it is important to take into account the effects of spatial distribution of plants, pollen productivity, pollen dispersal and size of the basin on pollen representation of vegetation. Pollen originating beyond the relevant source distance is a constant regional pollen rain, while differences in plant abundance within this distance are recorded as variance in pollen assemblages among sites (Sugita, 1998; Davis, 2000). Sugita (1994) has demonstrated in his theoretical studies that the RSAP for a lake with 50 m radius is the area within 300 m from lake shores.

The assumptions of Sugita model, which describes pollen loading on entire surface of the sediment basin and was developed to predict pollen deposition in lakes, are as follows (Sugita, 1994; 1998):

- The sampling basin is a circular opening in the forest canopy.
- Pollen dispersal is even in all directions.
- The dominant agent of pollen transport is wind above the canopy.
- Pollen productivity is constant for each taxon.
- The spatial distribution of each plant taxon is expressed as function of distance from a point at the centre of the basin.
- Arc-wise pollen deposition is expressed as a function of distance from point sources. The shape of the dispersal function is mainly determined by wind speed and species specific fall speed of pollen.

Sugita with colleagues (1997) have verified the theoretical calculations with empirical studies of Rainbow Lake A (Alberta, Canada) describing the influence of size and proximity of forest fire on pollen signals of disturbance. As pollen productivity and dispersion are species specific, it is important to verify the RSAP in different vegetation zones.

1.2. FORMATION OF POLLEN PROFILES[1]

Working out more precise reconstructions of past vegetation requires a detailed understanding of the factors affecting the vegetation development, pollen dispersion and sedimentation. It is

[1] The author considers pollen profile an aggregated whole of stratigraphically ordered pollen spectra of one core, the graphical expression of which is a pollen diagram. A pollen spectrum is a species and abundance composition of a pollen in one sample.

widely accepted that the most essential factor affecting the formation of vegetation on a large scale is climate and the pollen analysis has been used initially as a method for investigating past climatic changes and the method has been developed by many other scientists (von Post, 1916; Birks, 1981; Howe & Webb, 1983; Klimanov, 1984; Davis *et al.,* 1986; Ritchie, 1986; Kabailene & Raukas, 1987; Guiot, 1991; Seppä *et al.,* 2004). The basic prerequisites for these reconstructions were that the pollen profiles from the same climatic region are similar, can be stratigraphically correlated and correspond to main climatic parameters.

Practically, comparison of pollen profiles from sediment sections situated close to each other demonstrates some discrepancies (Tolonen & Tolonen, 1988; Simmons & Innes, 1996; Koff, 1997). It is obvious that besides the climate also other factors influence the development of vegetation as well as formation of pollen profiles in the sediment basin. Differences in topography, soils, hydrological regime *etc.* may occur within an area of kilometres or even hundreds of meters. As majority of pollen originates from quite a small area surrounding the sediment basin (Sugita, 1998), such factors may have great impact on the formation of pollen profiles, especially in the case of small sediment basins (Brubaker, 1975; Winkler, 1985; Gavin *et al.,* 2001; Hall *et al.,* 2002; Motzkin *et al.,* 2002; Parshall et al., 2003).

The topography determines the vegetation structure through slope gradient, aspect, exposition and microclimate (Rikkinen, 1989; Punning et al., 1995). The landscape topography influences also the speed and direction of the wind (Tammelin, 1991; Ramsay, 1993). Therefore, the transportation of pollen in atmosphere follows the corridors elongating the landscape topography (Gracia-Mozo, 2004).

Topography has also some impact on the pedogenesis and hydrological regime. Pedogenesis accelerated in the territory of Estonia after melting of the ground at the beginning of the Holocene. In further development, the heterogeneity of soils is mostly determined by the bedrock, topography, hydrologic regime, vegetation *etc.* (Reintam, 1995).

The successional development of the vegetation can be interrupted by various disturbances such as human impact, forest fires, plant diseases *etc.* Disturbances vary in spatial extent. The amplitude of disturbance and its location from the sediment basin determines its expression in the pollen spectra. Sugita with colleagues (1997) have shown that the disturbance size to be registered in pollen profile must be more extensive the further from lake it occurs.

Registering the disturbances using palynological method is complicated also due to their temporal shortness. As the influence of disturbance stops, the vegetation recovers during one succession cycle. Furthermore, it must be taken into consideration that in general one sediment sample represents signals from multiple vegetation periods, and therefore, temporally short disturbances are not registered in pollen profiles (Green, 1982; Moore *et al.,* 1991; Odgaard, 1992).

The influence of disturbances on vegetation structure can be exaggerated in conjunction with climatic and landscape characteristics. As a result of such disturbances, the species growing on the limit of their distribution area can become extinct (Fahrig, 1997). In the presence of stable environmental conditions, the vegetation recovers on disturbed areas after some time due to the succession (Clark, 1989; Zobel, 1993; He & Mladenoff, 1999; Pitkänen & Huttunen, 1999).

1.3. USE OF CHARCOAL ANALYSIS FOR DETECTING FOREST FIRES

In order to reconstruct the history of forest fires, charcoal analysis has been applied in addition to pollen analysis. There is a general acceptance that charcoal records are signals of fires in the paleoenvironment (Patterson et al., 1987; Clark, 1989; 1990). The forest fires have great influence on structure of vegetation, and therefore, could be reflected in pollen profiles. There is a great number of studies dedicated to fires initiated by man. In Estonia, Poska and Saarse (2002) have examined the human impact on vegetation structure during the last 3000 years. But also before human impact, the natural fires maintained forest succession cycles (Pitkänen & Huttunen, 1999). Periodically occurring forest fires ensure biodiversity in forests (Cwynar, 1977; Clark, 1989; Keeley & Fotheringham, 2000; Taylor, 2000; Whitlock, 2001).

So far there is no unified methodology neither recording and expressing charcoal abundance nor in the interpretation of charcoal data. Various methods have been used to present the results of charcoal analysis:

- number of charcoal particles counted in the pollen slides (Molloy & O'Connell, 1993; Saarse *et al.,* 1998);
- ratio of charcoal particles to pollen (Motzkin *et al.,* 1993; Sugita *et al.,* 1997; Tipping & Milburn, 2000);
- ratio of charcoal particles total area to pollen count (Odgaard, 1992; Sarmaja-Korjonen, 1992);
- concentration of charcoal particles (Gardner & Whitlock, 2001);
- area of charcoal particles per unit volume of sediment (Clark, 1984; Odgaard, 1992; Edwards & Whittington, 2000);
- area of charcoal particles per unit of weight of sediment (Sarmaja-Korjonen, 1992);
- charcoal accumulation rate (Cwynar, 1977; Clark, 1990; Laird & Campbell, 2000);
- size classes of charcoal have been distinguished and each class have been presented separately (Sarmaja-Korjonen, 1992; Blackford, 2000).

It is obvious that charcoal diagrams and interpretations based on these depend on the techniques chosen to present the results of analysis. Therefore, there is a need for methodological analysis to find out the most adequate way to present the results of charcoal analysis, whereas the charcoal curve most precisely reflects the history of forest fires.

2. OBJECTIVES

The aim of the study was to develop a methodology to estimate the role of disturbances in vegetation on formation of pollen profiles in small Estonian lakes. To carry out paleoecological investigations, it is important to consider how the size of the lake, and the position as well as the extent of the disturbed area influencing the reflections of disturbances in pollen profiles. The multifarious Estonian landscapes, with large forest areas affected insignificantly by man, and well-documented disturbances offer good basis to determine the potential limits of the palynological method on detecting the changes in the vegetation. In addition, the analysis also takes into consideration the importance of landscape characteristics like soil heterogeneity on formation of vegetation structure, and therefore, on formation of pollen profiles.

The main objectives of the study were as follows:

1) Develop a methodology enabling:
    a) to investigate how the disturbances occurred in vegetation are reflecting in pollen profiles, using map analysis for selecting the study areas and detecting the disturbances in vegetation;
    b) to evaluate the method by comparing the documental evidences of changes in vegetation structure with pollen and charcoal data.
2) Explore the most suitable way for presenting results of charcoal analysis whereby the charcoal data reflects the history of forest fires most precisely.
3) Assess the importance of size and position of disturbance patch in their reflection in pollen profiles.
4) Estimate the significance of heterogeneity of soils on formation of pollen profiles during the Holocene by example of the Viitna kame field and the Otepää Heights.

3. STUDY AREAS

To fulfil the objectives of the study sediment sequences of Estonian small lakes from different landscape regions were studied (Fig. 1, Table 1). To find out the relationships between disturbances in vegetation and pollen profiles the pollen and charcoal analysis were performed for upper sediment layers of four lakes (Fig. 1, sites 1-4). The selected study sites are closed lakes situated in forested landscapes, where, according to historical data, some disturbances have occurred (**I-II, VI**).

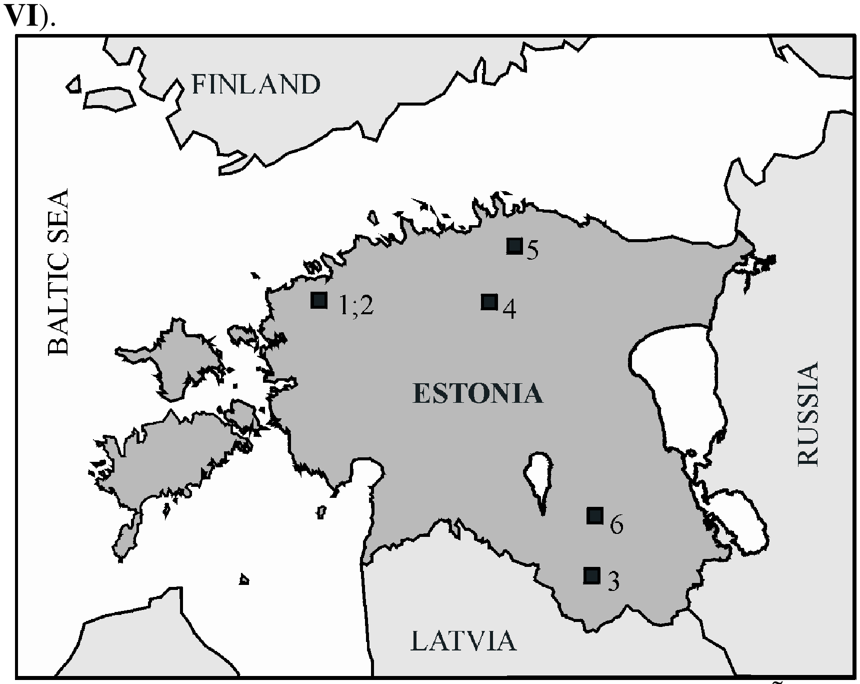

Fig. 1. Location of lakes studied. 1 - L. Tänavjärv; 2 - L. Mustjärv; 3 - L. Õdre; 4 - L. Matsimäe; 5 - L. Viitna Linajärv; 6 - L. Väike-Juusa.

Lake Tänavjärv is situated in north-western Estonia (Fig. 1). The landscape surrounding the L. Tänavjärv is flat. North of the lake lie boreal heath forests on sand dunes. To the south and east, there is a large bog system with ombotrophic bog forest as the prevailing vegetation type, where the pine (*Pinus sylvestris*) is a characteristic species. The surroundings of the lake have suffered from several forest fires during the 20th century.

Lake Mustjärv is situated 800 metres to the south of L. Tänavjärv (Fig. 1). The lake is surrounded by mire and the main vegetation type is the ombotrophic bog forest that consists mainly of pine. There is no historical evidence of any fires in the immediate vicinity of the lake, all forest fires having occurred more than 2 km away.

Lake Õdre is situated in southern Estonia (Fig. 1). It is a typical woodland lake, shaped with mosaic hills (105-110 m a.s.l.) of the Karula Upland. The main vegetation type around the lake is pine forest; on the south-eastern and north-western shores minerotrophic swamp forests with birches (Betula *pendula*) dominate. The main disturbance affecting the vegetation around the lake is several forest clear-cuttings.

Lake Matsimäe is situated in central Estonia (Fig. 1). The lake is surrounded by ombotrophic bog forest where pine trees are prevailing. Along the western shore, there is an esker covered with birch, alder (*Alnus glutinosa*) and spruce (*Picea abies*). The main disturbance registered is the establishment of gravel quarry on the esker in the 1960-s.

Furthermore, in two different landscape regions the long cores from lake and bog sediments, covering the all Holocene, were studied (Fig. 1, sites 5-6). **Lake Viitna Linajärv** (hereafter L. Linajärv) at Viitna kame field was chosen from North-Estonia (**III-IV**). The kame field is characterized by low-relief and gently rolling glaciated topography on the north-western slope of Pandivere Upland (Kont, 1984). The relative altitude of the area is about 20 m. In addition to limnoglacial kames and eskers, the area is featured by kettleholes, some of which are occupied by lakes or filled with peat deposits. Forests cover 90% of the territory around the lakes, the remaining 10% is under buildings, roads and beaches. Pine and spruce trees dominate in the forests, growing mainly on the elevations. Birch and other deciduous trees are growing mainly on lake shores and in depressions between eskers and kames. The number of different soil types is small and the soils are rather poor. The pollen profile from L. Linajärv sediment section was compared with the pollen profiles from close lying L. Pikkjärv (Saarse *et al.,* 1998) and kettlehole (Koff, 1984) sediments.

From the Otepää Heights at South-Estonia the lacustrine sediment core from **Lake Väike Juusa** (hereafter L. Juusa) was chosen (**V**). Lake Juusa is located in the central part of the Otepää Heights. The area is characterized by the distribution and genesis of various landforms, caused by the bedrock structure and accumulation processes (Raukas & Karukäpp, 1979). Due to the complexity of landforms, the diversity of soil types is high. Depending on the inclination of the ground and texture of the bedrock, over 300 soil taxons per square kilometre can be found on Otepää Heights. Therefore, the vegetation is diverse, characterised by small mosaic patches pursuant to the landforms. According to the geobotanical map of Estonia, the Otepää Heights belong to the region of spruce and mixed spruce forests (Laasimer, 1965). The depressions between the hills are occupied by minerotrophic mires with low number of species. The vegetation around L. Juusa consists of pine forests on its eastern side and mixed spruce forests on the western side. On northern and southern sides cultivated grasslands are dominant.

The pollen profile from L. Juusa is compared with other pollen profiles from the same region. One pollen profile is available from an overgrown lake 1 km NE of Otepää City (hereafter Otepää profile) analysed by Sarv (1979), the other pollen profile is from Lake Ala-Pika sediments studied earlier by Kihno (1998) in the marginal area of Otepää Heights.

Table 1. Characteristics of the lakes studied. Lake numbers as in Fig. 1.

Characteristic	Tänavjärv (1)	Mustjärv (2)	Matsimäe (3)	Õdre (4)	Linajärv (5)	Juusa (6)
Position	59°10'N 23°48'E	59°10'N 23°48'E	59°04'N 25°31'E	57°45'N 26°27'E	59°40'N 25°45'E	58°30'N 26°30'E
Length (m)	2300	300	340	260	390	250
Width (m)	830	270	230	140	180	160
Area (ha)	136.9	4.8	5.5	3.0	3.8	3.0
Max depth (m)	2.5	2.7	8.1	9.1	6.7	5.8
Dominate vegetation types on catchment	Boreal heath forest / Ombotrophic bog forest	Ombotrophic bog forest	Ombotrophic bog forest	Fresh boreal forest	Dry boreal forest	Cultivated pastures / dry boreo-nemoral forest

4. METHODS

4.1. SELECTION OF THE STUDY AREAS AND MAP ANALYSIS

To investigate the relationships between disturbances occurred in the vegetation and pollen profiles the lakes were chosen according to the following principles:

- lakes should be closed in order to exclude the possibility of pollen inwash and outwash by rivers;
- lakes lying in forested landscapes as the pollen dispersion of herbs pollen, dominating in open communities, is significantly different;
- lakes are similar by their trophic types, preferably dystrophic and semidystrophic lakes where the sedimentation rate has been constant during the studied period;
- the disturbances have occurred in the vicinity of the lakes and the documentary evidences of these is available.

All available maps of the study areas were digitised and landcover maps were composed using the cartographic software MapInfo Professional. Comparing the digitised maps from different time periods, the size and position of disturbed areas were investigated. Based on the comparison of pollen profiles and the characteristics of disturbances, the size of main source area of pollen (MSAP) of these lakes was estimated. Main source area of pollen is the area surrounding the lake which vegetation influences the formation of pollen profiles most significantly.

Two study areas (Fig. 1, sites 5-6) were selected to investigate the importance of landscape characteristics, especially the soils heterogeneity, on formation of pollen profiles during the Holocene. One region with poor heterogeneity and another with great heterogeneity of soils were chosen. The regions were preferred, where some palynological investigations were already carried out to compare these data with the results of the author. Also in this case, closed lakes were preferred. Vegetation, soil and topographic maps were created using the software MapInfo Professional to represent the landscape characteristics of lakes surroundings.

For creating the vegetation maps aerial photographs from different time period and forestry maps from State Forest Management Centre (RMK) were used. Soil maps are based on the Estonian large-scale soil map (M 1:10 000). For creating the topographical charts the topographic map from the beginning of the 1950s (M 1:25 000) was used.

4.2. SAMPLING

Sampling was performed in winter through ice. By coring from stable ice cover and with precise measurement of the depth of each lake at the coring point, it was assured that the upper layers of the sediments were not disturbed. Sediment sequences have been taken from the deepest part of the lake having in mind the sediment focusing effect (Davis & Ford, 1981; Håkanson & Jansson, 1983). Exception was made in the case of L. Tänavjärv, where the sediments are accumulated mainly on the western side of the lake (Saarse *et al.,* 1989). In order to find the suitable sampling point several corings were performed and the studied core was taken from the position where the sediment was the thickest.

In the case of L. Tänavjärv, L. Mustjärv, L. Matsimäe and L. Õdre, sediment sequences with length of 50–60 cm from the upper unconsolidated surface of sediment were taken using a modified Livingstone-Vallentyne piston corer (diameter 7 cm). The lithology of the sediment was described directly at the study site. Considering the high content of water in the samples and the expected sedimentation rate, 1 cm thick samples were taken continuously. It was estimated that in this case the relative age of one sample does not exceed 5–10 years, which is suitable to determine the influence of disturbances' on vegetation development. The sampling was performed at the site and samples wrapped in plastic were kept in refrigerator prior to analysis.

The bathymetry, sediment types and basin morphometry of L. Linajärv were investigated by coring at 13 points (**III**). Core for palynological and other analyses was extracted from the deepest part of the lake where the deposits layer is the thickest. The samples from upper loose sediments (0–60 cm) were taken using a modified Livingstone-Vallentyne piston corer (diameter 7 cm), and freeze-core technique was applied to collect undisturbed cores of surface sediment to depth of 120 cm. The more consolidated sediments from 120 cm to the mineral ground were sampled with Belorussian peat corer. The lithology of the cores was described in the field. Subsampling of the soft sediments was done immediately in the field. In this case, the subsampling was continuous in 1 cm intervals to the depth of 60 cm. The samples were put into plastic bags and stored in freezer. The Rest of the sediment core was divided into 50-cm-long pieces, wrapped in plastic and stored in freezer. Subsampling of long core was done in the laboratory. Samples taken with freeze corer were wrapped tightly into plastic and stored in the deep freezer until analysis.

The core from L. Juusa was taken from the deepest part of the lake where the water was 5 m deep. The upper layers of lake sediments (50 cm) were sampled using a modified Livingstone-Vallentyne piston corer (diameter 7 cm). Sediments from 50 cm below the sediment surface down to the mineral bottom were sampled with a Belorussian peat corer. The lithology of the sediments was described in the field immediately after coring. Subsampling of the soft sediments was done immediately in the field. In this case the subsampling was continuous in 1 cm intervals to a depth of 50 cm. The samples were put into plastic bags and stored in freezer. Rest of the sediment core was divided into 1-m-long pieces, wrapped in plastic and stored in freezer. Subsampling of long core was done in the laboratory.

In the case of L. Matsimäe, L. Õdre, L. Tänavjärv and L. Mustjärv the pollen and charcoal analysis were performed for upper sediment section with length of 30–40 cm. In this study, the results from upper 25 cm were used, which covers approximately 90–100 years. For this period, the documentary evidences of disturbances occurred in vegetation surrounding the lakes were available (**I-II**).
In the case of L. Linajärv and L. Juusa the samples for pollen and charcoal analyses were taken after every 20 cm (III-V). Considering the thickness of sediment sequence, it was assumed that with this sampling strategy there would be one pollen sample per 200 years. Additional samples were taken to improve the resolution in certain sections of sediment cores after the preliminary pollen profile was prepared. Supplementary samples were taken from these parts of core where remarkable changes in pollen profiles were noted and which needed more detailed investigation (**III-V**).

4.3. POLLEN ANALYSES

In all cases, except for L. Juusa, the samples were dried at 105 ºC and homogenised. For pollen and charcoal analyses a 50 mg dried sample was used. Because of high water content of samples taking the 1 cm^3 wet samples was complicated and therefore the drying of samples was necessary. In the case of L. Juusa, where the sediments density is higher, for pollen and charcoal analysis 1 cm^3 wet sample was used.

Samples for pollen and charcoal analyses were boiled in 10% KOH and treated according to standard acetolysis (Moore & Webb, 1978). The samples were not sieved at any stage of preparation. Three to six tablets containing a known number of *Lycopodium* spores were added to each sample at the beginning of treatment, thus enabling the calculation of pollen and charcoal concentrations (Stockmarr, 1971). In general, all pollen grains and spores were identified and counted to at least 500 arboreal pollen (AP) grains per level, which is sufficient for statistically reliable results (Berglund & Ralska-Jasiewiczowa 1986). Pollen percentages were calculated using the sum of terrestrial pollen grains (sum of AP and non-arboreal pollen (NAP)). In the case of Lakes Matsimäe, Õdre, Tänavjärv, and Mustjärv (**I**) also the pollen accumulation rate *I* (pollen grains cm^{-2} yr^{-1}) was calculated according to the following equation:

$$I = \frac{P \times LYC \times M}{lyc \times m \times S \times A}$$

where: *P* - number of pollen grains counted from the sample, *LYC* - total number of *Lycopodium* spores added, *lyc* - number of *Lycopodium* spores counted, *M* - dry weight of the whole sample (g), m - dry weight of the analysed sample (g), S - surface area of the sample (cm^2), and A - time of formation of the sample layer (yr).

Because of uncertainties in calculating the sedimentation rate the error in estimations of pollen accumulation rates can reach up to 30% of the result (Bennet & Willis, 2001). Therefore, the estimation of pollen accumulation rates is used only in studies considering the events of the last century. In these cases, the age estimations of sediment sequences are more reliable as the studied period is shorter and age calculations are controlled by different methods.

In the case of L. Linajärv and L. Juusa, pollen percentages were used as the compared pollen profiles prepared by other researchers were also presented as percentage diagrams. The age estimations of long cores were not reliable enough for calculating the pollen accumulation rates. Pollen calculations and diagrams were prepared using TILIA and TILIA.GRAPH (Grimm, 1991-1993).

4.4. CHARCOAL ANALYSES

From all the pollen slides charcoal particles $\geq 100\ \mu m^2$ were counted and their total surface was calculated by multiplying the lengths of their longest and shortest axes. The scale of microscope ocular was used for measuring the size of charcoal particles. As different authors have used varying techniques to present the results of charcoal analysis, the comparative analysis was performed to find out the technique, whereby the curve of charcoal particles represents most adequately the history of forest fires in region (**II**). The curves of the ratio of charcoal particles to arboreal pollen (chp AP^{-1}), the concentration of charcoal particles (chp g^{-1}), and the area of charcoal particles per gram of sediment ($\mu m^2\ g^{-1}$) from L. Tänavjärv and L. Mustjärv were compared with documentary evidence of forest fires in the region over the past 60 years.

Ratio of charcoal particles (chp) and AP in the pollen slide was calculated dividing the number of counted charcoal particles with number of counted AP pollen. As 500 AP pollen was counted from every sample, the shape of the curve of this ratio is similar to the curve of number of charcoal particles counted from sample, which is most often used method for presenting the results of microscopic charcoal analysis. As the shapes of these curves are similar, only the curve of charcoal particles per AP is presented.

For the calculations of the charcoal particles concentration (C) the following equation was used:

$$C = \frac{chp \times LYC}{lyc \times m}$$

where: chp - number of counted charcoal particles, LYC - number of added *Lycopodium* spores, lyc - number of counted *Lycopodium* spores, m - sample weight (g).

For the calculations of the total area of charcoal particles per unit of weight (C_s) the following equation was used:

$$C_s = \frac{chp_s \times LYC}{lyc \times m}$$

where: *chp_s* - total area of counted charcoal particles, *LYC* - number of added *Lycopodium* spores, *lyc* - number of counted *Lycopodium* spores, *m* - sample weight (g).

As the results (**II**) suggest, the area curve of charcoal particles per unit mass of sediment dry matter provides the best indicator of forest fires. Therefore, to present the results of charcoal analysis in cases of L. Linajärv and L. Juusa similar techniques were performed.

4.5. SEDIMENT DATING

For sediment dating various methods were used. The core from L. Matsimäe (**I**) and upper sediment layers from L. Linajärv (**III-IV**) were dated by using the ^{210}Pb method (data calculated by CRS model) (Appleby *et al.,* 1992), and as the reference levels, the layers with maximum ^{137}Cs activity (ref. yr=1986) were separated (Varvas & Punning, 1993). All ^{210}Pb datings were performed at the Centre for Environmental Monitoring and Technology, Ukrainian Hydrometeorological Research Institute in Kiev.

In the cases of Lakes Õdre, Tänavjärv and Mustjärv, the age depth curve was based on spherical fly-ash particles (SFAP) analysis (**I, II**). Particles were counted from specially prepared samples. In the chemical preparation of these, dried sediment (*ca.* 0.05 g) was boiled in hydrogen peroxide (8 h) to remove organic matter following standard procedures (Renberg & Wik, 1985). After this treatment *Lycopodium* spores were added to the samples to enable the calculation of SFAP concentrations. SFAP were counted at x400 magnification. Taking into account the history of high temperature combustion of fossil fuels in Europe and in Estonia, the sediment layers with a significant increase in SFAP concentrations were regarded as having accumulated towards the end of the 1940s (Punning & Alliksaar, 2000).

The plant remains from long core of L. Linajärv were dated by AMS method at Ångstrom Laboratory, Uppsala University in Sweden. The L. Juusa long core was AMS radiocarbon dated on terrestrial macrofossils at the Institute of Physics, Erlangen-Nürnberg University (Germany). As the other cores used for comparative analysis of formation of pollen profiles in the Holocene in Viitna and Otepää area were dated by using the conventional ^{14}C dating techniques (analysis were performed at the Institute of Geology, Tallinn Technological University), it appeared irrational to calibrate these data. Therefore, the ages of cores are given in uncalibrated ^{14}C years.

5. RESULTS AND DISCUSSION

5.1. ESTIMATION OF DISTURBANCES INFLUENCE ON FORMATION OF POLLEN PROFILES

The largest lake of this study was L. Tänavjärv (Fig. 2a; Table 1). Using aerial photographs, forestry maps and other documentary evidences it was determined that the surrounding of the lake have suffered from several forest fires during the 20th century. The last fire occurred in 1997 destroying the forest near the northern shore of the lake. Fires have also occurred in 1993 when ~460 ha and in 1980 when ~100 ha were burnt. The most extensive fire occurred in 1951/52, when an area of ~2000 ha of the forest was burnt. As a consequence, the pollen accumulation rate in this lake decreased (Fig. 3). The other known forest fires in surroundings of L. Tänavjärv were smaller by area and did not induce remarkable changes in pollen load to sediment. These results correspond to the Sugita's (1998) propositions that in the case of large lakes the size of the disturbed area has to be at least ten times larger than the lake, and the disturbance must occur at or very close to the lake shores to be clearly distinguished from pollen profile.

In the case of L. Mustjärv, lying ~800 m to the south of L. Tänavjärv (Fig. 2a; Table 1), all forest fires mentioned above have occurred more than 2.5 km from its shores. There was no detectable impact of these fires on the pollen accumulation into this lake (Fig. 3). Therefore, the author assumes that in the case of lakes with that size the disturbed area must be closer to lake shores to influence the formation of pollen profiles. Even a very large disturbance (1951/52 forest fire affected ~2000 ha) does not influence the pollen accumulation if the disturbance occurs kilometres away from the lake shores.

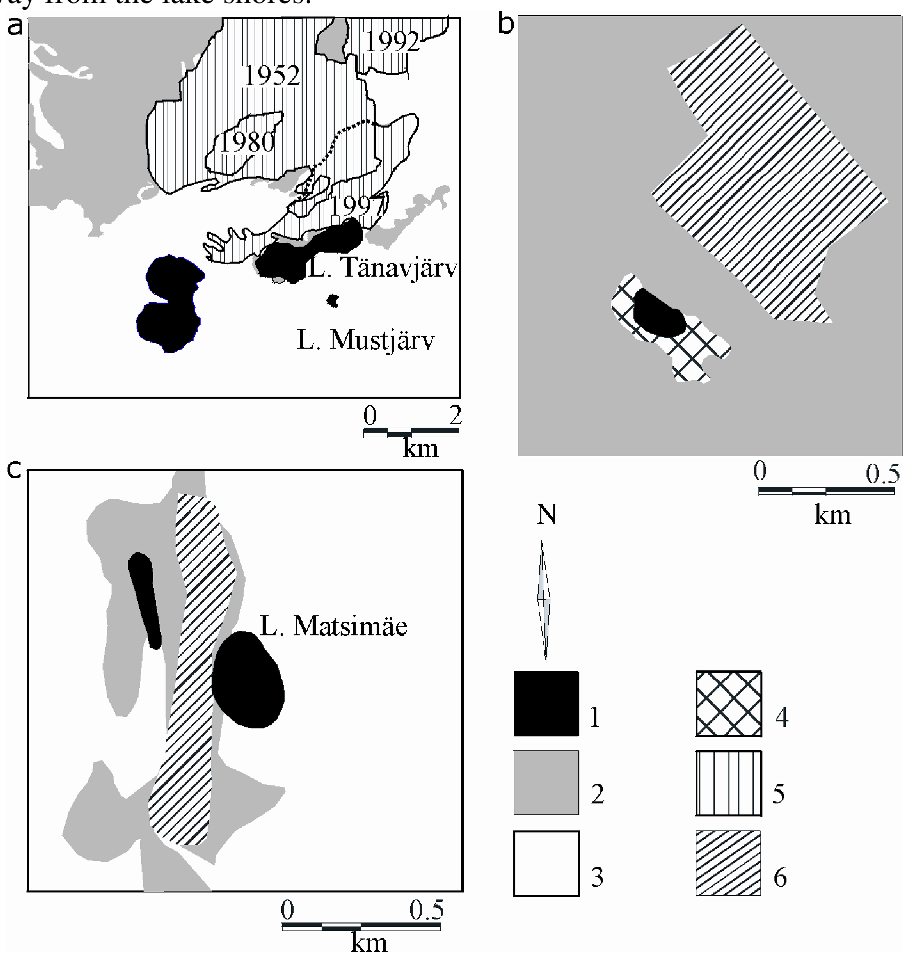

Fig. 2. Main vegetation units and disturbances around the studied lakes: (a) Lakes Tänavjärv and Mustjärv, (b) Lake Õdre, (c) Lake Matsimäe. 1 - lake; 2 – dry and fresh forest; 3 - ombotrophic bog forest; 4 - minerotrophic swamp forest; 5 - forest fires; 6 - forest clear-cutting.

From the forest management maps several clear-cuttings with different size and distance from shores of L. Õdre were registered. Nevertheless, pollen accumulation rate curves are not reflect any certain clear-cutting. The closest to lake shores and the most extensive (~48 ha) clear-cut occurred in the early 1950s when the limits of the disturbed area reached 250 m from lake shores.

Overriding area of this disturbance lies about 500–900 m from lake shores (Fig. 2b). Within the 500 m zone from lake shores the disturbed area covers ~15%. Increasing the width of explored territory to 900 m the share of disturbed area remains ~15%. Further increase in the explored territory causes the sharp decrease in the share of disturbed area.

From the forest management maps the author has registered that the most sizable disturbance in the vicinity of L. Matsimäe has occurred in the 1960s. The establishment of a gravel quarry led to the clear-cutting of the forest on the esker lying on western shore of the lake. As the lake is mostly surrounded by ombotrophic pine-dominating bog forests, the esker is a suitable habitat for spruce, birch and alder. Decrease in these types of pollen accumulation rates on 1960s can be associated with the clear-cutting (Fig. 3). Also the pollen accumulation rate of pine appeared decreasing to a small extent. The disturbance, with area ~17 ha, has occurred within 450 m from the lake shores (Fig. 2c). At the territory within 50 m from lake shores the disturbed area covers ~40%. Increasing the width of explored territory to 450 m the share of disturbed area decreases to ~15%.

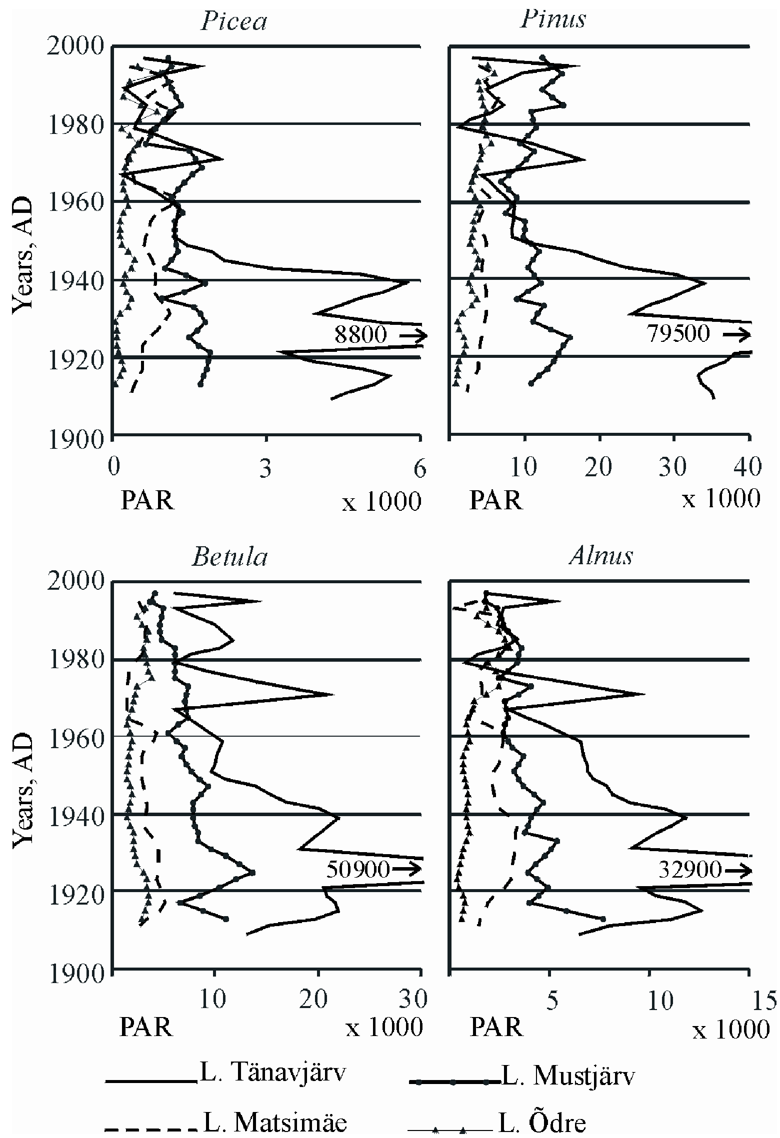

Fig. 3. Some pollen accumulation rate curves in the sediments of lakes Tänavjärv, Mustjärv, Õdre and Matsimäe; PAR – pollen accumulation rate, grains cm^{-2} yr^{-1}.

Taking into account the magnitude and position of disturbed areas in the surroundings of L. Matsimäe and L. Õdre, it appeared that in the case of small lakes (area 3–6 ha) in forested landscapes the main source area of pollen is within a couple of hundred meters from lake shores. Past disturbances could be reliably detected in cases when the disturbance occurred in the immediate vicinity of the lake and >15% of the surrounding territory was involved. In the case of a large lake (~137 ha) only disturbance embracing thousands of hectares can be detected in the pollen profiles.

The distance between the lake and the disturbed area, and the size of both are considered the most important factors influencing the disturbances reflection in pollen profiles. For more detailed studies also the factors like species specific pollen productivity and pollen dispersion should be considered. Furthermore, the landscape surface roughness must be taken into account as factor influencing the pollen dispersion by wind. Thus, the estimations of main source area of pollen can be quite approximate.

The results of this study confirm the outcome of the theoretical modelling (Sugita *et al.,* 1997; Sugita, 1998) how lake size and the location and size of a disturbance patch affect the pollen representation of disturbance. Also the results of the author's study assert that the threshold of detection is lower if the disturbance concerns a small lake (3–6 ha). The estimations of the MSAP size for small lakes are suitable for more detailed interpretation of the paleorecords, and provide a basis for understanding the size of the area where the history of vegetation can be palynologically reconstructed.

5.2. METHODOLOGICAL APPROACH OF CHARCOAL ANALYSIS FOR DETECTING THE DISTURBANCES IN VEGETATION

In forested landscapes, fire is one of the most important factors inducing disturbances. The charcoal particles originating from forest fires and deposited into the sediments are primary evidence from which reconstructions of past fire history are made (Tolonen, 1985).

To identify the most suitable way to present the results of charcoal analysis the comparison of documented forest fires and various methods for presenting the results of charcoal analysis was carried out by example of lakes Tänavjärv and Mustjärv. Four major forest fires were dated in the surroundings of L. Tänavjärv and L. Mustjärv in the 20th century (Fig. 2a). The most extensive of these occurred in 1951/52 when up to 2000 ha of forest were destroyed. In 1982, fire extended over nearly 100 ha about 3 km to the north-west of L. Tänavjärv and in 1993 a fire destroyed *ca.* 460 ha of forest about 7 km north of this lake. The most recent major forest fire was in 1997. This extended over 719 ha and was close to the western shore of the lake but mainly affected the area to the north of the lake.

The forest fire of 1951/1952 reached close to the northern shore of L. Tänavjärv. According to the age-depth curve, this fire should be recorded at the depth of 11–12 cm in the sediment (**II**). It is assumed that the 2 to 3-fold decrease in pollen accumulation rate values in the 1950s can be attributed to a forest fire (Fig. 3). As a consequence of the forest fire, AP production in the pollen source area decreased and the landscape became more open, resulting in distinctly lower pollen accumulation rate values (**I**).

As in the case of L. Tänavjärv, AP pollen accumulation rate values decline towards the top of the profile (0–10 cm), the ratio of charcoal particles to AP increases (Fig. 4a). In the case of L. Mustjärv, the accumulation rate of AP does not decrease, and therefore, the ratio of charcoal particles to AP is low at the uppermost sediment layers (0–9 cm) (Fig. 4d). These changes do not appear to be connected with forest fires in the study area and there is no evidence of regional fires at greater distances around the study area.

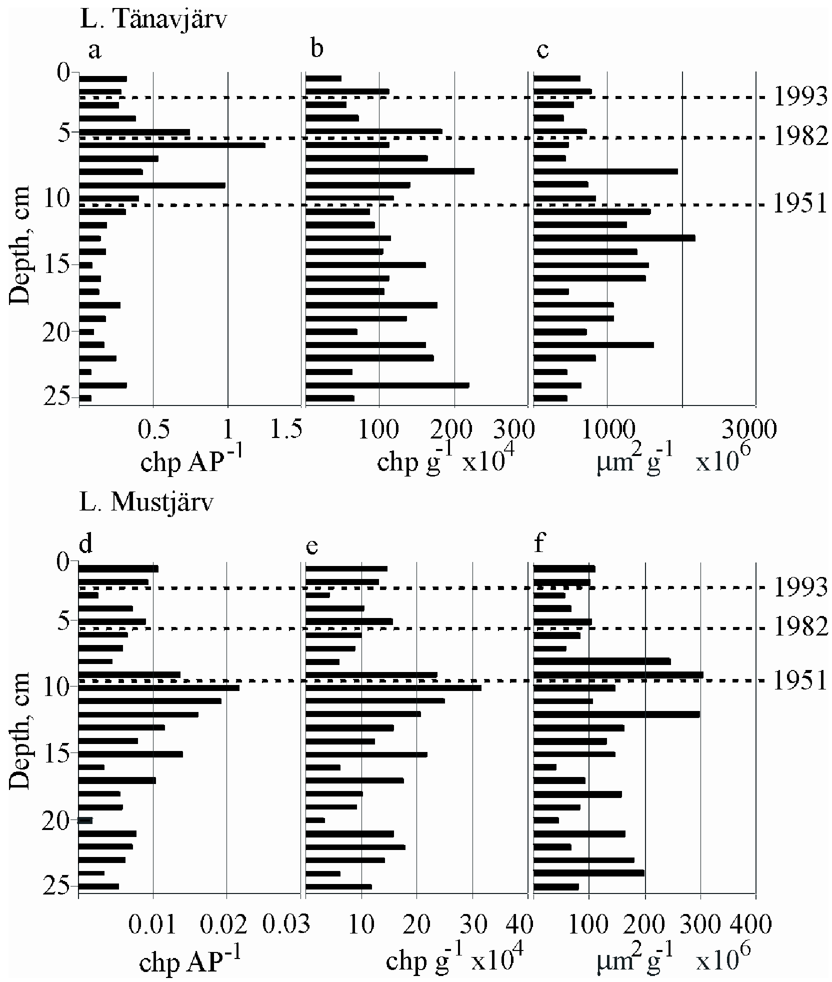

Fig. 4. Charcoal records of Lake Tänavjärv (a-c) and Lake Mustjärv (d-f): a & d - ratio of charcoal particles (chp) and AP in the pollen slide; b & e - number of charcoal particles per g of sample; c & f – total area of charcoal particles per g of sample.

In the case of L. Tänavjärv, the ratio of charcoal particles to AP pollen reflects the decrease in AP accumulation rate above 10 cm. As the curve for charcoal concentration values shows (Fig. 4b), at these depths the concentration of charcoal particles is somewhat, but not significantly, higher than in the remaining part of the core. In the case of L. Mustjärv, in upper 9 cm sediment layers the ratio of charcoal particles to AP pollen is rather low (Fig. 4e). Being fragile, charcoal particles may get fragmented during sample preparation; as a result, the number of particles and thus also their concentration in the samples will increase. Curves for charcoal particle concentration should therefore be interpreted with caution, as peaks may reflect factors other than fires in the charcoal source area. However, Clark (1984) showed that standard pollen samples preparation procedures (including sieving) systematically diminish the area and number of charcoal particles.

In the core from L. Tänavjärv, charcoal particles of size >100 μm^2 were counted. Particles up to 500 times larger were also noted. In the case of L. Mustjärv, the preparation of samples and analysis were carried out by using similar techniques and the charcoal particles appeared to be smaller in this lake. Several authors (Tolonen, 1985; Tinner *et al.,* 1998) have found that charcoal area and number co-vary if plotted against depth, and have concluded that measurements of microscopic charcoal from pollen slides are superfluous for reconstruction of regional fire history. In this study, the charcoal particles were mostly smaller than 500 μm^2. The total area curve is, in most cases, determined by the frequency of large particles. Hence, the charcoal concentration values and total area curves show somewhat different trends and do not co-vary as the above mentioned authors found.

The presence of large charcoal fragments from >1000 μm^2 up to 50,000 μm^2 gives strong evidence of the peak at 11–16 cm being related to the 1951/52 fire (Fig. 4c). However, the charcoal from that fire appears to be spread through the sediment layer dated from 1922 to 1952. Although the sedimentation rate (rate at which charcoal particles settle in the water column) of charcoal particles is rather high (Renfrew, 1973; Nichols *et al.,* 2000), redeposition, sediment mixing and delayed charcoal transport to the basin can result in charcoal peaks from a single fire that span a decade or more (Patterson *et al.,* 1987; Millspaugh & Whitlock, 1995). Due to the redeposition, bioturbation *etc.*, the charcoal could also have been transported downwards. However, the results of SFAP analysis and the results of other authors do not support the possibility that these processes could affect a 6 cm thick sediment layer spanning about 30 years. Furthermore, in this case also the other particles should be mixed in this layer. To date, there is no information about other forest fires in study area occurring during the period 1920–1950. For this reason author can only assume that the 1951/52 fire is reflected not only in one sample but over a 6 cm-thick sediment layer. Though, it must be borne in mind that there could have been undated forest fires before 1950 in the vicinity.

The evidence of a forest fire in the results of pollen and charcoal analysis depends on the extent of the fire, its distance from the lake and the main direction of the wind. The forest fire of 1951/52 is more clearly expressed in L. Tänavjärv than in L. Mustjärv. This fire appeared in the proximity of L. Tänavjärv but was *ca.* 2.5 km away from L. Mustjärv. In the core from the latter lake, pollen accumulation rate values are quite steady (Fig. 3). If there had been a significant effect from the 1951/52 fire on the vegetation in the L. Mustjärv pollen source area, a decline in pollen accumulation rate values would be expected at the depth of 8–9 cm, corresponding in time to the 11 cm depth in the L. Tänavjärv core. However, no such changes were observed. As Fig. 4f shows, the total area curve for charcoal particles in L. Mustjärv increased at the depth of 8–9 cm; this can be connected to the 1951/52 forest fire. Therefore the author concludes that, although no signals from the forest fire can be found in the pollen profile, such disturbance is reflected in the charcoal data. Author's findings demonstrate that the charcoal analysis gives clear evidence of forest fires at a greater distance from the lake than the pollen analysis alone may indicate.

The 1951/52 forest fire at that area was obviously exceptional in its long duration and spread. Thus both lakes reflect this disturbance. The later forest fires spread over much smaller areas. The 1982 fire, that affected some 100 ha, would be expected to show in both lakes at the depth of 5–6 cm. Although this fire occurred at approximately comparable distance from L. Tänavjärv as the 1951/52 fire appeared from L. Mustjärv, the total charcoal area curve from L. Tänavjärv shows no changes at this depth. The fire was probably too limited in its extent and also too distant from both lakes to give any signals in the charcoal records. Although the forest fire in 1993 involved a larger area, neither lake has any signals (*cf.* 2–3 cm depth) as the distance to the lakes was probably too large and the disturbed area too small. Also, the forest fire in 1997 has left no signals in either lake. The cores were taken in winter 1998, i.e. only half a year after the fire. This is obviously too short time delay to observe these changes in vegetation through pollen analysis.

The present study suggests that in the context of microscopic charcoal analysis from pollen slides the total area per gram of sediment curve for charcoal particles is the most effective indicator of forest fire history. Charcoal data presented in this way gave the clearest signals of fire occurrence in the vicinity of the lakes in question. The author's results also suggest that charcoal particles can carry signals of forest fires over greater distances than pollen.

5.3. ESTIMATION OF SOIL HETEROGENEITY INFLUENCE ON THE VEGETATION HISTORY

As several other authors have shown (Tauber, 1965; Brubaker, 1975; Winkler, 1985; Simmons & Innes, 1996; Sugita *et al.,* 1997; Parshall et al., 2003), in the case of small sediment basins the biggest influence on formation of pollen profiles has the vegetation growing in the immediate vicinity of the site. The author of this study has specified the main source area of pollen to some hundred meters wide vegetation belt around the sediment basin. Vegetation structure on that area is affected by landscape characteristics like soil, microclimate, hydrological regime, topography *etc*. Influence of these factors on formation of pollen profiles is less considered in paleoecological studies than climatic factors (Engström & Hansen, 1984; Pennington, 1986; Punning *et al.,* 1995; Willis *et al.,* 1997). As a consequence of these factors, the pollen profiles can differ from each other even if they are originating from sediment basins lying close to each other. Hereby the influence of soil heterogeneity on the formation of vegetation structure and therefore also on the formation of pollen profiles during the Holocene is under the investigation by example of Viitna kame field (**III; IV**) and Otepää Heights (**V**) (Fig. 1, sites 5-6). Three pollen profiles from both regions were used for this study.

At the first study area the author has analysed the lacustrine sediments of L. Viitna Linajärv (**III**; **IV**) (Fig. 5). For comparison, the pollen profiles from L. Viitna Pikkjärv (Saarse *et al.,* 1998) and a kettlehole situated nearby (Koff, 1984) sediment sequences were used. On surrounding territories of the studied sites *Cambic Podsols* are dominant. Also small patches with *Eutric Histosols* can be found at lower areas and on the shores of the lakes (Fig. 5).

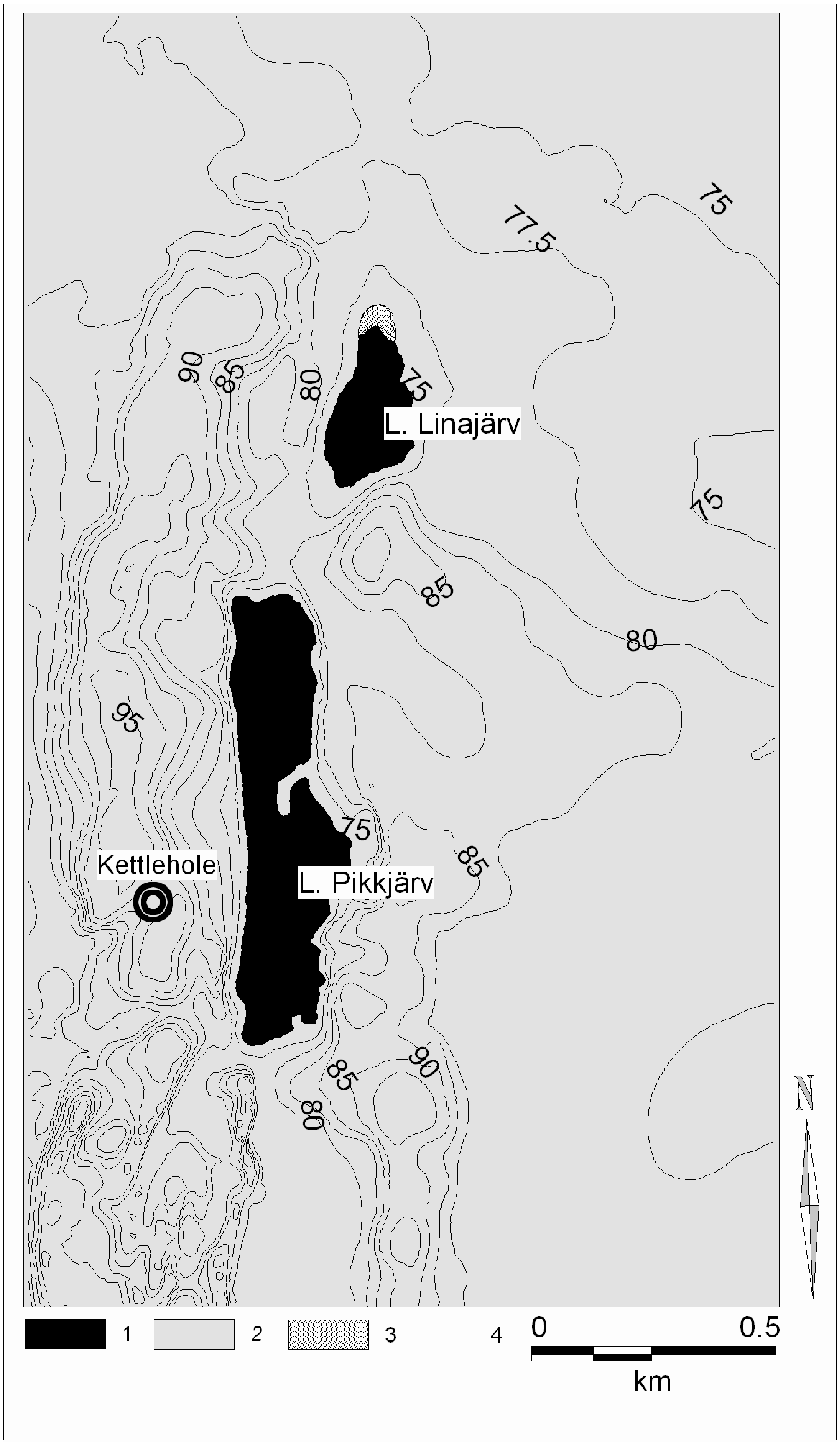

Fig. 5. Topography and main soil types around the studied cores from Viitna kame field. 1 - lake; 2 - *Cambic Podsols*; 3 - *Eutric Histosols*; 4 – isoline, m a.s.l.

All sediment sequences were dated with ^{14}C method, which enables comparisons in the unified timescale. The borders of local pollen assemblages zones (PAZ), separated by profiles authors are overlapping. There are minor differences in the case of pollen profile from kettlehole sediments. For example the *Ulmus* and *Tilia* pollen types appear approximately 1000 years later into this core when compared to cores from the nearby lakes. As the kettlehole is small forest hollow lying on the bottom of the small but deep valley, its main source area of pollen could be some tens of meters (Calcote, 1995; Sugita, 1998). Microclimatic factors could have had great impact on formation of pollen profiles of sediments from deep valleys (Punning *et al.,* 1995). The high share of herbs pollen originating from plants growing on swamps indicates also small source area of pollen from this sediment basin (IV; Koff, 1984).

Lake Pikkjärv is larger in area (~14.4 ha) than L. Linajärv, and therefore, it could be estimated that the main source area of pollen of first lake is wider than in the case of the latter. As the dominate soil types in the surroundings of both lakes are similar, the vegetation structure in the vicinity of both lakes is also alike. Consequently, the pollen profiles from both lake sediments do not differ significantly. For example *Alnus*, *Tilia* and *Ulmus* pollen types appear in both lake sediments approximately at the same time. The share of spruce pollen increases at the same time in both lake sediments. Also the shapes of pollen curves of main tree pollen types are similar.

In the Otepää Heights, the author analysed lacustrine sediments from L. Juusa (**V**) (Fig. 6a). The results were compared to other pollen profiles from the same region. One pollen diagram is available from an overgrown lake 1 km NE of Otepää (Sarv, 1979) (Fig. 6a). An other pollen diagram originates from sediments of L. Ala-Pika, 6 km NE of L. Juusa (Kihno, 1998) (Fig. 6b).

All studied sites are situating in the similar climatic conditions (Raik, 1967). Lakes Juusa and Ala-Pika are similar in size (~3 ha) and shape, therefore it can be assumed that the main source area of pollen of both lakes is rather similar. As the Otepää site is an overgrown lake, it can be handled similarly to other sites from Otepää Heights during most of the Holocene until Sub-Boreal Chronozone. The landscape characteristics of these sites were studied in the area within 400 m from lake shores, which is a reliable size of the main source area of pollen in the case of lakes under study (**I**).

The topography of the surroundings of these sites is rather similar (Fig. 6). Lake Juusa and the Otepää site are located in the central part of Otepää Heights, where relative altitude is 50–60 m (Fig. 6a). Lake Ala-Pika is situated in the marginal area of the Otepää Heights, where relative altitude is 30–40 m (Fig. 6b). In the immediate vicinity of the sites, the relative altitude is about 15 m.

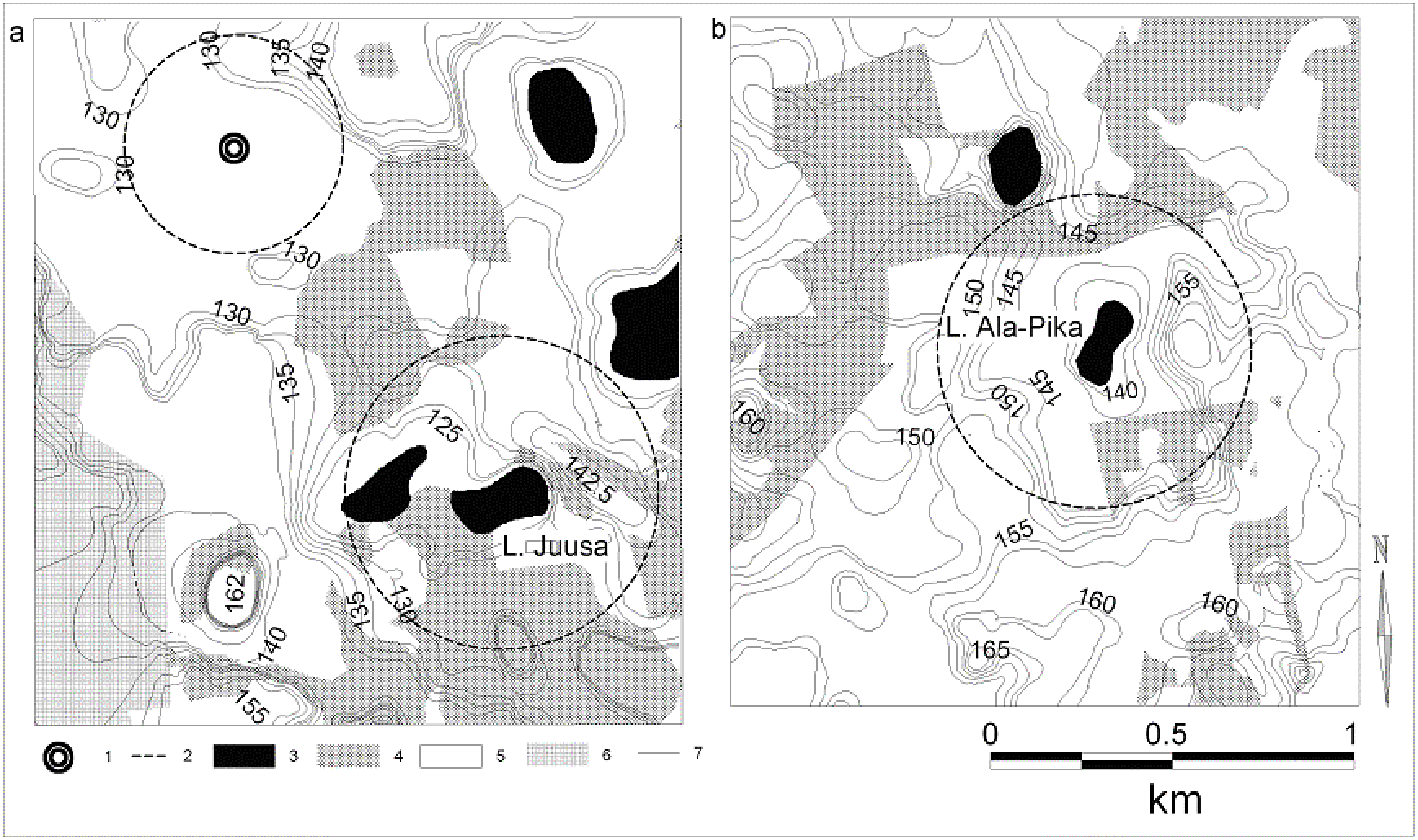

Fig. 6. Topography and landcover types around the studied cores from Otepää Heights. 1 - location of Otepää core; 2 - estimated limit of main source area of pollen; 3 - lake; 4 - forest; 5 - non-forested area; 6 - Otepää city; 7 – isoline, m a.s.l.

A significant factor differentiating the main source area of pollen of these study sites is the soil heterogeneity. Overview of the main soil types in the vicinity of the studied sites is given on Figure 7. In the surroundings of the Otepää site, the dominating soil types are *Stagnic Luvisols* and *Eutric Histosols*, also the share of *Cambic Luvisols,* deluvial and eroded soils is high. In the surroundings of L. Ala-Pika, dominant soil types are *Eutric Histosols*, *Cambi-Rendzic Leptosols, Mollic Cambisols,* deluvial and eroded soils. In the vicinity of L. Juusa the main soil types are *Eutric Histosols* and *Cambic Podsols*. The share of deluvial soils is high.

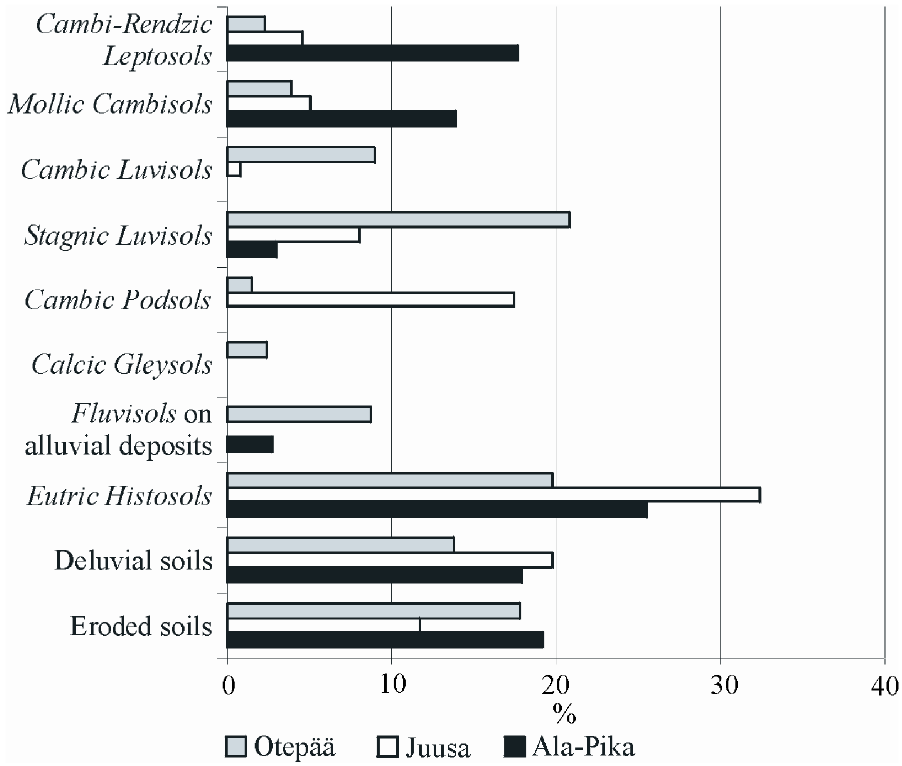

Fig. 7. Main soil types on the estimated source area of pollen of Juusa, Ala-Pika and Otepää study sites.

All three pollen profiles from the Otepää Heights are similar before Boreal Chronozone, but thereafter the diversity between the sites increases. The borders of local pollen assemblage zones do not overlap. Great differences are in shapes of main pollen types' curves and the first appearance of some pollen types differs (**V**). The most characteristic differences were observed in the spruce pollen content. In the Otepää pollen profile, the proportion of spruce pollen exceeded 10% level already at the end of the Boreal Chronozone. As spruce pollen is strongly underrepresented in modern pollen rain, 2–3% of spruce pollen seems to be sufficient to indicate its establishment (Saarse *et al.,* 1999). Based on this, it can be suggested that single spruce stands were present around the Otepää site already at the end of the Boreal Chronozone. In the Juusa pollen profile the content of spruce pollen starts to increase later, but still approximately 1000 years earlier than indicated in the Holocene stratigraphic chart of Estonia (Raukas *et al.,* 1995). The percentages of spruce pollen are very high in Sub-Boreal Chronozone in L. Juusa profile. The rapid decrease in spruce pollen in L. Juusa at the end of the Sub-Boreal is probably a result of forest fires, as the charcoal total area curve increases at the same depth. The content of pine pollen is relatively low and stable in L. Juusa and L. Ala-Pika cores when compared to the Otepää core.

As the compared sites are located close to each other, these peculiarities cannot be explained by climatic factors. The differences in the first appearance of certain pollen taxa into cores from closely lying sediment basins can be explained by differences in species invasion. The movement of plant range limits does not appear as a unitary front. Small populations of plants can appear scattered across the landscape outside of its continuous range limits. As the conditions change for more suitable for that certain plant species, these small patches expand and join with continuous distribution area (Ewing, 2002; Parshall, 2002).

Forest fires and human activity have also substantially contributed to the development of the L. Juusa pollen profile during the last two millennia. The first signals of human activity around L. Ala-Pika appear significantly earlier than in the case of L. Juusa (Kihno & Valk, 1999; **V**).

Comparing the formation of pollen profiles in sites of the Viitna kame field and the Otepää Heights it can be assumed that the soil conditions around the studied sites is one of the most important factors causing the heterogeneity of vegetation structure on main source areas of pollen of these sites, and therefore, have influenced the formation of pollen profiles during the Holocene. It can be assumed that similar heterogeneity of the soils has prevailed during the entire Holocene. Depending on the structure of parent material and hydrological conditions, the soil types similar to these which can be found from the same areas today, could start developing after the melting of ground at the early Holocene (Reintam, 1995). Author's assumptions about the significance of the influence of soil heterogeneity to the development of vegetation structure and therefore also to the formation of pollen profiles can be affirmed by studies of other authors. It is granted that especially during the early and middle Holocene the soil factor has greatest impact on formation of multifarious vegetation as later the human impact becomes more important (Gavin *et al.,* 2001).

In the case of Otepää Heights and Viitna kame field also the topography and surface roughness could significantly impact the pollen dispersion as these factors influencing the speed and direction of the wind at the near ground layers of atmosphere (Rikkinen, 1989; Ramsay, 1993; Garcia-Mozo *et al.,* 2004). Furthermore, it must be borne in mind that the changes in the water level in the lakes have an impact on the vegetation growing on the shores of the lake and that can also lead to changes in pollen profiles. Impact of these factors remains to be investigated in the future studies by the author.

SUMMARY

In this thesis the factors influencing the formation of pollen profiles in Estonian small lakes are under observation. For that purpose the methodologies were developed to study the disturbances occurred in vegetation and their role on formation of pollen profiles. The effect of the distance to sediment basin and the size of disturbance on pollen profiles were analysed. Furthermore, the comparison of analyses was carried out to identify the most adequate way to present the results of charcoal analysis. The size of the area from which the vegetation most greatly contributes to the formation of pollen profiles was analysed. These estimations contributed to authors' investigation about the influence of landscape characteristics on formation of pollen profiles and are essential

for planning further paleoecological studies. The soil heterogeneity appeared to be one of the most important factors influencing the formation of vegetation structure on main source area of pollen and therefore also the structure of pollen profiles.

The primary results of this thesis can be summarised as follows:

- Complex methodology was developed to explore the relationships between the disturbances and pollen profiles. Documentary evidence (forestry maps, aerial photographs *etc.*) stored in archives are sufficient for registering and characterising the disturbances occurred in Estonian forests during the last century. With precise chronological control the changes in vegetation structure on surroundings of sediment basin were compared with changes in pollen profiles. Based on this, it was possible to estimate the size of main source area of pollen for studied lakes.
- Various ways of presenting the results of charcoal analysis were evaluated in terms of methods most suitable for the adequate reconstruction of fire events in the vicinity of L. Tänavjärv and L. Mustjärv. The present study suggests that in context of microscopic charcoal analysis from pollen slides a curve of total area of charcoal particles per gram of sediment is the most effective indicator of the forest fire history.
- Considering the position and size of disturbances it was found that in the case of large lakes (such as in this study L. Tänavjärv, area 136.9 ha) only disturbances (forest fires) that took place repeatedly and embraced large territories (up to 2000 ha) close to lake shores are recorded in curves of pollen accumulation rates. The threshold of detection is lower if the disturbance concerns a small lake (3–6 ha). In the case of small lakes, the disturbance must occur within a couple of hundred meters from lake shores and it must embrace more than 15% of that territory to be reliably detected from pollen profile.
- Comparing the development of pollen profiles covering the entire Holocene deposits from Viitna kame field and Otepää Heights it was found that one of the most important factors inducing the multifarious vegetation structure on main source area of pollen from studied sites is the soil heterogeneity. Due to the effect of this factor the pollen profiles can differ greatly even if they originate from cores of close sediment basins.

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HÄIRINGUTE JA TAIMKATTE MOSAIIKSUSE KAJASTUMINE JÄRVESETETE ÕIETOLMU JA SÖEOSAKESTE PROFIILIDEL

Kokkuvõte

Paleoökoloogiliste uuringute eesmärgiks on möödaniku rekonstrueerimine, mis omakorda on aluseks keskkonnamuutuste prognoosile. Üheks laialdast kasutamist leidnud paleoökoloogiliseks uurimismeetodiks on õietolmu ja eoste analüüs. Setetes säilinud ning sellest keemilise töötluse ja rikastamise teel eraldatud õietolmu ja eoste liigiline ning arvuline koosseis võimaldab setteid stratigraafiliselt liigestada, selgitada taimkatte ja kliima arengut. Meetodit on nii Eestis kui ka mujal maailmas rakendatud möödunud sajandi algusaastatest.

Palünoloogiliste rekonstruktsioonide üheks keskseks probleemiks on uuritava soo või järve õietolmu baasala suurus. Õietolmu baasala on settimisala ümbritsev territoorium, millel kasvava taimkatte struktuur ja muutused selles mõjutavad kõige enam õietolmuprofiilide kujunemist settes.

Käesoleva töö eesmärgiks oli hinnata taimkattes toimunud häiringuliste muutuste mõju õietolmuprofiilide kujunemisele Eesti väikejärvedes. Püstitatud ülesande täitmiseks töötati välja kompleksmetoodika, mis võimaldab uurida taimkattes aset leidnud häiringute kajastumist õietolmu profiilidel, kasutades kartograafilist analüüsi sobivate uurimisalade leidmiseks. Üheks taimkattes häiringuid esile kutsuvaks teguriks on metsatulekahjud, mille esinemist saab lisaks muutustele õietolmuprofiilidel jälgida ka söeosakeste jaotuskõveratel. Kuna senini puudub ühtne metoodika söeosakeste analüüsi tulemuste esitamiseks, viidi läbi metoodiline võrdlus sobivaima söeosakeste kõvera esitamise viisi leidmiseks, mis peegeldaks toimunud tulekahjusid kõige täpsemini. Võttes aluseks häiringuliste muutuste ruumilise paiknemise ja ulatuse mõju nende kajastumisele õietolmukõveratel, hinnati kui suurel järve ümbritseval alal kasvav taimkate mõjutab õietolmuprofiilide kujunemist kõige enam. Õietolmu baasala suuruse hinnangu alusel käsitleti selle ala mullastiku heterogeensuse mõju taimkattestruktuurile ja sellega õietolmuprofiilide kujunemisele Holotseenis.

Doktoritöö olulisemad tulemused on järgmised:

- Töötati välja kompleksmetoodika, mis võimaldab uurida taimkattes aset leidnud häiringuliste muutuste ja õietolmuprofiilide vahelisi seoseid. Eesti arhiivides leiduvad aerofotod, metsanduslikud kaardid ja muud materjalid võimaldavad registreerida taimkattes aset leidnud häiringute esinemise ja nende ulatuse. Setete moodustumise aega teades on võimalik neis leiduva õietolmu muutusi seostada taimkatte struktuuris toimunud muutustega ning hinnata õietolmu baasala suurust.

- Tänavjärve ja Mustjärve setteläbilõigete söeosakeste sisalduse põhjal viidi läbi metoodiline analüüs, kus erineval viisil esitatud söeosakeste kõveraid võrreldi järvede ümbruse metsatulekahjude ruumilise paiknemise ja ulatuse andmetega. Leiti, et söeosakeste analüüsi tulemuste esitamisel peegeldab toimunud metsatulekahjusid kõige täpsemalt söeosakeste kogupindala sette massi- või ruumalaühikus.
- Võttes arvesse taimkattes aset leidnud häiringute ulatust ja asetust settimisala suhtes leiti, et suurte järvede puhul (näiteks käesolevas töös Tänavjärv, pindalaga 136.9 ha) peab veekogu vahetus läheduses kasvavas taimkattes toimunud muutus hõlmama ulatuslikku (kuni 2000 ha) territooriumi, et see muutus oleks õietolmuprofiilil selgelt jälgitav. Väikejärvede (3-6 ha) puhul võib häiringuline muutus hõlmata väiksemat territooriumi, kuid see peab toimuma järve kaldast mitte kaugemal kui mõnisada meetrit. Et muutus avalduks õietolmuprofiilil peab see hõlmama enam kui 15% territooriumist.
- Võrreldes omavahel kogu Holotseeni hõlmavaid õietolmuprofiile Viitna mõhnastikust ja Otepää kõrgustikult leiti, et mullastiku heterogeensus on üks olulisemaid tegureid mis on kujundanud taimkatte struktuuri õietolmu baasalal Holotseeni vältel. Seetõttu võivad mitmekesisemas maastikus õietolmuprofiilid üksteisest olulisel määral erineda isegi siis, kui nad pärinevad lähestikku paiknevate settimisalade läbilõigetest.

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