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Methodological and practical aspects of the presentation and interpretation of microscopic charcoal data from lake sediments

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Abstract. Analysis of microscopic charcoal particles is a useful part of palaeoecological research and is mostly used in conjunction with pollen analysis. However, there is considerable variation in the methodology of charcoal analyses. This paper considers various methods for the analysis of microscopic charcoal and the presentation of charcoal data in the context of a study of the upper sediments of two lakes in Estonia. The results are evaluated by comparing both the pollen and charcoal data with documentary evidence of forest fires over the past 60 years. Indications of fires both varying in extent and at different distances from the lakes are evaluated in both the pollen and charcoal diagrams. The results suggest that the total area curve for charcoal particles per unit mass of sediment dry matter ($cm^2\ g^{-1}$) provides the best indicator of forest fires. Fires in the study area are reflected differently in the charcoal and pollen curves. It is suggested that the charcoal data have the potential to indicate disturbance at a greater distance from the coring site than indicated by the pollen data.

Keywords: Charcoal – Pollen – Forest fire – Lake sediments – Estonia

Introduction

Charcoal analyses of lake sediments are an important part of palaeoecological studies and are the primary evidence from which reconstructions of past fire history are made (Tolonen 1985). There is general acceptance that charcoal records are signals of fires in the palaeoenvironment (Patterson et al. 1987; Clark 1989, 1990). Charcoal data have been employed in the study of palaeoclimate (Clark 1990), woodland community ecology (Green 1982) and human impact upon vegetation (Winkler 1985; Delcourt et al. 1998). Microscopic charcoal data, in particular, is a sensitive indicator of palaeoenvironment change whether caused naturally or by human impact (Patterson et al. 1987).

There is no single approach, however, to the interpretation of charcoal data nor to the methodology used in recording and expressing charcoal abundance. The simplest approach is the presentation of percentage pollen diagrams together with the number of charcoal particles counted in the pollen slides (Molloy and O'Connell 1993; Bos and Janssen 1996; Punning et al. 1997; Saarse et al. 1998; Veski 1998). Often the ratio of charcoal particles to pollen is presented (Patterson et al. 1987; Motzkin et al. 1993; Sugita et al. 1997; Blackford 2000; Tipping and Milburn 2000). Another approach is to divide the area of the charcoal particles by the pollen concentrations of terrestrial taxa and to show these as area of charcoal to pollen count (μm^2 pollen grains^{-1}) (Odgaard 1992; Sarmaja-Korjonen 1992). The concentration of charcoal particles in the sediment may also be estimated, similar to the way this is done in the case of pollen (particles cm^{-3}; particles g^{-1}) (Gardner and Whitlock 2001). In the literature, estimation of the area of charcoal particles per unit volume of sediment ($\mu m^2\ cm^{-3}$), is widely used (Clark 1984; Odgaard 1992; Blackford 2000; Edwards and Whittington 2000; Gedye et al. 2000) or, less frequently, per gram of sediment ($\mu m^2\ g^{-1}$) (Sarmaja-Korjonen 1992; Kangur 2000). Charcoal accumulation rate, i.e. the number and/or area of charcoal particles deposited per unit area per year may be estimated (particles or $\mu m^2\ cm^{-2}\ y^{-1}$) (Cwynar 1977; Clark 1990; Sugita et al. 1997; Rull 1999; Edwards and Whittington 2000; Gedye et al. 2000; Laird and Campbell 2000). Size classes of charcoal particles have also been distinguished and each size class has been presented as a separate curve (Sarmaja-Korjonen 1992; Rull 1999; Blackford 2000). Clark and Royall (1995) have shown that the pollen-slide method is suitable for the quantification of relatively small charcoal particles dispersed in the atmosphere from regional fire events. The thin section method has been suggested for the quantification of the relatively large particles produced mainly by local fires (Clark 1988).

Pollen analysis combined with the study of charcoal particles is of particular interest because it enables the effect of forest fires, one of the most important natural and human-caused sources of disturbance of natural vegetation, to be studied over considerable time spans (Moore 1982). Comparison of charcoal and pollen data from sediments with available cartographic and archive materials over a period of several decades or even centuries is highly valuable in the study of the relationship between pollen spectra and charcoal records and the vegetation and fire regimes that are recorded in these sediments. To help clarify this relationship it is important to determine the area of burnt forest around the sedimentation point. To reconstruct the scale of recent fires historical maps can be used. To identify the burnt area near the sedimentation point dendrochronology also has been used where historical sources have proved to be insufficient (Clark 1989; Pitkänen et al. 1999; Laird and Campbell 2000).

In this paper the results of pollen and charcoal analyses of the upper sediments (last ca. 60 years) from two lakes in north-western Estonia are presented (Fig. 1). Using documentary information on local forest fires during the 20th century, the most suitable way for presenting the results of charcoal analysis is explored. Also the effect on the reflection in the sedimentary record of the extent of fires and their distance from the lakes is shown.

The study area

Lakes Tänavjärv and Mustjärv are located in north-western Estonia. The use of larger scales (about 20-100 km) is suggested for the reconstruction of forest fires (Tinner et al.1998) and the size of study area chosen here is appropriate to the relevant pollen source areas of these lakes (about 10 x 10 km). The Baltic Sea lies to the north and west of the study area, while to the south and east there is a large bog system (17,000 ha). There is no information on forest fires in the immediate vicinity of the area other than that presented here (Fig. 1).

The vegetation in the vicinity of the lakes consists mainly of boreal heath and dry boreal forests on former Baltic Sea coast formations (Fig. 1). In the wetter, low-lying areas both forested and open peatlands are common.

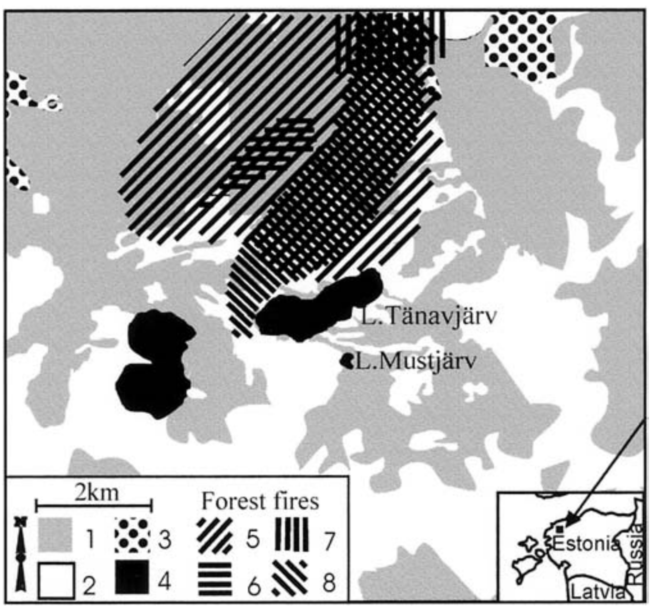

Fig. 1. Location of the study site, main vegetation units and disturbances around the studied lakes. 1 - forest; 2 - forested bog, 3 - crops and fallow land; 4 - lake. Forest fires: 5 - in 1951/52; 6 - in 1982; 7 - in 1993; 8 - in 1997

In the immediate vicinity of the lakes the dominant trees are birch and pine. The closest human settlements are located about 7 km to the north-east and south-west.

Lake Tänavjärv (59°10'N, 23°48'E) is ca. 1800 m long with the long axis oriented north-east/south-west. The area of the lake is 136.9 ha and the maximum depth 2.5 m. The lake is semi-dystrophic and precipitation-fed with no surface inlets or noteworthy outlets. The eastern and southern shores of the lake are sandy. In the vicinity of this lake there were several forest fires during the last century.

Lake Mustjärv (59°10'N, 23°48'E) lies 800 m to the south of Lake Tänavjärv. The area of the lake is 4.8 ha and the maximum depth 1.5 m. The lake has swampy shores with reeds and birch bushes and is surrounded by pine and birch towards the north and east and with an open mire landscape to the west. There is no historical evidence for any fire in the immediate vicinity of this lake.

Material and Methods

Sediment samples from the upper sediment layers of both lakes were taken from the deepest part of the lakes using a modified Livingstone-Vallentyne piston corer (diameter 7 cm). By coring from a 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 sediment were not disturbed. Descriptions of the lithology of the sediments were made at the study sites. Subsampling was continuous, each sample being 1 cm thick. Samples were kept in the refrigerator prior to analysis. Dry matter (DM) content was determined by drying the samples at 105°C until a constant weight was achieved. Several analyses were performed from the same sample and therefore only part of each was used for pollen analysis.

For this analysis, 50 mg of the dried sample was boiled in 10% KOH and acetolysed following standard procedures (Moore and Webb 1978). The samples were not sieved at any stage of the preparation. From 3 to 10 tablets containing a known number of *Lycopodium* spores were added to each sample at the beginning of treatment, thus enabling the calculation of total pollen and charcoal concentrations (Stockmarr 1971). Generally all pollen grains and spores were counted to a total of at least 500 arboreal pollen (AP) grains per level.

On the pollen slides charcoal particles larger than 100 μm^2 were counted (number of charcoal particles per pollen slide). The area of every charcoal particle was estimated by multiplying the lengths of the longest and shortest axes. Subsequently the ratio of charcoal particles to tree pollen (number of charcoal particles/AP grain), the charcoal concentration (number of charcoal particles/g dry sediment) and total area of charcoal ($\mu m^2 g^{-1}$ dry sediment) were calculated.

The age/depth scale was based on spherical fly-ash particle (SFAP) analysis. 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 and 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. Through consideration of 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 and Alliksaar 2000). Once this reference point (1945) in both lakes had been identified on the basis of the SFAP curve, the sediment above it was weighed and the mean annual sedimentation rate between the reference point and the sediment surface was calculated.

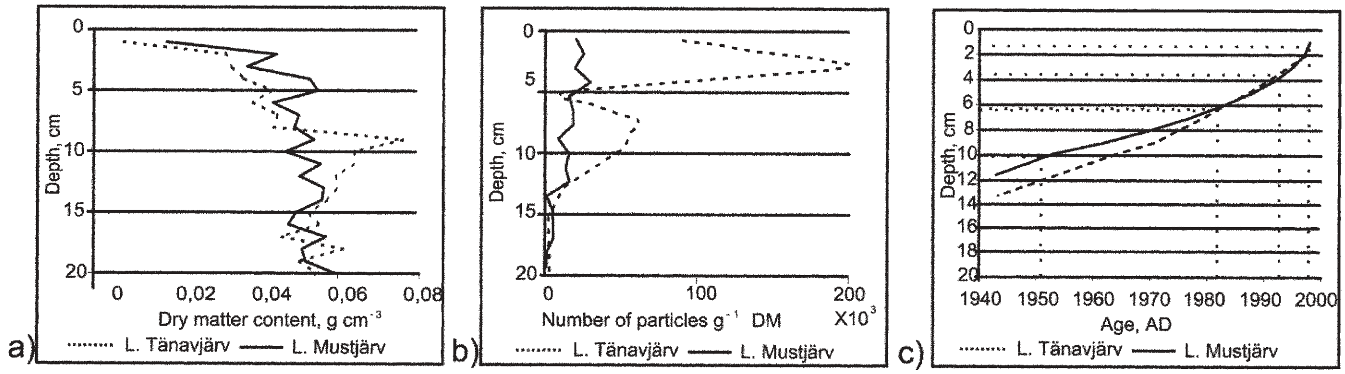

Fig. 2. (a) Dry matter content (g cm^{-3}); (b) Distribution of SFAP (number of particles g^{-1} DM) and (c) age-depth curve of the studied lake sediments

Using the dry matter values of every sample (Fig. 2a) and the mean annual sedimentation rate, the sample ages were estimated.

To reconstruct the environmental impact history we used both historical sources such as old forestry maps on which burnt areas were marked and land-use maps, together with oral information. This reconstruction is described in more detail in Koff et al. (2000).

Results

Four major forest fires are known to have occurred in north-western Estonia (Vihterpalu) in the 20th century (Fig. 1). The most extensive of these was 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 Lake 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.

In the course of the present work the temporal distribution of SFAP has been studied in both lakes, where the particle distribution curves show a typical trend, with specific features (Alliksaar 2000). Both of the SFAP profiles show three main features - the start of particle record, the rapid increase in SFAP concentration and the SFAP maximum followed by a sub-surface decrease (Fig. 2b). These features occur in most sediment profiles in Estonia and correlate well with the fuel combustion statistics for the region and ^{210}Pb dates from the cores (Alliksaar 2000; Punning and Alliksaar 2000). Thus the specific features of the SFAP curve can be used as reference layers for dating. The SFAP curves allow us to assign the year 1945 reference layer in Lake Tänavjärv to a depth of about 13 cm and in Lake Mustjärv to 11 cm (Fig. 2b).

The age/depth curves (Fig. 2c) suggest that the forest fire of 1951/52 should mainly be recorded at depths of 12 cm and 10 cm in Lakes Tänavjärv and Mustjärv respectively. The forest fire of 1982 should register in the charcoal and pollen diagrams at 6 cm depth in both lakes sediments. Traces of the 1993 fire should appear at a depth of 3 cm in both lakes. Pollen concentration curves from Lake Tänavjärv (Fig. 3) decline severely at 11 cm suggesting a forest fire in the vicinity of the lake. The environmental impact history has reconstructed in more detail in Koff et al. (2000).

The ratio of charcoal particles (chp) to AP increases in the uppermost third of the core (Fig. 4a) while this ratio is relatively low in the lower part of the profile. The concentration of charcoal particles is quite uniform over the whole core (Fig. 4b). In the lower part of the core, however, the concentration of charcoal is usually modest with only a few layers showing elevated numbers of charcoal particles. At 5 - 9 cm from the sediment surface, the con-

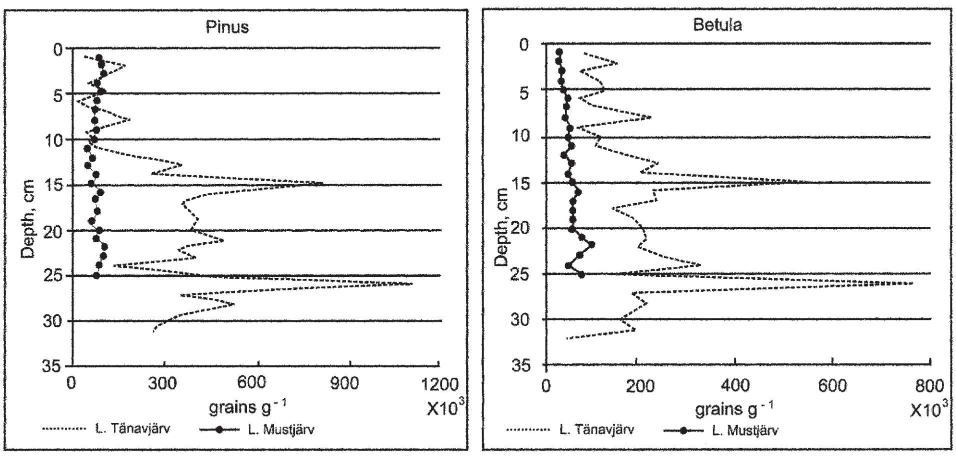

Fig. 3. Pollen concentration (grains g^{-1}) curves in the sediments of the studied lakes

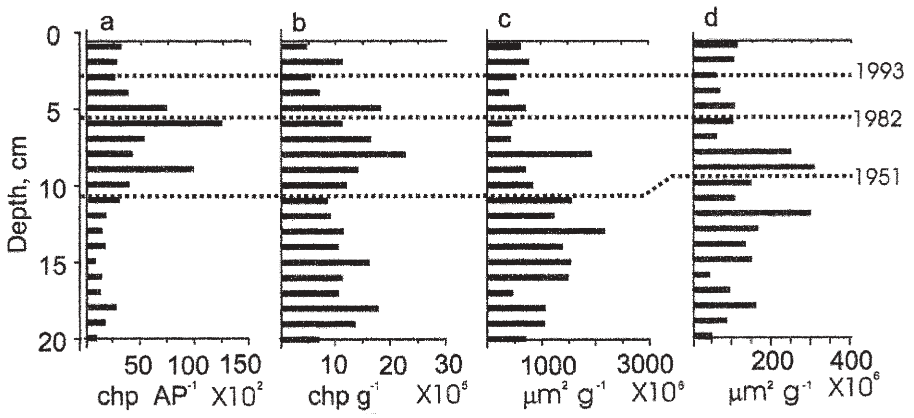

Fig. 4. (a-c) Lake Tänavjärv and (d) Lake Mustjärv charcoal records. (a) Ratio of the charcoal particles (chp) and AP in the pollen slide, chp AP^{-1}; (b) Number of charcoal particles per g of sample, chp g^{-1}; (c) Area of charcoal particles per g of sample, $\mu m^2 g^{-1}$; (d) Area of charcoal particles per g of sample in Lake Mustjärv, $\mu m^2 g^{-1}$

centration of charcoal particles shows a steady increase while in the uppermost part of the core concentration values are low.

The curve for total area of charcoal particles at Lake Tänavjärv is distinctly different from the other curves described above (Fig. 4c). In the lower part of the profile, the total area of charcoal particles (per gram dry sediment) is relatively small. The total area of charcoal particles increases at 11 - 16 cm. Here also the largest charcoal particles found in the whole core were recorded, some being as large as 50,000 μm^2. Another distinct peak is observed at 9 cm while in the uppermost part of the profile the values decrease.

The results of the charcoal analysis of the Lake Mustjärv sediments are generally similar to results of Lake Tänavjärv as presented above. Because of this only the curve showing the total area of charcoal particles is presented for Lake Mustjärv and is discussed further below. This curve shows elevated values at depths of 12 cm and 8 - 9 cm. Note that the values are generally an order of magnitude lower than those recorded from Lake Tänavjärv.

Discussion

The forest fire of 1951/1952 reached the northern shore of Lake Tänavjärv. According to the age-depth curve, this fire should be recorded at a depth of 11 - 12 cm in the sediment (Fig. 2). It is assumed that the 2 to 3-fold decrease in pollen concentration at 11 cm is attributable 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 concentration values (Koff et al. 2000).

As AP pollen concentration values decline toward the top of the profile (0 - 10 cm), the ratio of charcoal particles to AP increases (Fig. 4a). 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.

The ratio of charcoal particles to AP pollen (Fig. 4a) reflects the decrease in AP concentration 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. 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 be due to factors other than fires in the charcoal source area. However Clark (1984) showed that standard pollen procedures (including sieving) systematically diminish the area and number of charcoal particles.

The area of charcoal particles appears to be a much more accurate indicator of local fires than the number of particles per sample and charcoal concentration values. In several studies, the relationship between the size of charcoal particles and their source area is stressed, the smaller particles representing regional fires while the larger particles are more likely (though not necessarily) to be of local origin (Patterson et al. 1987; Sarmaja-Korjonen 1992; Tinner et al. 1998). These results have been questioned by Pitkänen et al. (1999) who suggested that charcoal in pollen-slides could indicate past local fire occurrence. This seeming contradiction may be due to the use of different methods, since Pitkänen et al. did not use sieves for pollen preparation (i.e. the big charcoal particles reflecting local fires were not eliminated during the pollen procedure).

In the core from Lake Tänavjärv, charcoal particles of size >100 μm^2 were counted. Particles up to 500 times as large were also noted but not scored separately; however, very large charcoal particles were relatively rare. 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 our case 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 from the dating 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 and Whitlock 1995). Because of redeposition, bioturbation etc. the charcoal could also have been transported downwards; however the results of SFAP analysis and literature sources 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 we can only assume that the 1951/52 fire at Vihterpalu is reflected not only in one sample but over a 6 cm-thick sediment layer. But it must be borne in mind that there could have been other forest fires before 1950 in the vicinity about which we just do not have any information.

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 Lake Tänavjärv than in Lake Mustjärv. This fire was rather close to Lake Tänavjärv (ca. 800 m distant) but was ca. 2.5 km distant from Lake Mustjärv. In the core from the latter lake, AP concentration values are quite steady (Fig. 3). If there had been a significant effect from the 1951/52 fire on the vegetation in the Lake Mustjärv pollen source area, a decline in AP concentration values would be expected at a depth of 8 - 9 cm depth, corresponding in time to the 11 cm depth in the Lake Tänavjärv core. However, no such changes were observed. We therefore assume that this fire did not have any significant effect on the vegetation in the Lake Mustjärv pollen source area. According to Sugita et al. (1997) and Sugita (1998) the relevant pollen source area for lakes of the size of Lake Mustjärv is about 300 - 800 m. Forest fires outside this range would therefore have had no influence on the pollen concentration. As Fig. 4d shows, the total area curve for charcoal particles in Lake Mustjärv increased at a depth of 8 - 9 cm; this can be connected to the 1951/52 forest fire. We may therefore conclude that, although no signals from the forest fire can be found in the pollen profile, such disturbance is reflected in the charcoal data. Our findings show that the charcoal analysis gives clear signals of forest fires at a greater distance from the lake than the pollen analysis alone.

The 1951/52 forest fire at Vihterpalu was obviously exceptional in its great duration and in that it was also very extensive. 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 5 - 6 cm depth. However although this fire was at approximately comparable distance from Lake Tänavjärv as the 1951/52 fire was from Lake Mustjärv, the total charcoal area curve from Lake Tänavjärv shows no changes at this depth. The fire was probably too limited in 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. Also, the forest fire in 1997 has left no signal in either lake. The cores were taken in the winter of 1998, i.e. only half a year after the fire. This is obviously a too short time delay to observe these changes in vegetation through pollen analysis.

Conclusions

The availability of dates and reliable archive materials provided an opportunity to investigate, by pollen and charcoal analyses, the upper layers of lake sediments as archives of forest fire history. Archive materials give information on forest fires in the study area in the last 60 years. The available chronological control was such that it could be predicted at which depths particular fire events might be expected. Various ways of presenting the results of charcoal analysis are evaluated in terms of those methods most suited to the adequate reconstruction of fire events in the vicinity of the two lakes studied.

The present study suggests that in context of microscopic charcoal analysis from pollen slides a 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.

Forest fires in the study area are reflected differently in the results of pollen and charcoal analyses. In the 1951/52 fire, 2000 ha of the forest surrounding Lake Tänavjärv was destroyed which resulted in greatly increased openness of the landscape around the lake. As a joint effect of these two factors, pollen concentration values in the Lake Tänavjärv profile declined by 2 - 3 times (Koff et al. 2000). At the same time the total area of charcoal particles per unit mass of dry matter increased. This fire did not significantly affect the pollen source area of Lake Mustjärv, and thus no changes are recorded in the AP concentration curves. At the depths that correspond to the forest fire, the total area of charcoal particles per gram of sediment increased. This suggests that charcoal particles carry signals of forest fires over greater distances than pollen. As regards the most recent fires, these have occurred at greater distances from the lakes and have involved smaller areas, so neither of the lakes studied record these events.

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