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Spatial variability of diatoms, subfossil macrophytes, and OC/N values in surface sediments of Lake Väike Juusa (southern Estonia)

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Abstract. The diatom assemblages, organic carbon to nitrogen (OC/N) ratio, and macrophyte remains in surface sediment samples from small dimictic Lake Väike Juusa in southern Estonia were analysed. The results obtained show that changes in the composition of diatoms, macrophyte remains, and OC/N values are in logical dependence on the water depth in the studied site. So the species richness and number of periphytic diatoms are higher in samples collected in the littoral area, from depths up to 3.5 m. The abundance of macrophyte remains is also higher in the littoral. The OC/N ratio, which reflects the share of planktonic matter in the bulk organic matter, has a tendency to increase from the littoral towards the profundal zone. The data obtained by the three different methods enable to apply this approach to study lake-level change in the past.

Key words: diatoms, macrofossils, OC/N, small lake, surface sediment.

INTRODUCTION

Lakes are excellent sensors of environmental change because their ecosystems respond physically, chemically, and biologically to changes in environmental conditions and these responses are recorded in various ways in lake sediments. This information may be used within certain limits for reconstructing the past changes in water quality and for identifying the natural state of the water body prior to human impact, thereby assisting in setting goals for lake remediation and restoration activities. Sedimentation patterns can change through time for a variety of reasons, one being changes in lake level (Verschuren, 1999). The fluctuations of water level alter the lake morphometry and transform the characteristics of the sedimentation zones (erosion, transportation, accumulation; Håkanson, 1977) of

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the lake bed, directly influencing sedimentation and resuspension. Therefore sediment studies have been successful in investigating lake-level variations in small temperate lakes (Digerfeldt, 1986; Dearing, 1997).

Significant changes in lake level influence the structure of marginal habitats and significantly alter the ionic composition and salinity of the water body. The fluctuations of lake level can cause changes in the diatom assemblages and may shift macrophyte zones. Life form or habitat group changes based on depth distribution (i.e. periphythic vs. planktonic) produce the most reliable evidence of water level change. That is why in freshwater lakes changes in the planktonic to non-planktonic ratio are often used to indicate water level fluctuations (Lotter, 1988; Barker et al., 1994; Hyvärinen & Alhonen, 1994; Yang & Duthie, 1995; Wolin, 1996; Brugam et al., 1998; Wolin & Duthie, 1999; Lotter & Bigler, 2000; Yang et al., 2003). Once the optimum values of species along an environmental gradient are obtained, these values can be applied to the same species in a sediment core to infer the past values of the environmental gradients (Yang & Duthie, 1995; Hall & Smol, 1999; Battarbee et al., 1999).

Macrophyte remains have been also widely used in the past environment studies (Birks, 1973, 1980, 2000; Watts, 1978) and their contribution to palaeolimnology has been validated (Ammann, 1989; Hannon & Gaillard, 1997; Lotter, 1999; Birks & Wright, 2000). A recent study of Tarras-Wahlberg et al. (2002) shows that water level fluctuations have a significant effect upon sediment characteristics and changes in aquatic vegetation assemblages. They found in L. Naivasha that water deepening caused the replacement of floating-leaved macrophytes by submerged plants in the profundal. Madsen et al. (2001) demonstrate that water movement affects sediment dynamics in and around submerged macrophyte beds, sediment composition, and particle size in freshwater environment.

However, several factors control the distribution of diatoms in a lake before the final deposition. Usually palaeoecologists use diatom records to study the trends of temperature, pH, nutrient status, and light penetration conditions (Hall & Smol, 1999; Battarbee et al., 2001). However, these factors are often autocorrelated. An increase in temperature can increase the effectiveness of photosynthesis and matter cycling activity, which affects the photic depth and the trophic status of the lake. The latter has an impact on the pH in the hypolimnion and nutrient extraction from surface sediments.

The distribution of many benthic and epiphytic diatom species is ultimately controlled by the distributions of aquatic macrophytes on which they live (Brugam et al., 1998). Therefore it is important to use multiple lines of evidence to support any supposed water level changes and to exclude other factors that may result in the same signals (Digerfeldt, 1986).

Some additional possibilities for estimating the origin of bulk organic matter are provided by the study of organic carbon to nitrogen ratio (OC/N) of bulk sediments. The variations of OC/N ratio mirror the changes in the proportion of higher plants with lower protein content (Wetzel, 1983). We used this approach in studies of sediment profiles in L. Viitna (Punning et al., 2004). The decrease of OC/N values in some sediment cores was in good temporal correlation with the rise of water level, and it was explained as a littoral vegetation habitat movement to the shallower area.

The aim of this paper is to study the composition of diatom flora, macrophyte remains, and OC/N ratios in a set of surface sediments from sites with different water depths in Lake Väike-Juusa and estimate the possibilities of using the obtained data for the reconstruction water-level fluctuations in the past.

STUDY SITE

Lake Väike Juusa (hereafter L. Juusa) is situated in the southern part of Estonia (58°06′ N and 26°30′ E) on the Otepää Heights (Fig. 1). The relief of the accumulative Otepää Heights is topographically varied and complex. Small depressions between hillocks were formed after the withdrawal of the Scandinavian Ice sheet during the Otepää stage about 12 200 BP and many basins like L. Juusa

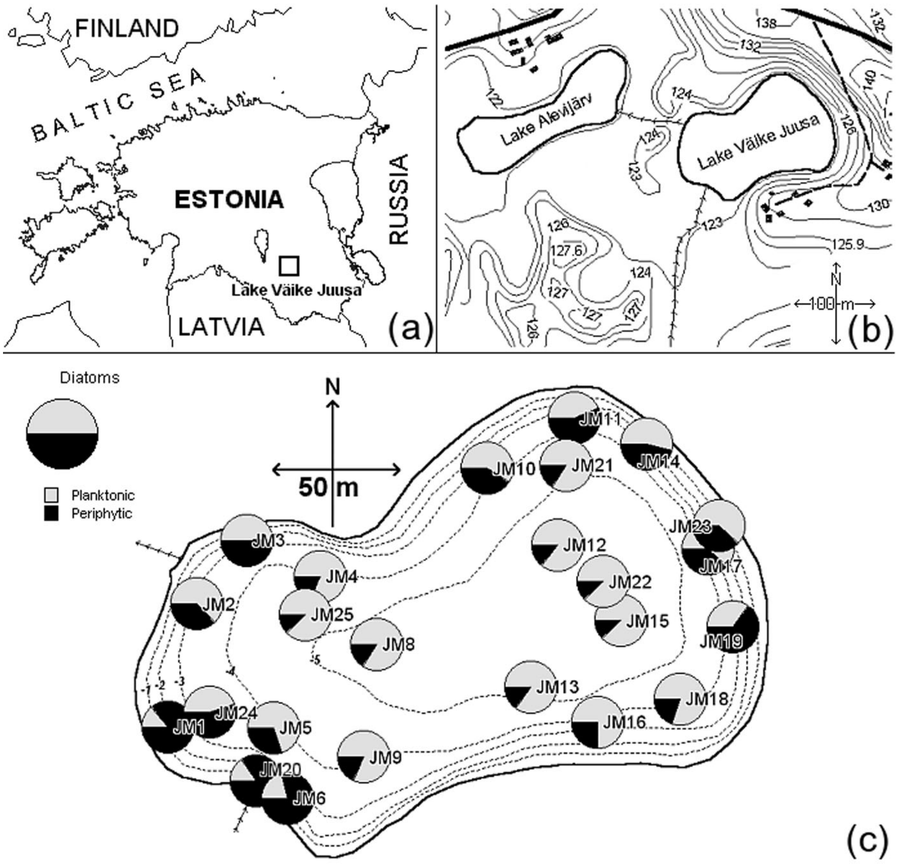

Fig. 1. Location of Lake Väike Juusa (a, b) and its bathymetric map, sampling sites, and percentage of planktonic and periphytic diatoms in surface sediments (c).

have a glaciokarst origin. The hillocks bordering the lake have steep slopes. To the west of the lake is a paludified area and a depression that connected now separated lakes Juusa and Alevijärv. There is one inlet from the east and also a man-made ditch, which connects lakes Juusa and Alevijärv. The mean summer temperature is 16.5 °C and the mean winter temperature is 6 °C. The mean annual precipitation is around 650 mm.

Lake Juusa is a small lake of 3 ha with a maximum length of 250 m and width of 160 m (Table 1). The mean depth is 3.7 m and the maximum depth is 6.0 m in the eastern part of the lake. It is a eutrophic dimictic lake with strong stratification during spring–summer. During summer the thermocline deepens from about 2.5 m in June to 3–3.5 m in July–August. The concentration of oxygen has a very distinct seasonal cycle. Its vertical gradient during the period of convective mixing is a consequence of higher consumption in the deeper layers compared to the supply by vertical transport. The oxygen content in the near-bottom layers approaches zero during the year. The decrease of temperature in September induces a gradual onset of autumnal circulation and the water column becomes unstratified by the end of October. The values of pH were about 7.7 in the surface of the water column and 6.6 at 5 m during 2002–2003.

The bottom sediments of L. Juusa are up to 12 m thick in the deepest point of the lake. The surface layers of sediments are brownish gyttja with a high content of water and organic matter. According to estimates from the ^{210}Pb data the uppermost 10 cm of sediment in the deepest point accumulated during the last 10 years.

The drainage area of L. Juusa is 55 ha of semi-open cultural landscape. The vegetation around the lake consists of pine forest on the hill to the west of the lake and mixed spruce forest on the eastern side. There was intensive agriculture around the lake until the 1990s; presently there is only some small-scale farming to the south.

The shoreline vegetation consists of 50 different taxa indicating the variability of habitats around the lake (Koff, 2004). The emergent macrophytes most frequently found are *Phragmites australis* and some *Carex* species. *Typha latifolia*, *Schoenoplectus lacustris*, and *Acorus calamus* are rather abundant and are distributed evenly along the shoreline. The floating-leaved plant *Nuphar lutea* is found occasionally. Submerged plants such as *Potamogeton praelongus* and *Elodea canadensis* are more widely distributed in the western part of the lake. Based on the macrophyte classification and typology of Estonian lakes (Mäemets, 1991) this type of vegetation is common for eutrophic lakes.

Table 1. Main characteristics of Lake Väike Juusa

Characteristic	Value
Maximum length, m	250
Maximum width, m	160
Surface, ha	3
Catchment area, ha	55
Volume, m^3	111 300
Perimeter, m	710
Maximum water depth, m	6.0
Average depth, m	3.7

MATERIAL AND METHODS

For lithological, OC/N, and diatom analyses 24 surface sediment samples (0–3 cm) from L. Juusa (Fig. 1) were collected using a Livingstone-Vallentyne piston corer. Samples were collected in September 2002 and 2003. For macrofossil analyses, which require a larger amount of material, the surface sediment samples were collected from the depth 0–10 cm using the same piston corer. The samples were packed in the field into plastic boxes and kept in a refrigerator prior to analysis.

Samples for diatom analyses were treated through standard procedures (Battarbee, 1986; Battarbee et al., 2001). Sediment was heated with 30% H_2O_2 in a water-bath until all organic material was oxidized, then some drops of 10% HCl were added to remove carbonates. The suspensions were mounted on slides using Naphrax. At least 350–500 diatom valves per sample were counted using a Carl Zeiss microscope with oil immersion objectives at magnifications of ×1000. The diatom taxonomy follows Krammer & Lange-Bertalot (1986–1997). The diatom abundance was expressed as percentage of the basic sum of total diatoms. The diagram was compiled using the TILIA GRAPH program (Grimm, 1990). Diatom optima with respect to water depth were determined by analysing the frequency of each species distribution along a depth gradient and using the weighted averaging technique (Yang & Duthie, 1995).

For macrofossil analyses 100 cm^3 samples were dispersed in water and washed gently through a sieve of 0.25 mm mesh aperture. Residues were dispersed in water and examined on a white plate under a stereomicroscope. For characterizing the abundance of total sedimentary components retained on the sieve in comparison with the preliminary volume of the sample the relative scale from 1 to 4 (1, 1–10%; 2, 10–25%; 3, 25–50%; 4, 50–75% retained) was used.

The general composition of each sample and relative abundance in terms of percentage estimates were noted by using a 10 × 10 square grid graticule inserted into one of the microscope eyepieces and moving the white plate with remains randomly to 10 different views and averaging the results. The main components of the sediment fraction (larger than 0.25 mm) were leaves and stems of mosses (mainly *Warnstorfia fluitans* and *W. exannulatus*); amorphous herbaceous debris (it was possible to determine only small roots of *Carex* sp., and epidermis of *Typha latifolia* and *Nuphar luteum*); ligneous parts (small pieces of wood or bark, etc.); and fragments of Mollusca shells. All seeds and fruit and examples of other identifiable remains were picked up and identified with the aid of reference collections and manuals for seed descriptions (Beijerinck, 1947; Katz et al., 1977; Birks, 1980; Grosse-Brauckmann & Streitz, 1992). The results are presented as number per 100 cm^3.

Total carbon and nitrogen and OC/N ratio were measured at Tallinn Technical University with an Elementar Analysersystem GmbH VarioEL and calculated as percentage of dry matter (DM). Loss on ignition (LOI) and mineral matter content were also measured using standard procedures (Dean, 1999). For the estimation of the carbonate content, mineral matter was heated at 950 °C for 120 min and the loss of weight indicated the carbonate content and also the content of mineral C. The mineral C content was subtracted from the total C to give the organic C (OC) content. This was then used to calculate the OC/N ratio.

RESULTS AND DISCUSSION

Diatoms

A total of 119 diatom taxa were recorded in the 24 surface sediment samples. Diatoms were abundant and well preserved at all sampling sites. A large number of infrequent taxa usually occur in species datasets, and therefore only the 42 taxa that were present with a relative frequency of >2% in a minimum of two samples were used in further analyses (Table 2). Mainly *Cyclotella bodanica*, *C. radiosa*, and *Stephanodiscus* spp. represented the planktonic diatoms in the surface sediments of L. Juusa (Fig. 2). Among the periphytic taxa *Achnanthes* spp., *Fragilaria* spp., and *Navicula* spp. were dominant. Some planktonic taxa (*Cyclotella striata*, *Aulacoseira italica*, *Cyclostephanus dubius*, and some small *Stephanodiscus* spp.) do not appear to be connected with water depth.

The planktonic taxa *Stephanodiscus hantzschii*, *Cyclotella bodanica*, *Aulacoseira ambigua*, *Stephanodiscus astraea*, and *Fragilaria ulna* are most abundant in diatom assemblages in sites deeper than 3.7 m. In the shallower areas of the lake, the periphytic taxa *Achnanthes clevei*, *A. minutissima*, *Amphora libyca*, and *Navicula* spp. are most common.

As a result, the optimum depth values for 42 diatom taxa were calculated using the weighted average (WA) technique (Table 2). This means that a simple estimate of the species depth optimum is thus an average of all the depth values for the lake sampling places in which that species occurs, weighted by the species relative abundance. A species is likely to be most abundant at sites near the optimum (Yang & Duthie, 1995). The WA-estimated depth optima corresponded well with the known habitat groups of diatoms: species known to be planktonic had depth optimum over 3 m (except *Fragilaria capucina*) and WA for the most abundant periphytic taxa were mostly below 3 m. The planktonic taxa *Cyclotella* spp. and *Stephanodiscus* spp. were major components of assemblages in samples from 3 m. *Achnanthes* spp., *Amphora* spp., and *Navicula* spp. were the main periphytic diatoms in the shallowest part of the lake.

The proportion of the planktonic and periphytic diatom assemblages in the surface sediments in L. Juusa showed a rather clear shift towards an increased abundance of planktonic taxa from the littoral to the profundal zone (Figs. 1, 2). The total abundance of the periphytic diatoms accounted for up to 60–80% of the diatom assemblages in sites between the water depths of 0.8 to 3.5 m. In deeper areas the proportion of planktonic diatom taxa increased reaching 80% of the total diatom assemblage below 4 m. The results suggest a very good correlation between water depth and planktonic diatom abundance ($r^2 = 0.71$).

As the spatial-temporal regularities of horizontal and vertical matter fluxes determine the sedimentation regime and redistribution of settling matter within

Table 2. Main diatom taxa in Lake Väike Juusa and weighted average (WA) (optimum) values of water depth

Planktonic taxa	WA, m	Periphytic taxa	WA, m
Asterionella formosa Hassall	3.8	*Achnanthes clevei* Grunow	2.3
Aulacoseira ambigua (Grunow) Simonsen	4.2	*Achnanthes exigua* Grunow	2.8
Aulacoseira italica (Ehrenberg) Simonsen	4.5	*Achnanthes lanceolata* (Brébisson) Grunow	3.3
Cyclostephanos dubius (Fricke) Round	4.1	*Achnanthes minutissima* Kützing	2.7
Cyclotella bodanica Grunow	4	*Amphora libyca* Ehrenberg	3.1
Cyclotella distinguenda Hustedt	4	*Amphora pediculus* (Kützing) Grunow	2.6
Cyclotella radiosa (Grunow) Lemmermann	3.8	*Cocconeis placentula* Ehrenberg	3
Cyclotella spp.	3.3	*Cymbella affinis* Kützing	3.3
Cyclotella striata (Kützing) Grunow	3.4	*Epithemia sorex* Kützing	3.5
Fragilaria capucina Desmazières	2.3	*Fragilaria brevistriata* Grunow	3.3
Fragilaria ulna (Nittzsch) Lange-Bertalot	4	*Fragilaria constricta* Ehrenberg	2.4
Fragilaria ulna var. *acus* (Kützing) Lange-Bertalot	4.2	*Fragilaria construens* (Ehrenberg) Grunow	3.5
Stephanodiscus astraea (Ehrenberg) Grunow	4.1	*Fragilaria leptostauron* (Ehrenberg)	3.6
Stephanodiscus hantzschii Grunow	4.3	*Fragilaria parasitica* (W. Smith) Grunow	3.4
Stephanodiscus spp.	3.5	*Fragilaria pinnata* Ehrenberg	3.1
		Gomphonema parvulum (Kützing) Kützing	2.3
		Gyrosigma acuminatum (Kützing) Rabenhhorst	3.5
		Navicula capitata var. *hungarica* (Grunow) Ross	3.3
		Navicula cari Ehrenberg	2.2
		Navicula cincta (Ehrenberg) Ralfs	2.7
		Navicula cryptocephala Kützing	2.9
		Navicula pupula Kützing	2.8
		Navicula radiosa Kützing	3
		Navicula schoenfeldii Hustedt	3.3
		Nitzschia spp.	3.1
		Pinnularia viridis (Nitzsch) Ehrenberg	3.8
		Stauroneis phoenicenteron (Nitzsch) Ehrenberg	3.5

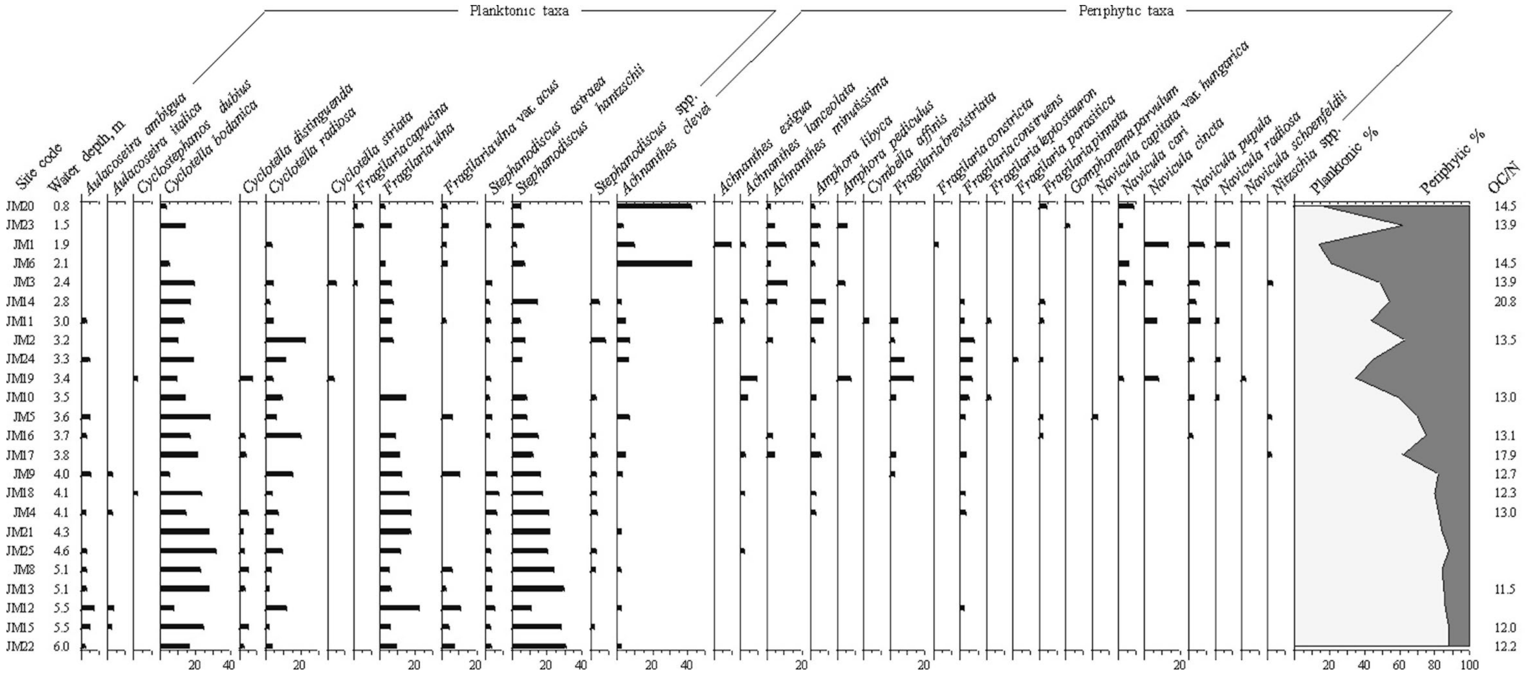

Fig. 2. The relative abundance distribution of diatoms in surface samples (Fig. 1) expressed according to the water depth. OC/N values of bulk organic matter are shown on the right.

lake basins the accumulated matter, including diatoms, will often be spatially redistributed (Bloesch, 1995). This means that horizontal movements of water masses in the lake significantly determine the distribution of diatoms in surface sediments. There are numerous studies showing that the qualitative composition and character of seston in sediments and its accumulation kinetics are essentially determined by the physical properties of the particles. Besides gravitational settling, fine-grain particles can be removed from the water column by being captured by organic particles and subsequent aggregation. Thomas et al. (2001) argued that gravitational settling might be important only for particles larger than 50 µm. In Lake Maggiore the sinking velocity of particles of size <10 µm is around 0.5 m day^{-1}, and of size 10–50 µm, 0.8 m day^{-1} (Callieri, 1997).

Besides that the sediment focusing and redistribution may have an important role in the accumulation of planktonic diatoms as well macrofossil remains, especially seeds. To exclude the impact of the redistribution of the sediment a complex study of different factors indicating the habitats of the diatoms is needed.

Subfossil macrophytes and OC/N values of bulk organic matter in surface sediments

The major part of the accumulated organic matter in the littoral zone originates usually from macrophytes whose abundance decreases with the distance from the shore and increase of water depth. Our data (Fig. 3) about the distribution of the subfossil macrophyte remains in the surface sediments in L. Juusa showed that the seeds of emergent plants such as *Carex* spp. and *Schoenoplectus lacustris* were represented in higher quantities in sites close to the shore. This indicates their tendency not to be moved very far from their habitats, supporting earlier studies of Birks (1973). Floating-leaved *Nuphar lutea* is occasionally found in the present day macrophyte vegetation close to sites JM1 and JM16 and its seeds were found in the same sites (Figs. 1 and 3). This confirms that the distribution of this species is site-specific. The same tendency is shown by submerged *Potamogeton praelongus*, whose seeds were found only in sites JM1, JM3, and JM6.

However, the seeds of macrophytes constitute only a small part of the accumulated organic matter of the sediment. The major part of macrophytes decomposes very quickly and it is nearly impossible to identify the tissues to taxon level. It is also known that emergent macrophytes have a much higher content of structural tissue than submerged or floating-leaved macrophytes. This structural tissue is of chemical composition relatively refractory to rapid microbial decomposition (Wetzel, 1983). The sediment diagenesis and post-sedimentational processes also affect macrofossil preservation. This complicates the interpretation of the data. It is, however, possible to determine whether these plant tissues belong to the herbaceous, ligneous, or moss fraction and to estimate their percentile composition.

We made an attempt to characterize the abundance of the amorphous decomposed organic matter in the sediments. The abundance decreased in relative

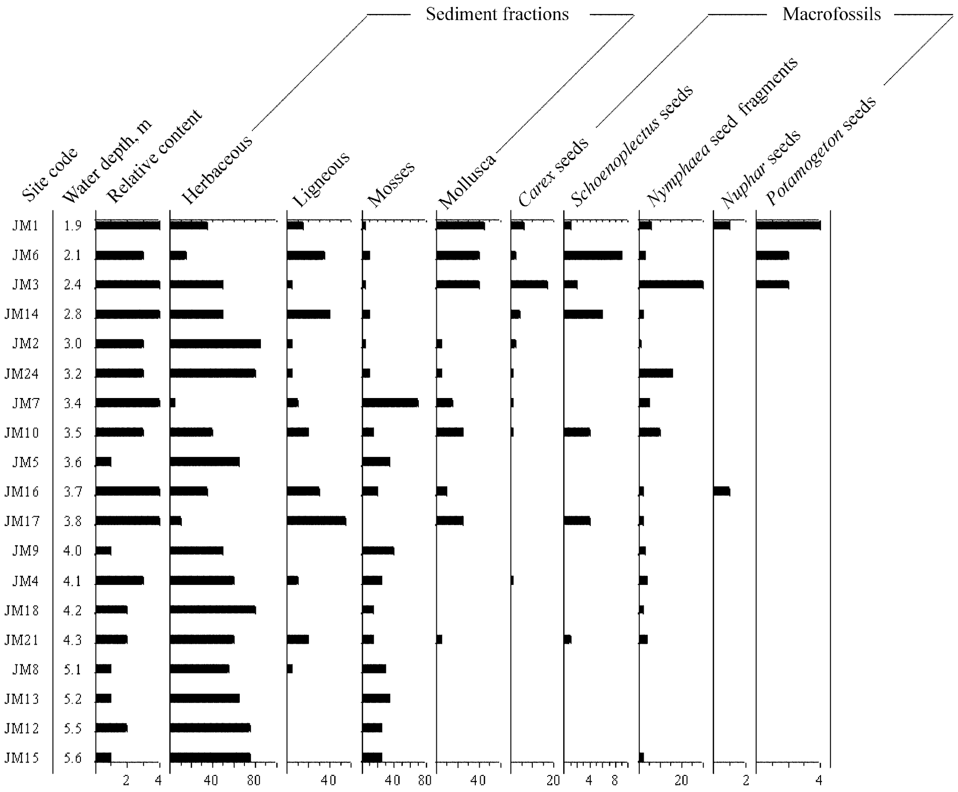

Fig. 3. The distribution of macrofossils in surface samples (Fig. 1) expressed according to the water depth. The relative content of the amorphous organic matter is given from 1 to 4, the fractions of the sediments in percentages and macrofossils as number of seeds per 100 cm^3 of the sediment.

scale from 4 to 2 at a depth of 4 m. In the sediment composition the proportion of ligneous and mollusca parts decreased as well. Deeper than 4 m the sediment retained less material and it consisted mainly of decomposed amorphous herbaceous parts and more resistant moss remains (Fig. 3).

To determine the origin of amorphous decomposed organic matter in the sediments OC/N analysis from the bulk samples was performed. It has been reported that OC/N ratios in lake sediment reflect to some extent the composition of organic matter in the process of sediment formation (Wetzel, 1983; Punning et al., 2003). As the protein content of organic matter produced by organisms varies, the OC/N ratio can be used to estimate the percentage of autochthonous planktonic matter in sediments (Punning & Tõugu, 2000). So, the OC/N ratio in eutrophic lakes with high plankton production is ca 7–8 and increases to 15–20 in dystrophic lakes in Estonia, where allochthonous organic matter dominates in the total OC (Punning et al., 2003).

There is a rather clear relationship between the OC/N ratio of the bulk organic matter in the surface samples in L. Juusa and sampling depth (Fig. 4). The obtained

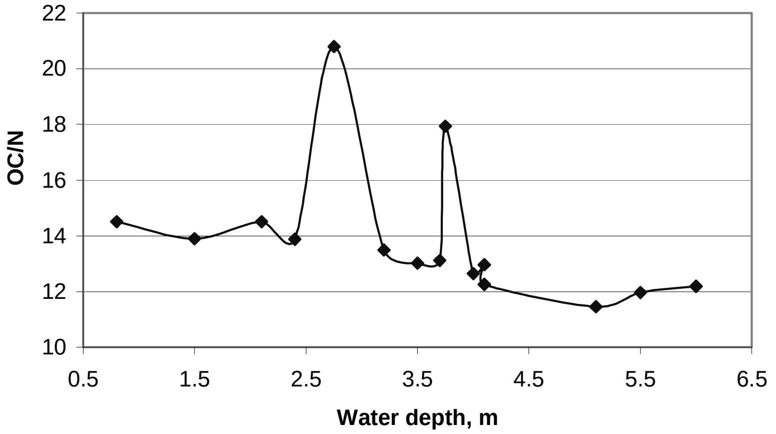

Fig. 4. The values of OC/N bulk organic matter in the surface sediments sampled from different depths.

data demonstrate that the proportion of planktonic matter increases towards the profundal zone and has practically constant values in areas deeper than 4 m. Rough estimates according to calculations presented in Punning & Tõugu (2000) show that in the deepest area of L. Juusa the proportion of non-planktonic matter is around 20% of total organic matter. The proportion of non-planktonic matter increases towards the littoral zone and reaches 30–35%. As there is only a very small inlet the non-planktonic organic matter is not carried from the catchment but mainly originates from macrophytes growing in the littoral zone. The OC/N values in samples from the littoral area, where the greatest abundance of macrophyte remains and periphytic diatoms was estimated, is about 15 decreasing to 12 in sites deeper than 3.5 m. The anomalously high percentages of non-planktonic matter in sites JM14 (62%) and JM17 (50%) are probably caused by the presence of ligneous plant remains (Fig. 3) from trees growing on the shore. The coarse-grain mineral matter in those samples and the abundance of macroremains suggest sediment focusing caused by steeper slopes in some areas of the littoral zone (Fig. 1).

CONCLUSIONS

We studied the depth distribution of diatoms, macrophyte remains, and OC/N ratio in bulk organic matter in the surface sediments of a small eutrophic dimictic lake in southern Estonia. The species richness of diatoms and number of periphytic taxa were higher in samples collected in the littoral zone where water depth is less than 3.5 m than in deeper areas. Here also the abundance of macrophyte remains was higher and the OC/N values in bulk organic had larger values. This suggests an increased share of non-planktonic matter in sediments.

Great changes took place in diatom assemblages and the content of macrophyte remains and the OC/N values reached their lowest and stabile values in the depth profile from the littoral to the profundal zone at a depth of some 3.5–4 m. The results obtained by these three approaches show a considerable link to the water depth of the sampling site, especially in the marginal areas of the lake. Therefore these results from modern samples can be used in interpretations of water-level changes in L. Juusa from long cores.

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Diatomeede, subfossiilsete makrofüütide ja OC/N-i väärtuste varieeruvus Väike Juusa järve (Lõuna-Eesti) pindmistes setetes

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On uuritud Väike Juusa järve pindmiste setete diatomeekoosluste, subfossiilsete makrofüütide leviku ja pindmiste setete OC/N-i väärtuste muutusi sõltuvana vastava setteproovi sügavusest. Saadud tulemused näitavad, et sügavuse suurenedes suureneb setetes planktiliste diatomeede suhteline osakaal. Et hinnata veemasside horisontaalse liikumise ja setete fookustamise mõju diatomeede ümberpaigutusele, teostati samades proovides ka subfossiilsete makrofüütide ja OC/N-i analüüs. Tulemused näitavad, et subfossiilsete makrofüütide jaotus on heas kooskõlas perifüütsete diatomeede jaotusega. Samuti vähenevad OC/N-i väärtused setteproovides litoraalist profundaali suunas. Saadud tulemused näitavad, et kasutatud komplekset metoodikat saab rakendada järvede veetaseme kõikumiste rekonstruktsiooniks.