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Human impact on Lake Ladoga as indicated by long-term changes of sedimentary diatom assemblages

Natalia N. Davydova[1], Minna Kukkonen[2], Heikki Simola[2] and Dmitry A. Subetto[1]

[1] *Institute of Limnology, Russian Academy of Sciences, Sevastyanova St. 9, 196199 St. Petersburg, Russia*
[2] *University of Joensuu, Karelian Institute, P.O. Box 111, FIN-80101 Joensuu, Finland*

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Lake Ladoga is the largest lake in Europe. Eutrophication of the lake, caused by various human activities, has been noticed since the early 1960s. Besides nutrients, Lake Ladoga is also affected by industrial pollution. In order to assess patterns and trends in the aquatic environment quality, we have applied Detrended Correspondence Analysis (DCA) to surface sediment diatom assemblages, collected from different parts of the lake in 1959–60, 1978–79 and 1991–94, and from the main inflowing rivers in 1983–85. The eutrophication process is evident as a general change of the diatom assemblages between the three sampling periods, e.g. appearance of *Diatoma tenuis* first in the Volkhov Bay area in 1978–79 and subsequently throughout the lake. The eutrophication appears most pronounced near the discharge sites of industrial and municipal effluents and main river inflows. The river sediment assemblages reflect patterns in the riverine inflow quality related to catchment geology and effluent loading.

Introduction

Lake Ladoga, with its surface area of 17 891 km^2 and volume of 837 km^3 is the largest lake in Europe, and among the fifteen of the world's largest freshwater bodies. Its drainage area (258 000 km^2) is extending to much of northwestern European Russia and eastern Finland.

The theoretical water retention time in Lake Ladoga is about 11 years, and mixing of the main pelagial water mass is effective. Nevertheless, there is areal and temporal variation in the water quality, particularly during times of thermal bar existence, when the shallow coastal waters are physically separated from the central water mass (Naumenko *et al.* 1996). There is evidence of eu-

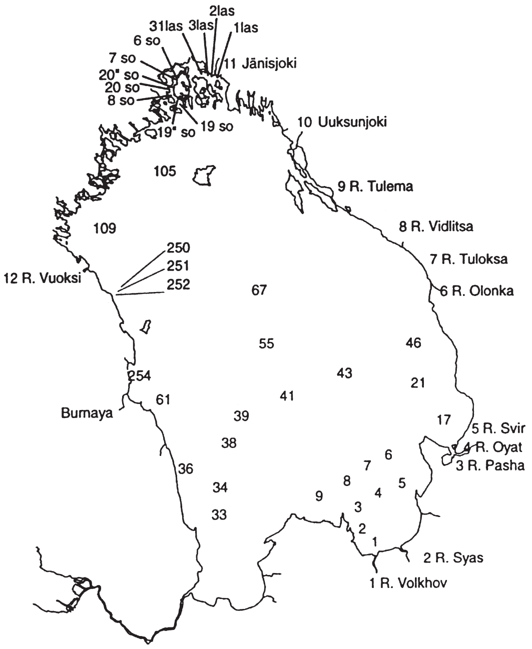

Fig. 1. Lake Ladoga and its main tributaries. Sampling sites for sediment surface diatom assemblages in the lake indicated with their site codes; river numbers refer to samples of riverine diatom assemblages.

trophication and water quality deterioration (increased nutrient levels, algal blooms) especially in some coastal areas near pollution sources, but also in the pelagial water mass (e.g. Drabkova *et al*. 1996, Holopainen *et al*. 1996).

Besides the considerable human impacts of today, affecting the water quality (Lozovik *et al.* 1997, Rumyantsev and Kondratyev 1999), there are also great natural differences in the water quality of the inflowing rivers, owing to geological characteristics of the large drainage area. The northern part of the drainage area consists of Precambrian crystalline bedrock, the Fennoscandian shield, whereas the southern part is on the younger sedimentary rocks of the Russian Plain; the intervening zone between these two areas consists of Quaternary clays and sands (Simonen 1990). The drainage waters of the northern inflows are on the average weakly buffered and more or less humic, while the southern river waters are more alkaline.

Since the late 1950s, a considerable body of data about the recent and sedimentary diatom flora of Lake Ladoga has been collected (e.g. Davydova 1968, 1969, 1990; Davydova *et al*. 1983, 1992, 1994). In this paper we are dealing with the surface sediment diatom assemblages contained in this long-term monitoring data set, i.e. samples representing the actual floras of the sampling occasions; palaeolimnological analyses of sediment core analyses are presented e.g. by Davydova *et al*. (1992), and Kukkonen and Simola (1999).

Material and methods

Monitoring of the surface sediments and sedimentary diatom assemblages of Lake Ladoga can be divided into four periods. During the first period (1959–60) the sediments were sampled at 101 sites for grain size, organic content and diatom assemblage analyses. During 1978–79, surface samples from the pelagial areas were taken. During the third period (1983–85) sediment samples were taken at 28 near-shore sites as well as from the mouths of 13 main inflowing rivers. The river samples, consisting of river bottom sediment, are in most cases taken from road bridges crossing the rivers near their outflow. The most recent investigations have been conducted during the joint Russian-Finnish studies in 1991–94, with altogether 60 sampling sites. Acid-cleaned diatom mounts usually represent the 0–1 cm surface sediment extracted from a gravity corer sample (Davydova 1985).

The present analyses have been conducted using DCA ordination (Detrended Correspondence Analysis; Hill and Gauch 1980, ter Braak 1986) of the diatom assemblages. As regards the lake sediment samples, the sampling sites of the different surveys are quite disparately distributed, so we have selected spatially representative sample sets for each period (18 sites for 1959–60, 19 for 1978–79 and 9 for 1991–94; of these, two sites have been sampled during all three surveys and 14 during two surveys). For the sake of taxonomic consistency, the multivariate analyses are solely based on the samples microscopically examined by N. Davydova. A complete list of the diatom counts is available on request at Karelian Institute (from author M.K.).

The sampling sites dealt with in this study are shown in Fig. 1. For the DCA of the diatom assemblages, all species exceeding 1% in at least one sample were included. The analyses were

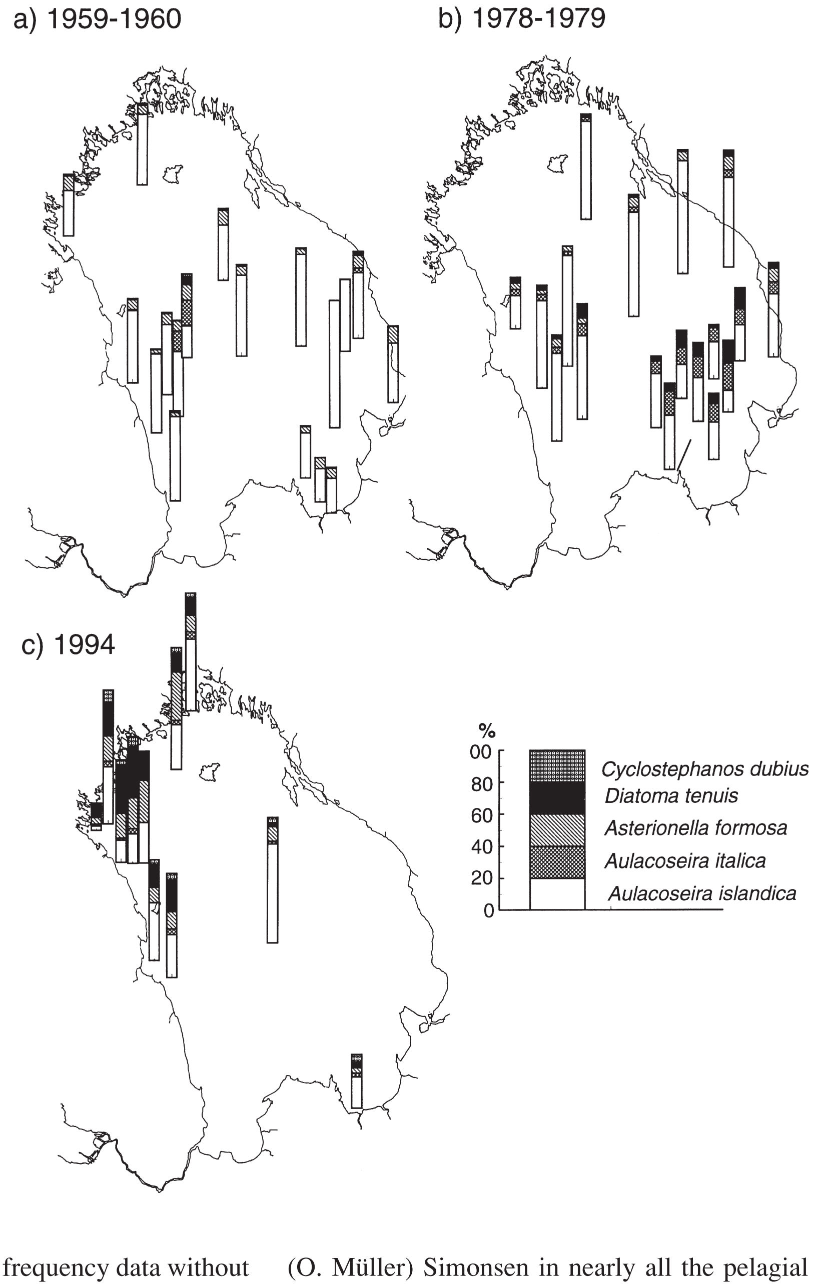

Fig. 2. Percentage proportions of five planktonic diatom species in the years 1959–60 (a), 1978–79 (b) and 1994 (c) of the total count of diatoms in samples representing both deep and shallow sites in the open pelagial lake (archipelago and sheltered bay sites are excluded).

performed on percentage frequency data without transformations.

Results

Pelagial area floral trends 1959–1994

During the first sampling period (1959–60), the most numerous diatom was *Aulacoseira islandica* (O. Müller) Simonsen in nearly all the pelagial samples, and the flora generally indicated oligotrophic state of the lake ecosystem (Davydova 1968). At some coastal areas like in the Volkhov Bay (sampling stations 1–5) and near the Burnaya River outlet (sampling station 39) *Aulacoseira italica* (Ehr.) Simonsen and *Asterionella formosa* Hassall were abundant (Fig. 2a). During the second period of investigations (1978–79) *Aulacoseira italica*, *Diatoma tenuis* Agardh and *Asterionella*

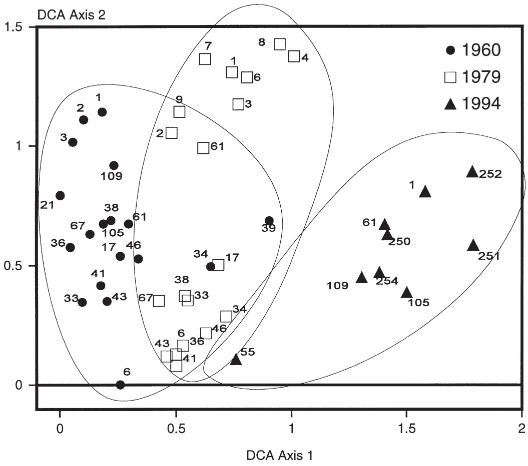

Fig. 3. DCA ordination of surface sediment diatom assemblages collected from the open pelagial sampling sites in the years 1959–1960, 1978–1979 and 1994. For site locations, *see* Fig. 1. Eigenvalues for the first and second axes are 0.252 and 0.128, respectively.

formosa were encountered as codominants of the plankton community, especially in the southern parts of the open lake (Volkhov Bay), where the assemblage compositions indicated b-mesosaprobic conditions (Davydova 1985; Fig. 2b). In 1991–1994, survey the frequency of *Asterionella formosa*, *Aulacoseira italica* and *Diatoma tenuis* was rather consistently increased in all stations as compared with 1978–79, whereas the frequency of *Aulacoseira islandica* was generally lower than in the previous surveys (Fig. 2c). In the middle of the lake, *A. islandica* was still a major component of the assemblage.

DCA analysis of the samples clearly shows the general trend in an ecosystem change (Fig. 3). The main gradient along the first DCA axis appears temporal; sites of each of the investigation periods show definite cohesion, so the 1959–60 samples form a definite cluster at low values of axis 1, and the most recent samples similarly cluster at high values. The 1979 samples are scattered in between: the southern and eastern Volkhov and Svir Bay samples, together with one site (nr 61) near the Burnaya River outlet, deviate from the central and northern sites. This illustrates the situation already noted by Davydova *et al.* (1983): riverborne loading entering the Volkhov Bay was especially reflected in an increase of *Diatoma tenuis* in the SE areas of the lake (Fig. 2b). In 1994, the eutrophication effects had become evenly distributed throughout the pelagial (Fig. 2c). Hence, the situation in 1979 pinpoints a critical phase in

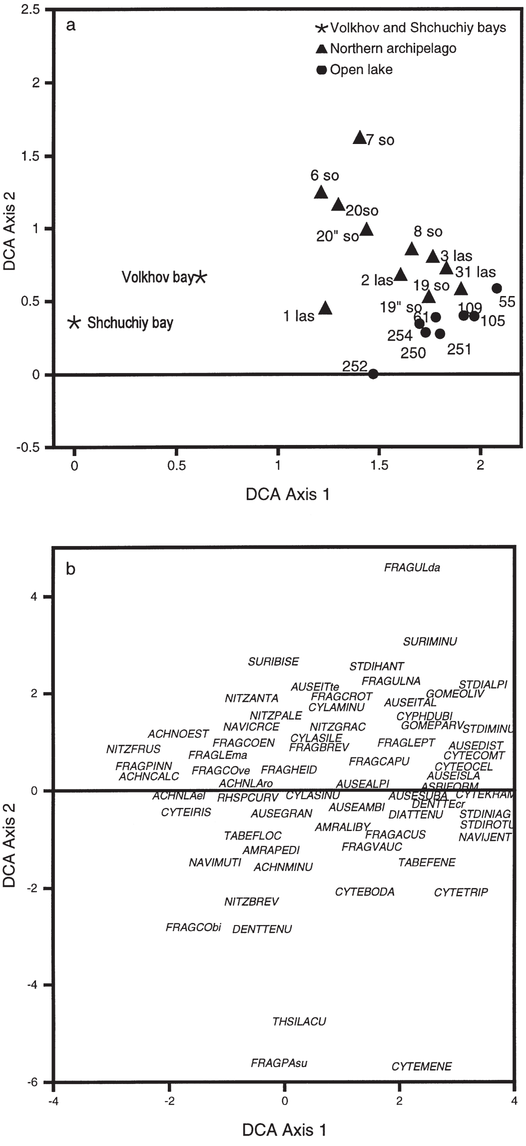

Fig. 4. DCA ordination of sampling sites (a) and diagnostic diatom species (b) of the surface sediment samples collected in 1994. Both open pelagial and sheltered littoral sites are included in this data. Eigenvalues for the axes 1 and 2 are 0.282 and 0.099 respectively. The two heavily polluted bays (Shchuchiy and Volkhov) appear as outliers, and also the samples from the northern archipelago emerge as a group distinct from samples representing the open pelagial area. Acronyms for the taxa are according to van Dam *et al.* (1994).

ecosystem transition.

DCA of the 1994 samples, including both pelagial and some near-shore and archipelago sites is shown in Fig. 4 (a: sites, b: species). The most polluted sites appear in the restricted areas of point-source pollution, the Shchuchiy Bay and at the mouth of the Volkhov River. Also the northern archipelago area, including sites within the influence of effluents from Sortavala and Läskelä, differs from the samples representing the open pelagial areas, which in this ordination cluster closely together.

In general, the diatom assemblages of the 1994 survey can be characterized as indicative of meso-eutrophic conditions. Some key species can be tracked at the periphery of the species ordination (Fig. 4b; acronyms for the taxa according to van Dam *et al.* 1994); thus, *Nitzschia frustulum* (Kütz.) Grunow (*NITZFRUS*), *Fragilaria* spp., *Achnanthes* spp. and *Rhoicosphenia curvata* (Kütz.) Grunow (*RHSPCURV*) characterize the most heavily polluted areas. All these taxa are littoral. Their high abundances also reflect the habitat characteristics of these shallow sites. The pelagial stations, clustering at high axis 1 scores and low axis 2 scores are on the other hand associated with abundance of several planktonic taxa (*Cyclotella* spp., *Thalassiosira lacustris* (Grunow) (*THSILAC*), *Stephanodiscus* spp., *Tabellaria fenestrata* (Lyngb.) Kützing (*TABEFENE*); Fig. 4b).

Riverine diatom assemblages

The riverine diatom assemblages consisted mainly of periphytic taxa such as *Fragilaria* spp., *Eunotia* spp., *Navicula* spp., *Cymbella* spp. and *Achnanthes* spp., but also some planktonic species, e.g. *Aulacoseira islandica, A. italica, A. alpigena* (Grunow) Krammer, *Stephanodiscus minutulus* (Kütz.) Cleve & Möller and *S. hantzschii* Grunow.

In case of the riverine assemblages, geology of the drainage area appears to be the strongest factor behind the ordination, and a lesser impact of human activities in the respective river environments can be found. The quality of inflowing water is essentially determined by geology: water flowing through the northern crystalline bedrock area is low-buffered, acidic and in most cases humic. Typical species with overall high abundances in the northern rivers include the epiphytic *Eunotia veneris* (Kütz.) De Toni, *E. bilunaris* (Ehr.) Mills and *Achnanthes minutissima* Kützing and the benthic *Frustulia rhomboides* (Ehr.) De Toni. In contrast, the southern rivers, draining the Russian Plain area with its sedimentary rocks, are naturally well-buffered and alkaline. The catchments of the southern rivers, as well as that of the Olonka River (6) on the intervening zone, are extensively cultivated, with consequent high nutrient loading. The diatom assemblages of the southern rivers are characterized by e.g. *Rhoicosphenia curvata* and *Opephora martyi* Héribaud. The geological and land use pattern is reflected in the axis 1 scores of the samples (Fig. 5), with the northern rivers attaining generally higher scores than the southern ones. The rivers Syas (2) and Volkhov (1), which are strongly impacted by industrial effluents are disjunctly positioned in this ordination, with low axis 2 scores (Fig. 5).

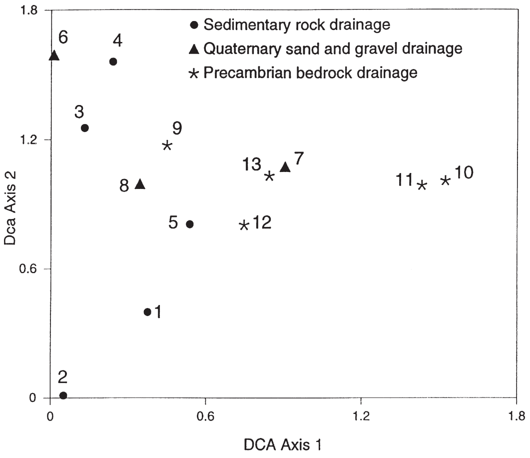

Fig. 5. DCA ordination of riverine sediment diatom assemblages, collected in 1983–1985, representing mainly periphytic flora of the rivers. For river numbers, *see* Fig. 1. Symbols denote the predominant geology in each river's drainage area. Eigenvalue for axis 1 is 0.195 and that of axis 2 is 0.126.

Discussion and conclusions

Assemblages of diatom frustules in surface sediments can be regarded as temporally and spatially integrated samples of living diatom communities. Owing to their integrative character, and while the ecological requirements of different diatom taxa are fairly well known, analysis of such samples is a cost-effective means of obtaining monitoring data of the environmental conditions in aquatic environments. The surface sediment diatom assemblages mainly represent diatom production in the different algal communities in the vicinity of the sampling site during a reasonably short period of time preceeding the sampling occasion. However, the complex processes of sedimentation, sediment transportation, redeposition and diagenetic destruction of frustules will affect each site on a unique way, so that some caution is called for when comparisons are made between sedimentologically and hydrologically different sites.

As regards the special conditions in Lake Ladoga, water mixing in the open pelagial area is quite effective, so the floral assemblages appear fairly homogeneous, and the ordination gradients consequently short. Nevertheless, definite spatial patterns emerge even for the pelagial samples (c.f. Fig. 2b), in addition to the general observation that coastal sites are on the average more eutrophic than the central deep areas.

The data dealt with in this paper covers a time span of critical importance as regards the environmental strain of Lage Ladoga. Since the late 1950s the ecosystem has changed from general oligotrophy into meso-eutrophy. The present pattern of increased nutrient loading especially at some sheltered coastal areas of the lake and near the inflows of some rivers, seen in the diatom assemblages, is in accordance with other monitoring data, e.g phytoplankton (Holopainen *et al.* 1996), water chemistry (Lozovik *et al.* 1997) and benthos studies (Slepukhina *et al.* 1996).

According to stratigraphic diatom analyses of dated sediment cores (Davydova *et al.* 1983, Kukkonen and Simola 1999), a gradual ecosystem change, conceivably due to human impact, has in fact been continuing for a considerably longer time even in the pelagial areas. The most notable indicator of this change is the decline of *Aulacoseira islandica* at least since the 1700s (Kukkonen and Simola 1999).

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